Passivity-based Screening to Identify Critical Nodes for Converter Interoperability in Power Systems

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***Abstract*—The foundation for a passivity-based screening method is introduced with the objective of narrowing the scope of interaction studies for converter interoperability assessment to only those locations where stability issues may arise. With the growing prevalence of renewable energy sources and converter-based generation in the power system, converter interoperability studies are becoming increasingly important. Ensuring that a new converter will not negatively interact with other converters and grid elements can be a challenging and time-consuming undertaking. Screening methods to reduce the effective area to consider in interaction studies can provide a tool to reduce the complexity. However, established methods rely on empirical observations and experience to determine interaction likelihood. The proposed method provides a way to screen for converter interoperability issues using the concept of passivity to provide stability guarantees. Although presently limited to converter interactions with a passive system, it provides the basis for a full screening method between any two systems. The method is tested in Simulink by simulation of a 39-bus system with a 2-level converter, demonstrating the validity of the proposed approach.**

***Index Terms*—interoperability, power converters, power systems, stability, passivity, harmonic interactions**

I. INTRODUCTION

The degree of converter-based power generation in the electricity grid is steadily increasing and this trend is expected to continue as adoption of renewable energy resources increases. Converter-interfaced renewable plants do not inherently behave as standard synchronous generator-based power plants, and are typically characterized by low inertia and the presence of harmonics across a wide frequency range. Moreover, the power electronic converter interfaces can create problematic interactions with other elements in the grid such as other power electronic converters, synchronous generators, and filters [1]. As the share of converter-based resources increases, additional care must be taken to ensure these resources do not cause harm to the grid operation or to other components.

Interaction issues can occur at a wide range of frequencies (from subsynchronous to supersynchronous) [2], and with a wide variety of causes, from control loop interactions to nonlinear functions and harmonic or resonance interactions [3]. There are various stability assessment methods that can be used to analyze potentially problematic interactions. The most extensive, reliable approach is to use time-domain simulations using an electromagnetic transient (EMT) simulation tool. In this approach, the system components are modeled explicitly including the switching behavior of power electronics, such as in [4]. While this type of study is the most reliable, it is the most time-consuming, both in terms of creating models and running simulations. Detailed models of each converter and all other elements involved in the study must be available, and a wide array of operating conditions must be examined. With an increasing number of converters, the operating points to consider grows exponentially for an already time-intensive process.

Such time-domain studies are, however, often unavoidable to ensure the interoperability of new, large converters to the grid. It is then highly beneficial to identify in advance possible critical locations to focus upon, and also to reduce the size of the power system to consider in the studies. Indeed, a first step can be to apply a screening method to simplify regions of the power system where it is reasonable to assume with a certain degree of confidence that interactions may not occur. In this sense, screening methods do not aim at directly conclusive results but rather to limit the scope of the work of detailed analyses with conservative assumptions.

Several basic types of studies are commonly used in industry for initial screening. Short circuit levels are calculated at the point of connection of the devices/systems under study and in the vicinity. This method will show stronger and weaker buses. In general, undesirable interactions between converters are more likely in weak buses than in stronger parts of the grid. Impedance sweeps are also commonly applied to provide information on the resonance frequencies at selected nodes [5]. Furthermore, potential interactions (including risk for sub-synchronous torsional interactions (SSTI)) between a power-electronics converter and the shaft of (large) synchronous generators can be screened using the Unit Interaction Factor [6], [7]. Screening for SSTI can also be performed by calculating the electrical damping when a perturbation in mechanical speed or torque of a generator is introduced [8]. While positive electrical damping indicates that rotor oscillations will be damped, negative electrical damping may damp, sustain, or even amplify rotor oscillations, depending on the available mechanical damping. These methods, in general, indicate a risk of negative interactions and a need for detailed studies.

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One of the most common screening methods is the Multi-Infeed Interaction Factor (MIIF), which was first developed in [9] for new LCC HVDC connections and popularized further in [10]. The MIIF gives an indication of how strongly linked two HVDC systems are, with a high factor indicating strong coupling. The MIIF is determined empirically by measuring the ratio of voltage drops between two buses given a roughly 1% voltage drop at one of the buses. It can be calculated as:

$$MIIF_{e,n} = \frac{\Delta V_e}{\Delta V_n} \tag{1}$$

where ΔV_e is the measured voltage drop at an existing bus with LCC, and ΔV_n is the voltage drop at the new LCC bus. Ref. [10] suggests that if the MIIF between two buses is less than 0.1, the risk of interaction issues between the two can be ignored. This value of 0.1 is based on empirical observations. The concept was further developed for application to VSC HVDC in [11]. In addition to the MIIF, there are other similar metrics, some of which can be calculated analytically [12]. However, none of these screening methods provide a strong scientific basis for what values/conditions interactions between converters and other converters or grid elements can be safely ignored in an interaction analysis.

