Exploring an Impedance-Based SCR for Accurate Representation of Grid-Forming Converters

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***Abstract*—The strength of an electrical network connection point is often characterized by the short circuit ratio. Analysis of the fault current contribution at the node can provide information on system impedance, voltage stability, maximum power transfer and system recovery time. However, the introduction of more power converter connected generation decreases the validity of the current short circuit ratio definition. Mainly, the parameters that determine the strength of a connection point cannot be inferred from the fault level contribution. This article presents a discussion on the pitfalls of quantifying the strength of an electrical network using fault current contribution. The limitations of the method for converter dominated networks are presented and alternative definitions from literature are discussed with drawbacks explored. Further considerations for a new index are described, and the article suggests utilizing system impedances for investigation of different stability components. Varying converter control algorithms are explored in terms of impedance, both grid-following and grid-forming. Grid-forming structures without a current loop were found to provide the greatest improvement in voltage stiffness.**

Keywords—SCR, Grid Stiffness, Converter Impedance, Network Stability, Grid Forming Converters

I. INTRODUCTION

The percentage of renewable generation connected to electricity networks is increasingly rapidly [1]. While crucial for combatting climate change, the resultant increase in penetration of power electronic converters raises some concerns. Converter connected generation (CCG) differs from traditional synchronous generators in multiple ways and significant research focuses on reduction of system inertia [2]. However, fault current contribution, voltage stiffness and impedance also differ greatly. Hence, conventional measures of grid strength are not applicable in converter dominated networks. A common measure of voltage stability or grid strength is the short circuit ratio (SCR) [3]. In traditional systems this is defined by the fault current available at a specific connection point. It also provides information about the impedance of the connected systems. Higher SCR grids are considered stronger, more stable and less susceptible to voltage variations. The conventional definition of SCR is a single value that provides a quick estimation and the simplicity is a crucial factor for its widespread utilization.

The traditional definition of SCR is not valid for modern power converter dominated networks (PCDN). A PCDN is a grid where the penetration of CCG is sufficient to dominate system dynamics. Placing a numerical limit on converter penetration for a PCDN is challenging as it is highly system dependent [4]. In general, as most converters are limited to 1.1-1.2 p.u. current, the fault current provision is very low resulting in a small SCR and reduced stability. However, grid strength and fault current provision may not be as mutually inclusive as once thought when considering converters. Two families of converter control are explored. Firstly, traditional grid-following control where the converter synchronizes to the voltage at the point of common coupling (PCC) using a phase locked loop (PLL). Secondly, grid-forming (GFM) algorithms which connect via a power synchronizing loop or similar and do not require a pre-existing voltage. Both converter families possess the 1.1-1.2 p.u. current limit but GFM converters are considered stiff voltage sources, enhancing voltage stability with reduced sensitivity to variations. From the traditional definition of SCR, the grid strength may be assumed weaker than it is in terms of voltage stiffness. This suggests that a single measure of grid strength based on fault current contribution is incorrect for converter dominated systems. Fault current level is important but should be considered as a separate entity. The lack of fault current is clearly an issue but could be solved with recalibrating network protections in some cases.

Some work exists attempting to redefine SCR for converter dominated system. The Weighted Short Circuit Ratio (WSCR) has recently been applied in Texas [5], while GE developed the Compound Short Circuit Ratio (CSCR) [6]. Both aim to provide a more accurate estimation of fault current contribution by disregarding the contribution from CCG. CIGRE provide a new metric called the Short Circuit Ratio with Interaction Factors [7]. This includes a component representing the voltage interactions between two buses and allows the consideration of voltage stiffness that is independent from fault level contribution. An extension to this, known as the equivalent circuit short circuit ratio (ESCR) is also proposed which utilizes the per-unit impedance of an equivalent circuit to account for interactions [7].

