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Abstract

Impedance-based method has been increasingly adopted to assess the stability of inverter-based resources (IBRs). To get a better view of the state-of-art and challenges for implementing the impedance-based dynamic analysis, a survey with general/specific questions has been initiated by IEEE Task Force on Frequency-Domain Modeling and Dynamic Analysis of HVDC and FACTS. The feedbacks are collected from universities, national labs, transmission system operators (TSOs), power plant developers, as well as IBR vendors. It is interesting to note that while many common understandings have been established in practices, certain gaps still exist among different stakeholders. This article intends to bridge this gap by sharing a summary of the survey, including questionnaires, responses from different stakeholders, and the analysis of survey results. The challenges for different stakeholders using impedance-based method are identified, which hopefully shed a light on the future research work.

A Survey on Impedance-based Dynamics Analysis Method for Inverter-based Resources

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Abstract— Impedance-based method has been increasingly adopted to assess the stability of inverter-based resources (IBRs). To get a better view of the state-of-art and challenges for implementing the impedance-based dynamic analysis, a survey with general/specific questions has been initiated by IEEE Task Force on Frequency-Domain Modeling and Dynamic Analysis of HVDC and FACTS. The feedbacks are collected from universities, national labs, transmission system operators (TSOs), power plant developers, as well as IBR vendors. It is interesting to note that while many common understandings have been established in practices, certain gaps still exist among different stakeholders. This article intends to bridge this gap by sharing a summary of the survey, including questionnaires, responses from different stakeholders, and the analysis of survey results. The challenges for different stakeholders using impedance-based method are identified, which hopefully shed a light on the future research work.

I. Introduction

The legacy power grids that are dominated by electrical machines are gradually evolving as power-electronic-based power systems with high proportion of inverter-based resources (IBRs) and active loads. The multi-timescale control dynamics of IBRs may interact with one another and with grid dynamics, leading to resonances and instabilities in a wide frequency range [1], [2]. Addressing these challenges call for new methods and tools for dynamics analysis of IBR-dominated power systems.

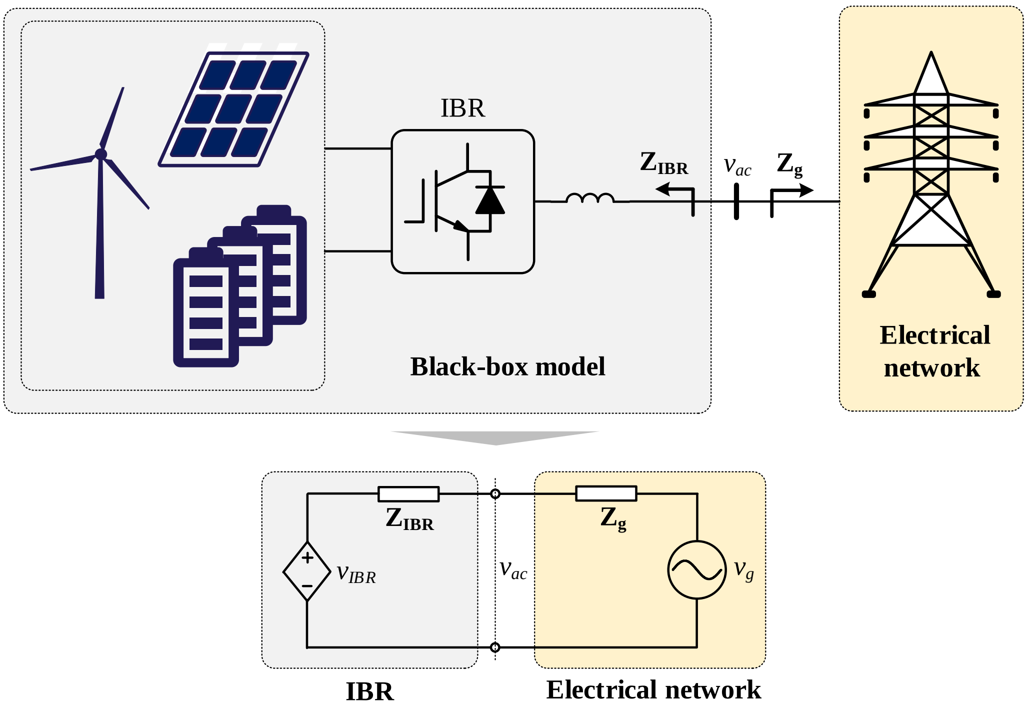


Fig. 1. Impedance-based dynamic analysis for IBR-dominated power system.