This work presents the basis for a screening method to narrow the scope of interaction studies, allowing for a smaller system with narrowed operating points to be studied in-depth. The screening method is based on the concept of passivity, and defines a region where a converter and a part of the network together form a passive system. A passive system can provide guarantees about the stability, and this allows the proposed method to provide stability assurances such that unstable interactions outside the screening area are not possible, while other methods can only provide relative measures about the degree of expected interactions. The method as presented here is limited to converter interactions with passive systems, but will be extended to include other non-passive converters.

II. Passivity of Converters

The proposed method for interaction studies uses the concept of passivity to give an indication of stability. The method is limited to small-signal passivity considerations that can be performed on a specific operating point by examining the real part of the equivalent impedance of the converter. A passive system is defined when the real part of the equivalent impedance/admittance (as shown in Fig. 1) is non-negative [13]:

$$\Re(Z_{eq}(s)) > 0 \tag{2}$$

A system is inherently stable if it is passive, and two passive systems connected together will also be stable as there is net energy adsorption [14]. In this way, it can be used as a criteria for stability. An equivalent impedance can be defined for the converter, the grid, a subset of the grid, or a combination. The converter impedance, and possibly the grid impedance, are operating-point dependent. Therefore, changes to the grid conditions will affect the impedance,

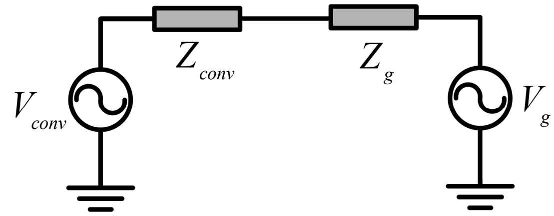


Fig. 1. Equivalent impedance of converter and grid

and by extension, passivity, of the converter. Note that (2) refers to single-phase systems or balanced, symmetrical 3-phase systems.

Converters typically have frequency regions of non-passivity due to time delays and switching behavior [15]. This is called *partial-passivity*. However, if the converter is passive in frequency regions where there is a resonance in the grid, unstable behavior is highly unlikely [13]. Therefore, examination of passivity at grid resonances provides a good determination of grid-converter interaction risks. Passivity has been used as the basis of several converter control strategies [16]–[18].

Converter impedance or admittance can be measured by series or shunt injection of voltage/current. These can be measured in sequence domain, such as [19], or in dq-domain, such as [20]. In the example case used, series d- and q-voltage injection is used. The admittance and impedance are defined as:

$$\mathbf{Y_{dq}}(s) = \begin{bmatrix} Y_{dd}(s) & Y_{dq}(s) \\ Y_{qd}(s) & Y_{qq}(s) \end{bmatrix}, \quad \mathbf{Z_{dq}}(s) = \begin{bmatrix} Z_{dd}(s) & Z_{dq}(s) \\ Z_{qd}(s) & Z_{qq}(s) \end{bmatrix} \tag{3}$$

where

$$\begin{bmatrix} V_d(s) \\ V_q(s) \end{bmatrix} = \mathbf{Z_{dq}}(s) \begin{bmatrix} I_d(s) \\ I_q(s) \end{bmatrix} \tag{4}$$

The impedance and admittance are linked as follows:

$$\mathbf{Z_{dq}}(s) = \mathbf{Y_{dq}}(s)^{-1} \tag{5}$$

When the impedance is determined using measurements, two sets of linearly independent perturbations should be applied, e.g. an injection of d-axis voltage and an injection of q-axis voltage [21].

It can be shown that when a MIMO impedance is used (a dq impedance for example), the power dissipation and therefore passivity [15], can be assessed by examining the eigenvalues of:

$$\mathbf{Z_{dq}}(j\omega) + \mathbf{Z_{dq}}^H(j\omega) = \begin{bmatrix} a & c^* \\ c & b \end{bmatrix} \tag{6}$$

where *H* denotes the Hermitian conjugate, and *a*, *b*, and *c* can be found as:

$$a = Z_{dd}(j\omega) + Z^*_{dd}(j\omega) = 2\Re\{Z_{dd}(j\omega)\} \tag{7}$$

$$b = Z_{qq}(j\omega) + Z^*_{qq}(j\omega) = 2\Re\{Z_{qq}(j\omega)\} \tag{8}$$

$$c = Z_{dq}(j\omega) + Z^*_{qd}(j\omega) \tag{9}$$

Active power is dissipated when the eigenvalues of (6) are positive, and the system can be classified as passive when this is true for all frequencies. When the system is symmetric, $Z_{dd}(s) = Z_{qq}(s)$ and $Z_{dq}(s) = -Z_{qd}(s)$. This implies that c will be zero, and a and b are equal and the eigenvalues can be evaluated by examining a only. In symmetrical conditions, it is therefore sufficient to ensure $\Re\{Z_{dd}(s)\} > 0$ for passivity. Consideration should be given to the method of evaluating passivity, but in all other regards, the methods presented here are applicable to both SISO and MIMO impedances.