This article will further expand on the key areas that should be considered for determining grid strength of converter dominated networks. Utilization of system impedances is suggested in the paper as a promising method of characterizing system strength. The nature of impedance analysis means the approach is scalable and applicable to a wide range of networks. Current work on alternative SCR methods is discussed and similarities to the impedance method are showcased. A novel method of determining an equivalent impedance-based SCR (ISCR) using a MIMO impedance network is suggested and present limitations of implementation are provided. This method is used to address the voltage stability issues and indicates the pitfalls of classifying system strength with a single value. In addition, the impedance method allows the consideration of different converter controller behavior. GFM and GFL converters are undistinguishable using current definitions of SCR. While state of the art work on voltage interactions begins to incorporate this, the converter impedance provides further information on why voltage interactions differ.

II. AN OVERVIEW OF GRID STRENGTH

Historically, grid strength has been used almost exclusively for determining the robustness of a network connection point, with SCR implemented as the main measure [5]. Determined by the ratio of short circuit power delivered during three-phase faults to the nominal power available, the SCR is a good measure of responsiveness to dynamic system events [8]. In a traditional network, the lower the SCR, the higher the impedance of the network and increased susceptibility to voltage deviation is observed.

A. Short Circuit Ratio

In most studies, the Thevenin equivalent grid reactance is related to the bus voltage, rated power and SCR ratio at the point of connection:

$$SCR = \frac{\left(\frac{E^2}{Z_n}\right)}{P_n} \tag{1}$$

Where E, Z_n and P_n are the network voltage, impedance and active power contribution respectively. The SCR ratio determines the extra current provided during three-phase faults. A large fault current normally indicates a small impedance and increased grid strength. However, this definition is based solely on the physical impedance of the network and not the effective impedance influenced by control parameters. Power converters are limited to between 1.1 – 1.2 p.u. current to prevent damage and the fault level is, therefore, not determined by physical impedances. Due to this, the contribution to SCR by the traditional definition is significantly less:

$$SCR = \frac{1.2 I_c E}{P_n} \tag{2}$$

Where I_c is the converter current. In this case the maximum SCR possible would be 1.2. However, this is not an accurate measure and GFM converters while not providing fault current, can contribute greatly to the voltage stiffness at the PCC.

III. ALTERNATIVE SCR DEFINITIONS

Multiple network operators globally have proposed new stability indices based on short circuit ratio for networks with a high penetration of CCG [5-7]. Simpler indices look at the contribution of fault current and use this to infer information about the voltage stability, interactions and grid stiffness. Other methods look to include interaction factors to directly analyze the effect of voltage deviations on the network.

A. Composite Short Cicuit Ratio

Composite Short Circuit Ratio (CSCR) is a method proposed by GE [6]. The approach considers the grid strength seen by all electrically close converters. A common AC bus is created, and it is assumed all converters of interest are connected to the bus. The CSCR is then determined without a current contribution from the converters:

$$CSCR = \frac{CSC_{MVA}}{MW_{VER}} \tag{3}$$

Where CSC_{MVA} is the fault level contribution excluding converters and MW_{VER} is the sum of nominal power ratings of the connected converters.

B. Weighted Short Circuit Ratio

Weighted short circuit ratio (WSCR) [9] has recently used in defining operational limits in Texas [5] and is a similar approach to CSCR. The approach covers the total transmission of power from CCG at key points in the network. WSCR is defined as:

$$WSCR = \frac{\Sigma_i^N SCMVA_i \times P_{RMW_i}}{\left(\Sigma_i^N P_{RNW_i}\right)^2} \tag{4}$$

Where $SCMVA_i$ is the short circuit capacity at bus i and P_{RMW_i} is the rated power output of the ith converter.

Both CSCR and WSCR give a better idea of the available fault current. However, the index is generated solely from the fault current contribution and power ratings without considering interactions. There is no way to distinguish the control methodology used, in some cases converters may not contribute fault current but do contribute to voltage stiffness at the PCC. This would enhance the strength at the node but both WSCR and CSCR would predict reduced stability due to the lower fault level.