The impedance-based dynamics analysis method is increasingly used to screen stability risks of IBR-dominated power systems, mainly due to its advantage of dealing with black-box model [3]-[4], as shown in Fig.1. Over past years, Numerous efforts have been devoted, from both academia and industry, to advance this technology [5]-[6]. However, certain gaps persist among different stakeholders. An over-simplified grid system with a few or even single IBR is often used by academia for the impedance-based dynamic analysis. Such a simplified system may not be capable of reflecting all practical challenges in complex electrical systems, where thousands of IBRs can be configured in meshed and radial network structures. On the other hand, industry practicing engineers may not be aware of the latest advances in the impedance modeling theory and dynamics analysis.

To bridge the gaps, the joint IEEE Power Electronic Society (PELS) and IEEE Power and Energy society (PES) Task Force on Frequency-Domain Modeling and Dynamic Analysis of HVDC and FACTS made a questionnaire survey on the impedance-based dynamics analysis, aiming to obtain insights into the latest state of the art and challenges with using this method. The survey got 46 responses from a diverse range of participants (54% from academia, 46% from industry), including universities, national labs, transmission system operators (TSOs), power plant developers, as well as IBR vendors across the globe. More detailed statistics of the survey participants are given in Table I and II.

This article intends to share the survey results and summarize both common and unique challenges for different stakeholders in implementing impedance-based method, which hopefully shed a light on the future research work.

TABLE I
RESPONDENT SECTOR STATISTICS

RESPONDENT SECTOR	NUMBER
University	25
National lab	3
TSO	5
Power plant developer	1
IBR vendor	12

TABLE II
GEOGRAPHIC LOCATION OF RESPONDENTS

GEOGRAPHIC LOCATION	NUMBER
North America	8
Europe	23
Asia/Pacific	15

II. QUESTIONNAIRE AND RESPONSES

The questionnaire is designed with 5 general questions and 6 specific technical questions, each question and the corresponding response is listed as follows.

A. *General Questions*

1. Do you use the impedance-based (frequency scan) method for dynamics analysis?

A. Yes
B. No
C. Not yet, may use it in the future

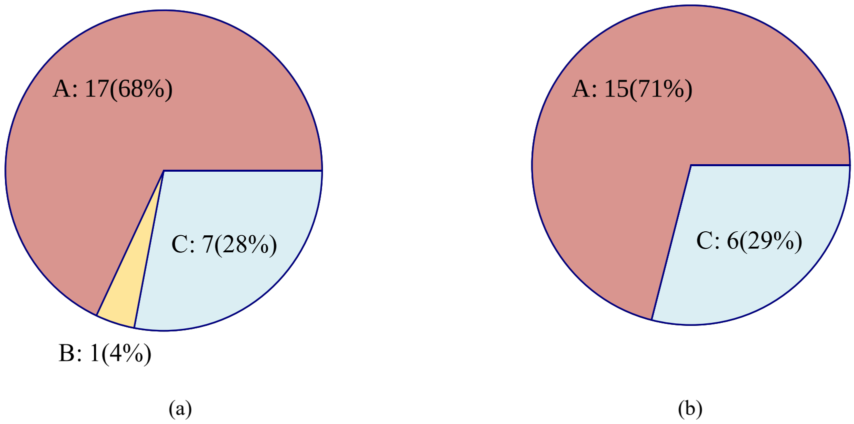


Fig. 2. Response to Q1. (a) Response from academia. (b) Response from industry.