III. Passivity-based Screening

This section describes the proposed screening method for reducing the area in a grid network that must be examined for detailed interaction studies.

A. Passivity in the Presence of a Resonance

A resonance present in a passive system will not result in instability since any oscillations resulting from excitation of the resonance will eventually decay. Conversely, a resonance present in a non-passive system may cause increasing oscillations, leading to instability. Note that a non-passive system is not necessarily unstable. This coincides with the objective of a screening method, i.e. it will not provide a final assessment of stability, but rather a conservative conclusion of where instability is not possible. Therefore, the passivity of the equivalent impedance at the point of connection of a potential source of resonance will determine stability. This is shown with an LC circuit in Fig. 2, where the passivity at Point R can be calculated by examining the real part of the equivalent impedance.

An LC circuit is used in this work to demonstrate the concept of passivity-screening clearly, but resonances can come from many sources, including other converters and their interactions with the grid. The filters of converters, for example, are often a combination of inductances and capacitances, which can create a resonance with the grid.

The passivity of the equivalent impedance as seen from the LC will change depending on where in the grid the sources of non-passivity are and where the LC is located, implying changing stability conditions at different locations in the grid.

B. Distance-to-Passivity

As the electrical distance from a converter to a given bus increases, the positive resistances in the lines will progressively negate the non-passivity of the converter until, at a far enough distance, the converter and lines combined will become passive. This is expressed diagrammatically in Fig. 3. If the bus is sufficiently far from the converter such that the equivalent impedance at this bus is passive, stability can be ensured. This is similar to the process used in [22] to encapsulate a non-passive generator with part of the grid to create a passive subsystem.

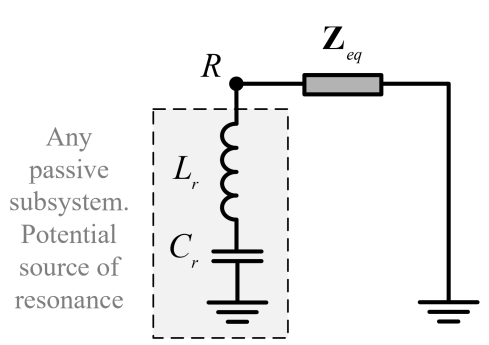


Fig. 2. An LC resonance with an equivalent impedance

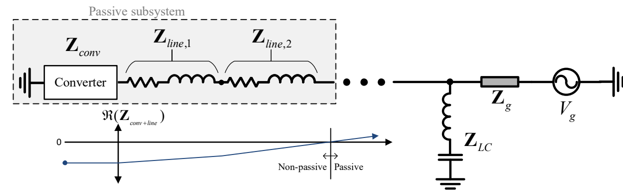


Fig. 3. Diagram showing increasing electrical distance to a resonance.

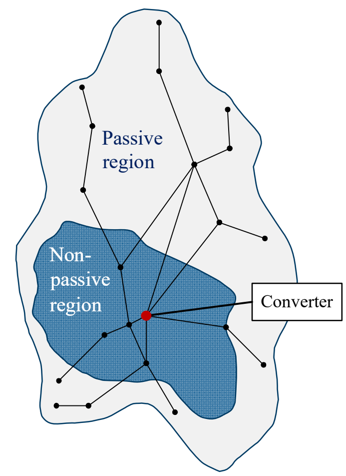


Fig. 4. Passive and non-passive regions surrounding a converter.

When a sufficient grid model is available and the impedance of the converter is known, the passivity at a potential source of resonance can be calculated at different points in the grid. This will lead to a passive and non-passive region, as shown in Figure 4. Since passivity of a system guarantees stability, potential interactions with elements in the grid outside the non-passive region can be safely ignored. The area for more in-depth interaction studies can be effectively reduced to the non-passive region.