C. Equivelent Circuit Short Circuit Ratio

The equivalent circuit short circuit ratio (ESCR) bases the SCR on the equivalent per-unit impedance of the system [7]:

$$ESCR = \frac{1}{Z_{sys,PU}} = Y_{sys,PU}$$

Where $Z_{sys,PU}$ and $Y_{sys,PU}$ are the system impedance and admittance, respectively. The metric suggests the maximum network impedance that the converter can operate under. However, the impedance due to converter control is not considered. This method forms the basis for a novel approach proposed in this paper utilizing converter admittance models to extract an equivalent SCR.

D. Short circuit ratio with interaction factors

The short circuit ratio with interaction factors (SCRIF) looks to augment previous definitions of SCR with a component that captures voltage deviations. This begins to alleviate some of the issues encountered with previous methods. For example, the increased voltage stiffness introduced by GFM converters can now be represented. This voltage sensitivity is captured via:

$$IF_{ij} = \frac{\Delta V_i}{\Delta V_j} \tag{5}$$

The SCRIF is then determined:

$$SCRIF_i = \frac{S_i}{P_i + \Sigma_j\left(IF_{ij} \times P_j\right)} \tag{6}$$

Subscript j represents all electrically close converters or buses. IF_{ij} is the interaction factor of bus j on bus I, ΔV_i and ΔV_j are the voltage deviations at the ith and jth bus, respectively, S_i and P_i are the fault level contribution and nominal power rating at bus i and P_j is the nominal power at bus j. This suggests that a stiff voltage source inserted at bus i, would decrease the interaction factor, raise the SCRIF and bus i would become more stable.

E. Further considerations

In the modern network, the traditional definition may not be sufficient as discussed.. Moreover, a value determined at a single frequency (50 or 60 Hz) does not provide sufficient information about susceptibility to sub-synchronous and super-synchronous disturbances. These fluctuations are becoming more prevalent as more CCG is added to the network that cannot be considered as simple, decoupled single-input single-output (SISO) system. A modern definition of grid strength should include information about fault current provision at fundamental frequency as well as information about voltage stability and interaction across a range of frequencies.

IV. CONVERTER CHARACTERISTICS

Converter operation in any network is dependent on the control goals and topology. Two types of converters are considered in this work: conventional GFL converters and more modern GFM converters. Both exhibit different properties which are likely missed using traditional definitions of SCR. This section explores the differences in converter output impedance for GFL and GFL controllers and how this affects operation in weak grids.

A. Impedance modelling of converters

In each case it is easier to determine the converter admittance first and inverting to find impedance if needed. A small-signal model is created in the synchronous reference frame incorporating all aspect of control and physical impedances. The inputs and outputs are arranged as:

$$Y_c = \frac{y}{x} = \frac{\Delta I}{\Delta V} \tag{7}$$

Where Y_c is the converter admittance which in the dq-frame forms a multiple-input multiple-output (MIMO) system:

$$Y_c = \begin{bmatrix} Y_{qq} & Y_{qd} \\ Y_{dq} & Y_{dd} \end{bmatrix} \tag{8}$$

All system components are modelled using this method. From a stability perspective, impedance-based methods have been widely applied to numerous different systems [10]. Current analysis methods involve constructing detailed state-space models of individual grid components and converters. This allows the investigation of mechanical effects behind the converter that may propagate to the AC system [11].

As more functionality is added to converter controllers e.g. frequency support, reactive power support and negative sequence regulation, interactions become more likely and problematic [12]. This is reflected in the converter impedance but not in current definitions of SCR. To accurately represent all system interactions the impedance should be modelled in the synchronous frame forming a MIMO system. For basic systems such as simplified current controllers or Thevenin equivalent grids the impedance is Mirror Frequency Decoupled (MFD) in the synchronous frame or diagonally dominant in the sequence frame [13]. The system can then be manipulated to determine the SCR from the two MIMO eigenvalues, which for the simple systems described are equal. However, complex controllers are different. Unique control goals are applied to the active and reactive axes in the synchronous reference frame. This removes the equality between the diagonal terms and can also increase axes coupling. This leads to two different impedance eigenvalues that can be manipulated to determine two possible SCRs. This could suggest a different rating for active and reactive power flow, but further research is required to confirm this.