2. What is your level of confidence on analysis results if using the impedance-based method?

A. Very confident: the impedance-based analysis results agree with EMT simulations (and/or field measurements).

B. Confident: the mismatch between impedance-based analysis results and EMT simulations (and/or field measurements) are acceptable or explainable.

C. Less confident: the mismatch between impedance-based analysis results and EMT simulations (and/or field measurements) are often not acceptable, nor explainable.

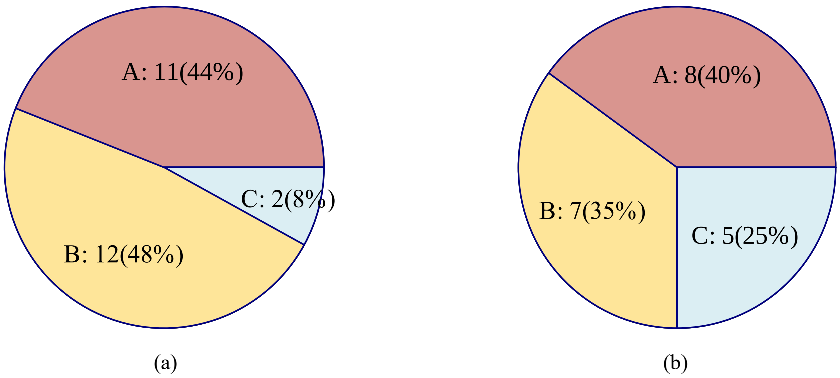


Fig. 3. Response to Q2. (a) Response from academia. (b) Response from industry.

3. For Transmission System Operators (TSOs) and power-plant owners/developers, please select 3 most challenging issues for using impedance-based method.

A. No high-fidelity EMT models that can be used for impedance measurement

B. No automated tools for impedance measurement

C. Too time consuming to measure impedances over multiple operating points

D. No method to verify the accuracy of measured impedances

E. No theory/method for impedance-based dynamics analysis of multi-IBR systems

F. Mismatch between impedance-based analysis results and EMT simulations (and/or field tests)

G. No clear insight into cause of instability can be provided from black-boxed impedance models

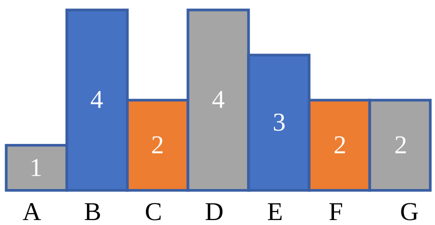


Fig. 4. Response to Q3 from TSOs and power-plant owners/developers.

4. **For vendors of inverter-based resources, please select 3 most challenging issues for using impedance-based method.**
   A. No high-fidelity EMT model of electrical system that IBR is connected to
   B. No impedance specifications/requirements for control dynamics of IBRs
   C. No efficient tools for impedance modeling and impedance measurement
   D. Too time consuming to measure impedances over multiple operating points
   E. No theory/method for impedance-based dynamics analysis of multi-IBR systems
   F. No clear design guideline obtained from impedance modeling

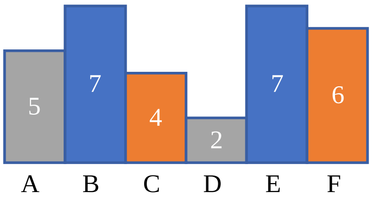
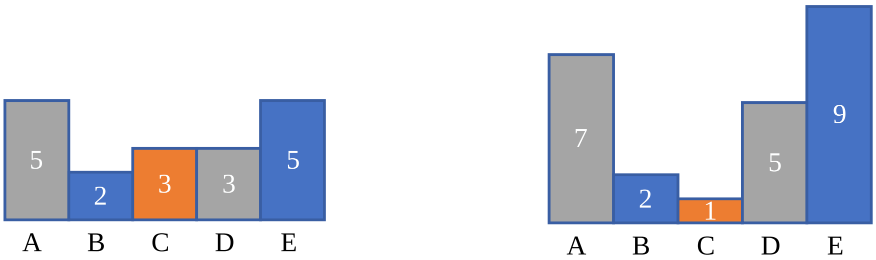


Fig. 5. Response to Q4 from IBR vendors.