C. Screening Methodology

This distance-to-passivity concept can be used to develop a screening method for potential interactions, shown in a process diagram in Fig. 5. The known impedance of the converter can be combined with a grid impedance model to calculate the equivalent impedance, $\mathbf{Z}_{eq}$, as seen by each bus n in the system. Note that $\mathbf{Z}_{eq}$ is the total impedance as seen by a particular bus, including the converter and grid. This

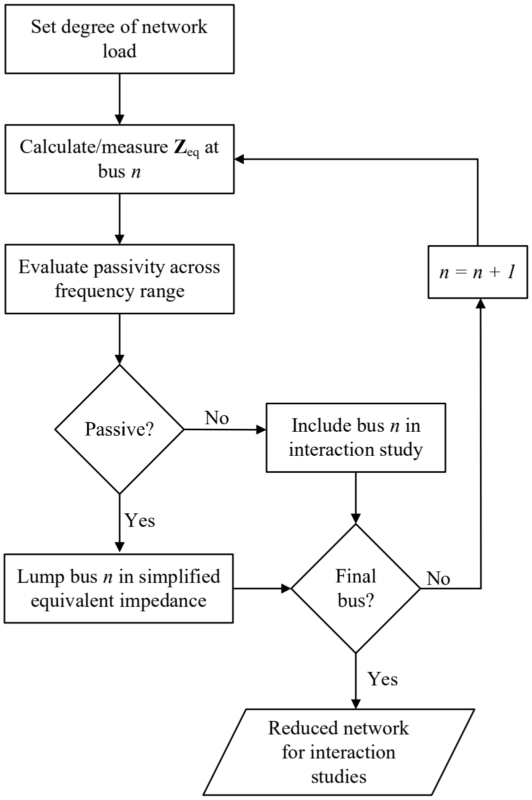


Fig. 5. Procees diagram of passivity-based screening.

impedance can be measured directly at a bus or calculated analytically through series/parallel combinations of impedance models. The passivity at each bus can be calculated using the equivalent impedances, resulting in a set of passive and non-passive buses. The passive buses can be safely "ignored" for resonance studies and lumped into an equivalent impedance. Note that in networks consisting of buses in series, the process in Fig. 5 only needs to continue until the first passive bus is reached, as additional series impedances will make the system more passive. However, care should be taken to consider the effect of parallel connections when the network has many interconnections between buses. To be conservative, all buses can be analyzed.

Any passive system connected to a bus whose equivalent impedance is also passive will result in a stable system. Therefore, even connecting a system that contributes to a resonance (such as an LC circuit or another passive converter) at this bus will result in a stable system.

Note that the grid model may include loads and generators or not, depending on the level of conservativism desired. This is discussed in further detail in Section IV-B. Additionally, note that the impedance is calculated for a specific operating point. Changes in the grid conditions or converter set-points will affect the operating point, and the analysis should be performed for all expected operating conditions.

IV. Impedance Model Considerations and Example System

The passivity of a system can be directly calculated from the system equivalent impedance, and therefore an accurate impedance model is essential to a passivity-based screening method. Interoperability issues can occur over a wide range of frequencies and so passivity should be examined over a wide frequency-band. Therefore, frequency-dependent impedance models are needed for the converter and the grid. The equivalent impedance of the converter, Z_{conv}, and the grid, Z_g, are shown in Figure 1.

Impedances are often measured or calculated in the dq- or sequence-domain. Reference [21] has shown that these domains are equivalent and can be transformed from one to another. However, practical considerations may favor one over the other. Control schemes for converters often use the dq-frame for control signals, although these require a reference transformation angle. It may be simpler to inject and measure signals in the sequence domain. An algorithm for measuring impedance in dq-domain is presented in [23], while sequence impedance measurement is presented in [19], in particular for converters and wind turbines.

Passivity can also be obtained by examining admittance. It may be simpler in some cases to measure admittance than impedance. The equivalent impedances in Fig. 1 can be replaced by admittances as necessary.

A. Converter Impedance

A 2-level converter controlled as a virtual synchronous machine (VSM) is used as an example converter, based on the models developed in [24] and [25]. An analytical state-space model for the VSM model is also derived and verified in [24], [25]. The model has the grid voltage in d- and q-axis, $v_{g,d}$ and $v_{g,q}$ as model inputs, and the converter output voltage and current, $v_{cv,d}$, $v_{cv,q}$, $i_{cv,d}$ and $i_{cv,q}$ as outputs. The converter impedance can be solved for by using the individual transfer functions from grid voltage to output voltage and grid voltage to output current as follows:

$$\mathbf{Z_{dq}} = \begin{bmatrix} \frac{V_{cv,d}(s)}{I_{cv,d}(s)} & \frac{V_{cv,d}(s)}{I_{cv,q}(s)} \\ \frac{V_{cv,q}(s)}{I_{cv,d}(s)} & \frac{V_{cv,q}(s)}{I_{cv,q}(s)} \end{bmatrix} = \begin{bmatrix} \frac{V_{cv,d}(s)}{V_{g,d}(s)} \cdot \frac{V_{g,d}(s)}{I_{cv,d}(s)} & \frac{V_{cv,d}(s)}{V_{g,q}(s)} \cdot \frac{V_{g,q}(s)}{I_{cv,q}(s)} \\ \frac{V_{cv,q}(s)}{V_{g,d}(s)} \cdot \frac{V_{g,d}(s)}{I_{cv,d}(s)} & \frac{V_{cv,q}(s)}{V_{g,q}(s)} \cdot \frac{V_{g,q}}{I_{cv,q}} \end{bmatrix} \tag{10}$$