B. Grid-following Converters

The most common type of GFL converter is a current controlled converter. These implement active power control with either PCC voltage control or reactive power support. The synchronization with the grid is provided via a PLL. The output impedance of GFL converters tends to be quite high when compared with GFM converters, which are further discussed in IV.C. A comparison of MIMO GFL [12] and GFM [11] converter admittance is provided in Fig. 1. where the admittance is of the form shown in (8).

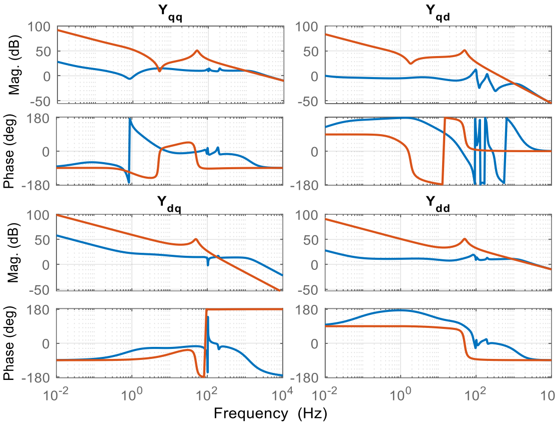

Fig. 1. Comparison of GFL (blue) and GFM (orange) converter admittance

From Fig. 1, the GFL converter has a smaller admittance across a wide frequency range. The smaller the admittance or the larger the output impedance, the less stiff the voltage becomes and contributes negatively to the network. The large impedance means that significant fluctuations in terminal voltage can be observed. Couple this to a weak network where the PCC is already unstable and large variations in voltage and current can occur. The large output impedance is mainly due to the control algorithm which is not captured by most definitions of SCR. When using CSCR or WSCR the index will reduce due to the increased power capacity with no increase in short circuit level. Hence, the stability of the bus will appear reduced due to the introduction of a GFL converter. However, the reason for the instability is likely misinterpreted.

Sub-synchronous reactions in windfarms connected to weak grids have been reported [14]. One reason given for the manifestation is the negative damping provided from the PLL in GFL controllers [15]. The negative damping is visible in Fig. 1. as regions where the phase is not between -90° and 90°. The presence of negative damping is easily identifiable by right-hand plane zeros in the impedance model of the converter.

C. Grid-forming Converters

Grid-forming converters are named due to the ability to construct a network voltage. Therefore, synchronization is not achieved by PLL and a power synchronization loop or similar is implemented [16]. The control loop used in this work synthesizes the converter voltage angle based on the dynamics of the synchronous machine swing equation [11]. Some algorithms utilize an inner loop current controller as this allows for overcurrent protections. But the addition of an internal current loop increases the output impedance of the converter. Fig. 2, illustrates the difference between two types of GFM control. The first with an internal current loop and the second without.

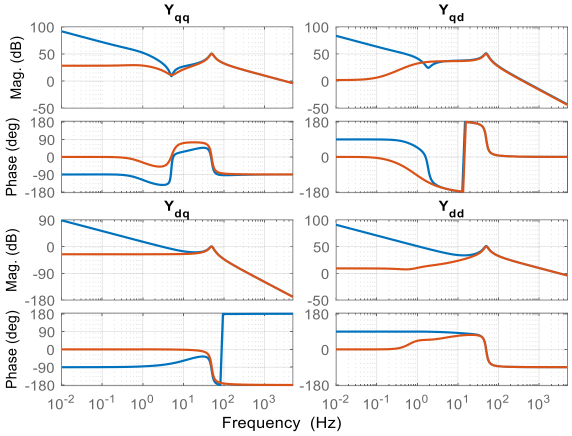

Fig. 2. Admittance of GFM without CC (blue) and with CC (orange)

From Fig. 2, it can be seen in all channels that the inclusion of the current loop decreases the output admittance. It is especially prevalent near 0 Hz which represents the 50 Hz component in the stationary reference frame. If the GFM is to increase the voltage stiffness at the PCC, then the output impedance should be as low as possible. Hence, no inner loop current control should be present.