5. **What need to be further developed for using impedance-based method?**
   A. Defining clear specifications on impedance profiles of IBRs
   B. Improved efficiency and accuracy of impedance measurements in offline EMT simulations
   C. Impedance-measurement tools in controller-hardware-in-the-loop tests
   D. Impedance-measurement tools in field tests
   E. Impedance-based stability and sensitivity analysis methods for multi-IBR systems



(a) (b)

Fig. 6. Response to Q5. (a) Response from TSOs and power-plant owners/developers. (b) Response from IBR vendors

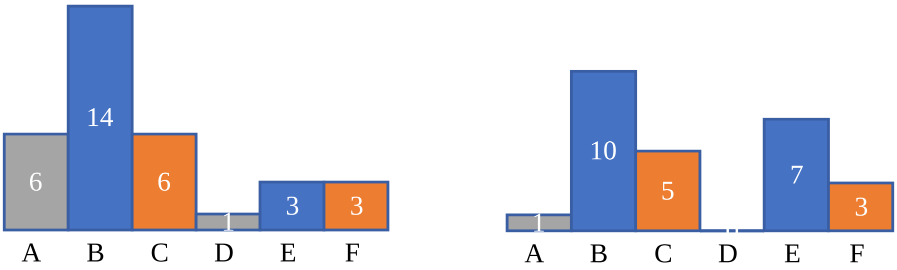
B. *Technical Questions*

6. **How do you select frequency range and frequency resolution for impedance measurement?**
   A. Nyquist frequency of IBRs.
   B. Based on specific frequency range of oscillations.
   C. The maximum frequency of a black-box model specified by vendors
   D. No clear guideline

(a) (b)

Fig. 7. Response to Q6. (a) Response from academia. (b) Response from industry.

7. **Do you have any preference over the reference frames of impedance model, i.e., stationary ($\alpha\beta$) or rotating (dq) reference frame, albeit they are mathematically equivalent?**
    A. Stationary ($\alpha\beta$) reference frame
    B. Rotating (dq) reference frame
    C. Positive-/negative-sequence
    D. Positive-sequence only
    E. No preference
    F. Will do measurement in both frames and make cross-validations between them



(a) (b)

Fig. 8. Response to Q7. (a) Response from academia. (b) Response from industry.

8. **Do you use the multiple-input multiple-output (MIMO) impedance matrix for dynamics analysis?**
    A. Yes, because the accurate impedance model of three-phase balanced IBR is a 2x2 matrix
    B. Yes, but the MIMO impedance matrix can be reduced to SISO impedance transfer function beyond certain frequency
    C. No, because no efficient tool for measuring impedance matrix is available
    D. No, only the single-input single-output (SISO) impedance transfer function is used for dynamics analysis

(a) (b)

Fig. 9. Response to Q8. (a) Response from academia. (b) Response from industry.

9. **How do you verify the measured impedance model?**
    A. Check if the marginally stable case predicted by the impedance model agree with EMT simulation tests
    B. Check if the step response of impedance model match with that of EMT simulation model
    C. Compare the measured impedance data with theoretically derived impedance model
    D. No clear guideline for verification
    E. Not applicable: prefer to transform the impedance model to time-domain state-space model.