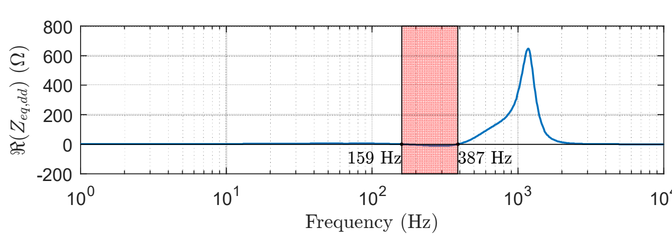


Fig. 6. Real part of converter impedance with red area showing non-passive frequencies.

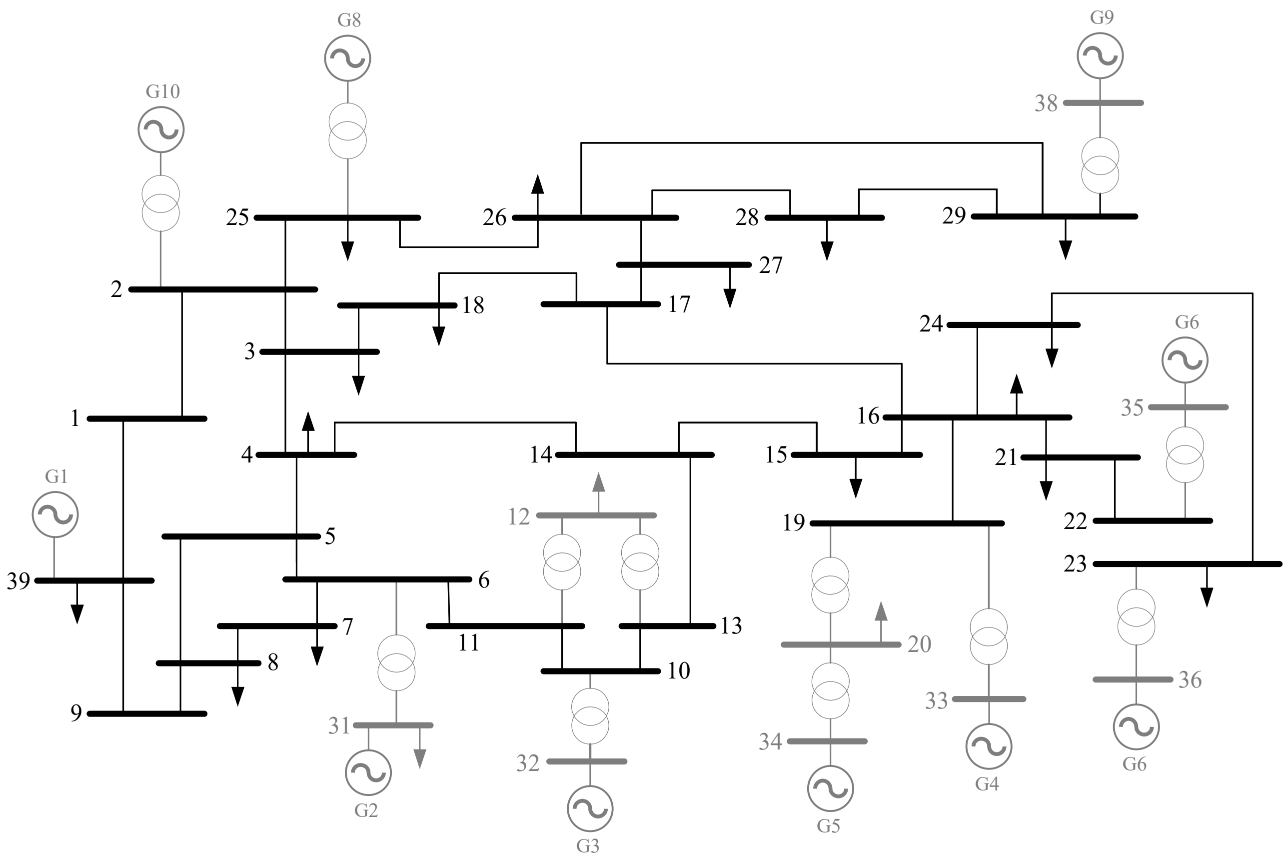


Fig. 7. Grid model used in example case, IEEE 39 bus system. Gray buses and lines are not considered.