Since GFM converters operate as a voltage source the stability of the system reacts differently to SCR than with GFL converters. As the grid strength increases, the stability worsens due to the increased sensitivity of active power to phase deviations resulting in poor operation of the synchronization algorithm [17]. Due to this, multiple GFM converters in proximity are likely unstable due to the increased grid strength. At low frequencies, negative damping provided by the converter is suggested as a reason for unwanted interactions. Both the magnitude and ranges of negative damping are lower for GFM when compared to GFL converters. However, the impact still requires attention to ensure that the small region does not interact with any other system resonances. This aspect is not covered in detail by any previous definition of SCR.

V. IMPEDANCE-BASED STABLITY INDICES

A. *Impedance-Based Stability vs SCR*

Impedance-based stability is widely reported in literature and is a useful tool for determining the voltage stability of a network [10]. When considering a converter connected to a grid, the current at the PCC is determined via:

$$I_{pcc} = \left(I_c - V_g Y_c\right) \cdot \left(\frac{1}{1 + Z_g Y_c}\right) \tag{9}$$

Where I_{Pcc} is the current at the PCC, I_c is the converter current V_g is the grid voltage and Z_g is the grid impedance. The closed-loop stability is determined from Nyquist analysis of the open loop gain - $Z_g Y_c$. This is the ratio between the converter impedance and the grid impedance. Similarly the interaction factor in a WPP is defined by Cigre as [7]:

$$IF_{ji} = \frac{\Delta V_j}{\Delta V_i} = \frac{\Delta I_i Z_{ji}}{\Delta I_i Z_{ii}} = \frac{Z_{ji}}{Z_{ii}} \tag{10}$$

This represents an impedance ratio based on the reaction between buses j and i, indicating some equivalences between the impedance-based stability method and voltage interaction factors. Both suggest the ratio between two impedances dictates the level of interaction that may occur. One benefit of the impedance approach is the modularity. The whole system model is not required and simple mathematical combinations of individual network components can be utilized. Instead of applying Nyquist to the closed loop control system ratio, the eigenvalues of the individual impedance matrix at 50 Hz can be manipulated to find the equivalent ISCR. This approach is influenced by the ESCR method but extends the idea to MIMO systems covering all interactions. This gives an indication of the voltage stability of the network. When the controller is considered, the equivalent SCR deviates from the previous definitions.

B. *Extraction of impedance at 50 Hz*

An impedance-based definition of SCR requires the ability to determine the impedance of the bus at 50 Hz. For a Thevenin grid this offers no complications. However, determining the converter output impedance is challenging as it dependent on the control. The impedance at 50 Hz must be extracted by injecting a current disturbance and measuring the voltage response. If small-signal models discussed in IV.A are implemented the combined impedance of a network and converter can be analyzed. In cases where the model is described in the synchronous reference frame, the impedance should be determined at 0 Hz. This does offer some issues if poles and zeros are present in the impedance transfer function at 0 Hz. This results in a large definition of the impedance at that point which may be incorrect.

The unique contribution of GFM and GFL to the network can be investigated using the admittance models. This is like the ESCR from III.C but the contribution is now based on converter output admittance instead of physical impedances. The GFM and GFL converter structures are a virtual synchronous machine (VSM) and a power voltage current controller (PVCC). Both are described in detail in [11]. The systems considered are a stand-alone Thevenin Equivalent grid, a combination of the grid and a GFL converter and a combination of the grid and a GFM converter. The grid impedance is constant throughout. The SCR indices are then calculated based on another similar rated converter being added to the PCC. The traditional SCR is compared with the CSCR and the new equivalent ISCR for the three systems in Table I.

TABLE I. COMPARISON OF SCR METRICS

System	**Trad. SCR**	**CSCR**	**Imp SCR**
Network	1	1	1
Network + GFL	1	0.5	0.94
Network + GFM	1	0.5	2.6

From Table I, all three SCR definitions are equal for the passive network, validating the new ISCR method. In the case of GFL, traditional SCR over-estimates the strength of the network slightly while CSCR significantly underestimates the network strength. The impedance SCR shows a slight reduction in stability which is expected for GFL. In the case of GFM, both traditional SCR and CSCR underestimate the increase in voltage stiffness provided by GFM converters. The results indicate that an impedance-based SCR can account for the different characteristic of GFL and GFM. In the case of the ISCRs, both eigenvalues were equal so only one SCR is shown. If the initial network connection is weakened, or more complex control algorithms are added the eigenvalues deviate and two unique values are obtained.

C. *Frequency range considerations*

Current definitions of SCR look at contribution at 50 Hz. This is important as it represents the largest component. However, with sub and super-synchronous oscillations becoming more prevalent the voltage stability across a wider range of frequencies should be considered. This is achievable by utilizing the frequency responses of converters. However, the issue lies in quantifying the results. It is challenging to extract a single value across the frequency range that is representative of the stability at all frequencies. A common approach in these situations is to consider the largest or worst-case component. However, in a system defined at 50 Hz, other problematic components may be overshadowed by the large contribution at the nominal frequency.

D. *Considerations of complex controllers*

With impedance-based stability analysis there is no stability or strength rating that can be achieved. In practice, the criterion determines if the system is stable or unstable without offering much information on the degree to which the system is stable. Further consideration should be given to how a new metric would relate to the old in this case. Looking at stability margins would likely rate the system on a different scale to what is currently implemented. Some may argue that gain and phase margins or similar could be used but as converter controllers become more complicated the SISO representations do not cover all interactions. Hence, simple SISO techniques for minimum phase systems are no longer valid. MIMO models represented in either the synchronous frame or sequence frame are preferred for the modern network [12]. However, this leads to further challenges when using impedance ratios to determine grid strength. If the impedance is represented by a 2x2 MIMO matrix then it is possible to have two different short circuit ratios. The two are unlikely to be completely independent but considerations on how to quantify the strength of a system using MIMO representations are paramount to the adoption of an impedance-based metric.

VI. CONCLUSION

The current definition of SCR is not sufficient for power converter dominated networks. Alternative approaches excluding converter fault current contribution are more valid but still lack the required information on converter interaction. Interaction factors can be used to investigate these parameters at 50 Hz. Similarities between interaction factors and impedance-based stability have been documented. GFL and GFM converters have the same fault current contribution but vastly different impedances. GFL has a higher impedance than GFM indicating that GFM provides a stiffer voltage source. Additionally, including an internal current loop in a GFM controller increases the impedance and reduces voltage stability. Further benefits of the impedance method include easy alteration of circuit topology, accurate representation of converter interactions and stability information across a wide frequency range. However, challenges arise when trying to determine a single metric like SCR to quantify grid-strength. Instead, it is suggested that each component of grid-strength be analyzed independently.

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REFERENCES

[1] Department for Business Energy and Industrial Strategy, "Energy Trends UK, April to June 2021," *Statistical Release. September 2021,* 2021.

[2] Q. Hong, M. Asif Uddin Khan, C. Henderson, A. Egea-Àlvarez, D. Tzelepis, and C. Booth, "Addressing Frequency Control Challenges in Future Low-Inertia Power Systems: A Great Britain Perspective," *Engineering,* 2021, doi: 10.1016/j.eng.2021.06.005.