An additional filter, a shunt RL branch, is added to the converter to more easily adjust the non-passive behavior of the converter as desirable. The impedance of the total converter is then calculated as the parallel impedance of this filter and (10). Under these conditions, the converter has very nearly symmetrical behavior, implying that $Z_{dd}(s) = Z_{qq}(s)$ and $Z_{dq}(s) = -Z_{qd}(s)$. As discussed in Section II, the passivity can then be determined by examining $\Re\{Z_{dd}(s)\}$. For simplicity, only the dd-impedance is used in the remainder of the work. Fig. 6 plots the real part of the converter dd-impedance for the specific converter. The converter is non-passive in the region between 159 Hz and 387 Hz.

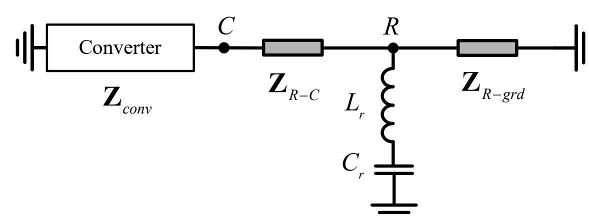


Fig. 8. Impedance representation of a converter connected at Bus C, an LC circuit connected at Bus R, and the remaining grid impedance.

B. Grid Impedance

As the converter can have non-passive regions in a wide range of frequencies, the grid model must also be sufficiently accurate at the same range of frequencies. Ref. [26] provides an overview of various methods for obtaining a frequency-dependent network equivalent. To use passivity as a screening method, not only is a frequency-dependent model needed, but it is needed at all points in the grid to be screened.

1) Example Grid: The example grid used to test the proposed screening method is based on the IEEE 39-bus system, shown in Figure 7, with transmission lines modeled as series RL branches. Note that the generators and buses with transformers are not used, and are marked in gray instead of black in the figure. This is to provide a grid model that is more operating-point independent and to provide a conservative "worst-case" scenario. At higher frequencies, the generators will act as a passive impedance, and thereby increasing the effective resistance in the grid. The loads in the system are considered to show their effect on the distance-to-passivity.

A case with no loading, 0.1% loading, and 1% loading are considered. No loading is the most conservative case and will result in the largest area to consider in interaction studies; however, no loading may be too conservative a consideration and a large reduction in study area may be gained by considering a small percentage of loading.

In addition to the standard 39-bus system, possible interconnection to a larger grid is modeled as an equivalent impedance behind a voltage source. This equivalent impedance is intended to be expandable to encompass any buses deemed not required for detailed interaction studies.

The grid model is used to find several important impedances. The first is to determine the equivalent line impedance between the test bus and converter bus ($\mathbf{Z}_{R-C}$ in Fig. 8). If the test bus n is iterated over all the buses, the impedance between the converter bus and each other bus is necessary. Additionally, the impedance from each test bus n to ground is required ($\mathbf{Z}_{R-grd}$ in Fig. 8). This impedance to ground includes any loads and a possible equivalent remaining grid impedance, but not the converter. Note that the converter can be included in this impedance, which would directly give the total equivalent impedance as seen at Bus n. Finally, the grid model can be used to calculate the equivalent impedance of the remaining buses to exclude from an interaction study. These impedances can be calculated analytically through combination of line and load impedances or measured directly.

C. Resonances

A resonance creates the amplification of voltage or current at certain frequencies and results from the interaction of inductances and capacitances in the grid. Resonances can come from many sources including synchronous generators, other converters, reactive compensation, and others [1]. To create a resonance in the example system, an inductance and capacitance (LC) is connected at the test bus. This LC is a passive system and, if the equivalent impedance at the point of connection is also passive, this will result in a stable system. The LC parameters can be adjusted to create a resonance in the non-passive frequencies of the converter.

Figure 8 shows the equivalent impedances for a generalized grid configuration, where the converter is connected at point C, the test bus at point R. The equivalent impedance of the converter and grid from point R, given by $\mathbf{Z}_{eq}$ in Fig. 2, can be determined as follows:

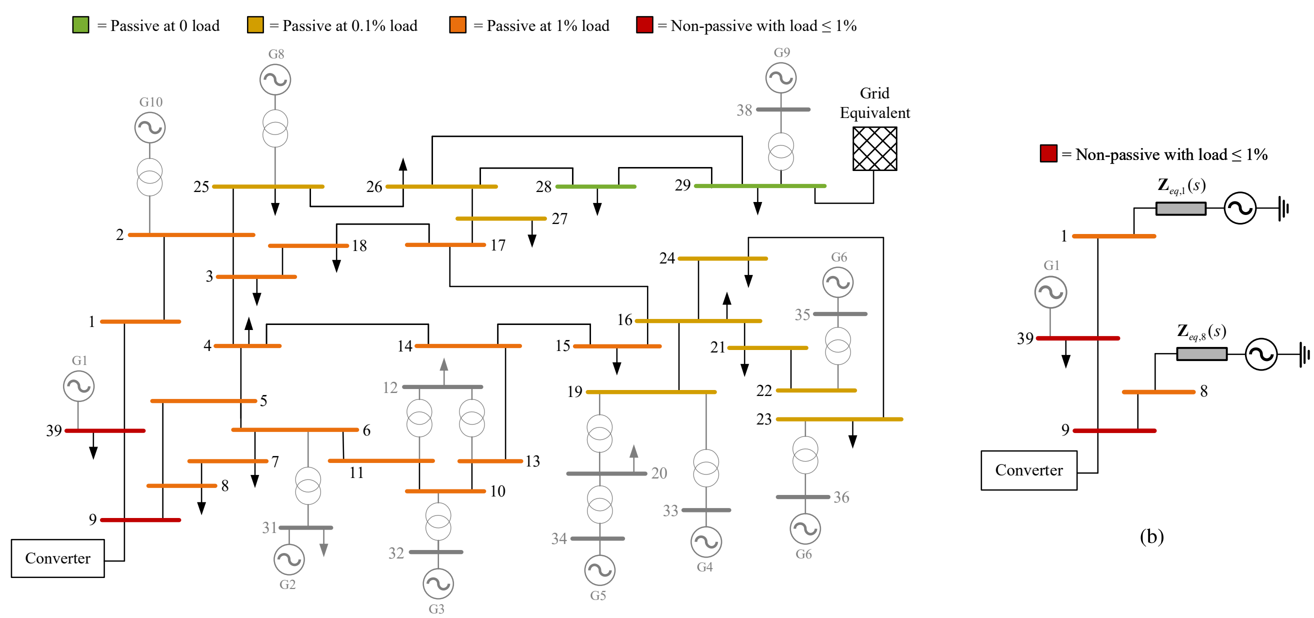
$$\mathbf{Z}_{eq,R} = (\mathbf{Z}_{R-C} + \mathbf{Z}_{conv}) || \mathbf{Z}_{R-grd} \tag{11}$$

where the converter impedance, $\mathbf{Z}_{conv}$, is determined according to Section IV-A, and $\mathbf{Z}_{R-C}$ and $\mathbf{Z}_{R-grd}$ are determined according to Section IV-B.

V. Validation through Simulation

The passivity-based screening method is applied to the 39-bus system shown in Fig. 7, with gray buses ignored. The converter is placed at Bus 9 and the passivity at each other bus is calculated using the process shown in Fig. 5. The buses are then color-coded in Fig. 9a to indicate which buses are electrically distant enough to realize passivity with different loading levels. Three loading levels are examined: no loading, 0.1%, and 1%.

With no loading, only the furthest two buses, Bus 28 and 29, have passive equivalent impedances. This indicates that



(a)

Fig. 9. (a) 39 bus model with passivity calculated at each bus across all frequencies with various loading levels when a converter is connected at Bus 9. (b) Reduced grid model for interaction studies if 1% nominal load is assumed.

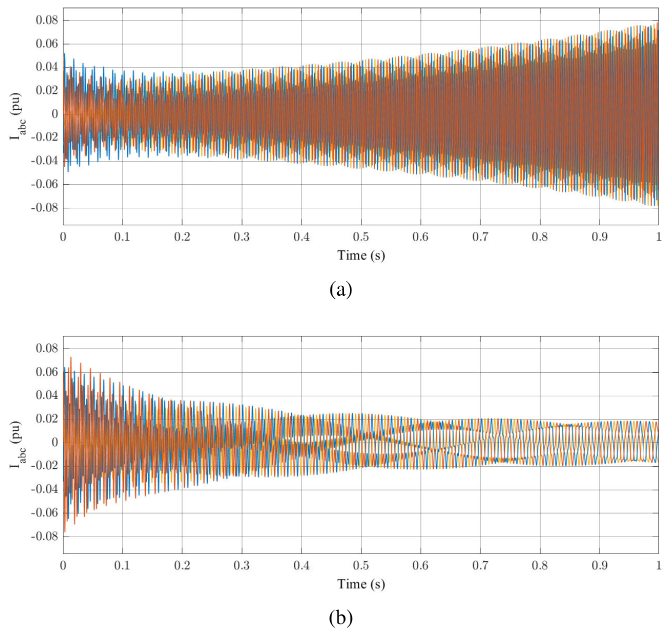


Fig. 10. Current at the test bus with resonant frequency approximately equal to 250 Hz. (a) Test bus = 1, exhibiting non-passive behavior. (b) Test bus = 28, exhibiting passive behavior.