[3] National Grid ESO, "Operability Strategy Report 2021," *System Operability Framework 2021,* 2021.

[4] C. Collados-Rodriguez, M. Cheah-Mane, E. Prieto-Araujo, and O. Gomis-Bellmunt, "Stability Analysis of Systems With High VSC Penetration: Where Is the Limit?," *IEEE Transactions on Power Delivery,* vol. 35, no. 4, pp. 2021-2031, 2020, doi: 10.1109/tpwrd.2019.2959541.

[5] NERC, "Integrating Inverter-Based Resources into Low Short Circuit Strength Systems - Reliability Guideline," 2017.

[6] R. Fernades, S. Achilles, and J. MacDowell, "Report to NERC ERSTF for Composite Short Circuit Ratio (CSCR) Estimation Guideline," *GE Energy Consulting,* 2015.

[7] CIGRE, "Connection of wind farms to weak AC networks," *Working Group B4.62,* 2016.

[8] H. Shun-Hsien, J. Schmall, J. Conto, J. Adams, Z. Yang, and C. Carter, "Voltage control challenges on weak grids with high penetration of wind generation: ERCOT experience," 2012 2012: IEEE, doi: 10.1109/pesgm.2012.6344713.

[9] Y. Zhang, S.-H. F. Huang, J. Schmall, J. Conto, J. Billo, and E. Rehman, "Evaluating system strength for large-scale wind plant integration," 2014 2014: IEEE, doi: 10.1109/pesgm.2014.6939043.

[10] X. Wang, F. Blaabjerg, and P. C. Loh, "An impedance-based stability analysis method for paralleled voltage source converters," 2014 2014: IEEE, doi: 10.1109/ipec.2014.6869788.

[11] C. Henderson, D. Vozikis, D. Holliday, X. Bian, and A. Egea-Àlvarez, "Assessment of Grid-Connected Wind Turbines with an Inertia Response by Considering Internal Dynamics," *Energies,* vol. 13, no. 5, 2020, doi: 10.3390/en13051038.

[12] C. Henderson, L. Xu, and A. Egea-Alvarez, "PN admittance characterisation of grid supporting VSC controllers with negative sequence regulation and inertia emulation," in *(EPE'21 ECCE Europe)*, 6-10 Sept. 2021 2021, pp. P.1-P.10.

[13] G. Amico, A. Egea-Alvarez, P. Brogan, and S. Zhang, "Small-Signal Converter Admittance in the pn-Frame: Systematic Derivation and Analysis of the Cross-Coupling Terms," *IEEE Transactions on Energy Conversion,* vol. 34, no. 4, pp. 1829-1838, 2019, doi: 10.1109/tec.2019.2924922.

[14] L. Fan and Z. Miao, "Wind in Weak Grids: 4 Hz or 30 Hz Oscillations?," *IEEE Transactions on Power Systems,* vol. 33, no. 5, pp. 5803-5804, 2018, doi: 10.1109/tpwrs.2018.2852947.

[15] M. Davari and Y. A.-R. I. Mohamed, "Robust Vector Control of a Very Weak-Grid-Connected Voltage-Source Converter Considering the Phase-Locked Loop Dynamics," *IEEE Transactions on Power Electronics,* vol. 32, no. 2, pp. 977-994, 2017, doi: 10.1109/tpel.2016.2546341.

[16] J. Khazaei, Z. Miao, and L. Piyasinghe, "Impedance-model-based MIMO analysis of power synchronization control," *Electric Power Systems Research,* vol. 154, pp. 341-351, 2018, doi: 10.1016/j.epsr.2017.08.025.

[17] R. Rosso, X. Wang, M. Liserre, X. Lu, and S. Engelken, "Grid-Forming Converters: Control Approaches, Grid-Synchronization, and Future Trends—A Review," *IEEE Open Journal of Industry Applications,* vol. 2, pp. 93-109, 2021, doi: 10.1109/ojia.2021.3074028.