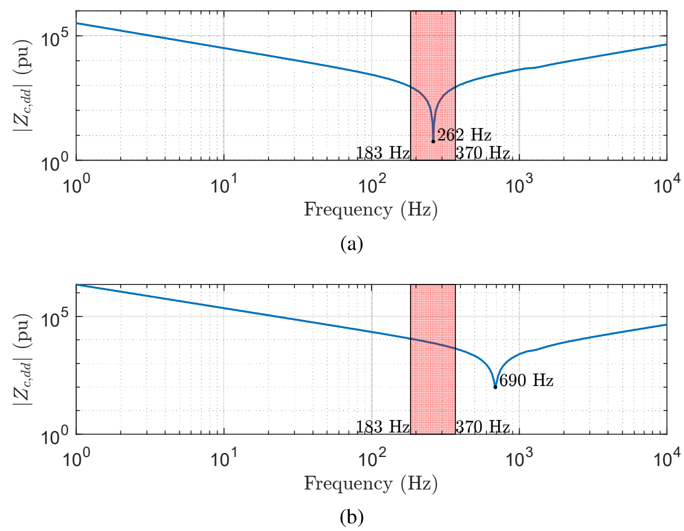


Fig. 11. Total impedance at the resonance when the resonance is connected to Bus 1, with red area showing the non-passive region of the equivalent impedance. (a) With $f_{res} = 262$ Hz. (b) With $f_{res} = 690$ Hz.

any passive system connected at these two buses will result in a stable system and can be excluded from a detailed interaction analysis. By including 0.1% of the nominal load, the passive area increases dramatically to include all the yellow-colored buses. Again, a further drastic increase in passive area is seen by including 1% nominal load, shown by all the orange buses. In this example, when 1% nominal load is included, resonance interactions can only occur at Bus 9 and 39. An example of the simplified system with grid equivalents is shown in Fig. 9b, when 1% nominal loading is assumed. The buses to examine in detail are greatly reduced from the full grid model. The subsystem becomes passive somewhere between Bus 39 and Bus 1, and between Bus 9 and Bus 8; therefore, the transmission lines between these should be modeled explicitly. However, the remaining grid after the first passive buses can be modeled as as frequency-dependent impedances.

The system is simulated in MATLAB Simulink to substantiate the screening process. When the LC circuit is connected to Bus 1 with no loading and with an L and C chosen such that the resonant frequency is approximately 250 Hz, unstable oscillations can be observed (Fig. 10a). When the LC is moved further from the converter to Bus 28, which is passive, stable behavior and decaying oscillations can be observed (Fig. 10b).

Note that the impedance of the LC with the equivalent impedance at the point of connection is shown in Fig. 11a. The resonant frequency is within the non-passive region of the equivalent impedance as seen by the LC bus, and therefore some resonance interaction such as in Fig. 10a can be expected. However, if the resonant frequency is shifted, by changing the capacitance of the LC for example, to that seen in Fig. 11b, an unstable interaction should not be expected as the resonance is not in the non-passive region, and indeed, none is observed in simulation. The screening method proposed in this work does not consider the resonant frequency since information about other converters or other source of resonances is assumed to be unknown. However, if information about potential resonance frequencies is known, the screening method can be extended to examine the passivity at these frequencies instead of a global passivity across all frequencies. In this way, the interaction study area may also be decreased.

VI. Conclusion

This work has demonstrated how the concept of passivity can be effectively used as a screening method for converter interaction studies. Passive systems (ones with positive damping) are guaranteed to be stable, and two passive systems connected together will also be passive. A converter, however, will typically have frequency ranges of non-passivity. The non-passivity of a converter can be compensated for by positive resistances in a network, until the converter and a portion of the network can be considered as a passive subsystem. The proposed screening method assesses the electrical distance from a converter to reach passivity. At a far enough distance, the equivalent impedance of the subsystem (converter combined with some of the network) as seen at this point will be passive, and the stability of the system can be ensured when connecting any additional passive system at this bus. This defines a passive and non-passive region in the grid, where unstable interactions can occur with resonances in the grid within the non-passive region. By examining the passivity at different points in the grid, the effective area to study for interactions can be reduced to the non-passive region.

Buses that are passive can be reduced in a simplified impedance model, with only the non-passive buses retained for the in-depth interaction study. The grid model can include some degree of loading and/or generation, depending on the level on conservatism desired. Increased loading of the system will generally reduce the non-passive area for the interaction analysis.

It should be noted that an opposite-type of screening can also be performed, where the converter is progressively moved further away from a fixed bus until the combined converter and network reach passivity. This provides information about where a converter can be placed to ensure no harmful resonance interactions occur. Additionally, only the interaction of a single non-passive converter with other passive elements is considered. Further work will expand this to include multiple non-passive elements.

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