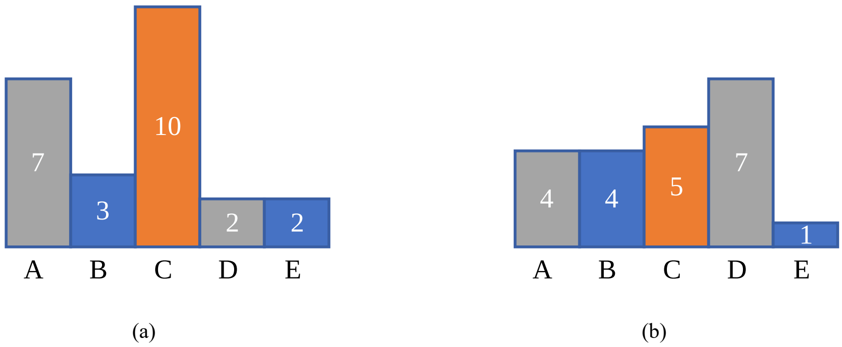


Fig. 10. Response to Q9. (a) Response from academia. (b) Response from industry.

10. Do you use aggregated impedance model of multi-IBR system for dynamics analysis?

A. Yes, while the aggregate model may not be 100% accurate, it can be used for preliminary dynamics analysis

B. No, the aggregated impedance model cannot accurately capture the dynamics of multi-IBR systems

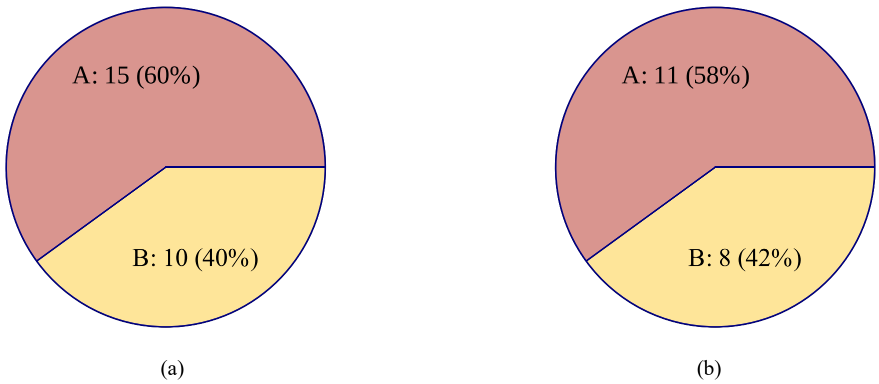


Fig. 11. Response to Q10. (a) Response from academia. (b) Response from industry.

11. If aggregated impedance models are inaccurate, what factors will contribute most to the inaccuracy?

A. Different steady-state operating points of individual IBRs

B. Control interactions between IBRs in an aggregated model

C. Different parameters of controllers and passive components such as filters and cables

Fig. 12. Response to Q11. (a) Response from academia. (b) Response from industry.

12. How do you deal with the impact of operating point on the impedance-based method?

A. Cover as many operating points as possible in the impedance measurement

B. Select multiple operating points following certain guideline, and be confident that the selected operating points cover the worst case

C. Select multiple operating points following certain guideline, but not sure if the selected operating points cover the worst case

D. No guideline on how to select operating points, but simply rely on engineering judgement

(a) (b)

Fig. 13. Response to Q12. (a) Response from academia. (b) Response from industry.

III. Key Results and Analysis

A. *State-of-the-Art*

Fig.2 clearly demonstrates that almost all respondents have used or intend to use the impedance-based method for dynamic analysis. There is also an increasing awareness on how the method should be correctly implemented. As indicated in Fig. 9, the vast majority of respondents recognize the necessity of employing multiple-input multiple-output (MIMO) impedance matrices, rather than single-input single-output (SISO) impedance transfer functions, for the accurate stability assessment in both $\alpha\beta$ or dq frame [6].

While most respondents express confidence in the effectiveness of impedance-based method, industry respondents exhibit lower levels of confidence compared to their academic counterparts (see Fig. 3). This disparity may be attributed to the fact that industries tend to encounter more complex electrical systems, which increases the likelihood of divergence between impedance-based predictions and EMT simulations/field measurements results.

B. *Challenges for the Industry*

Based on the response of Q3 and Q4 (Figs. 4-5), both the unique and common challenges faced by TSOs/power plant developers and IBR vendors in implementing impedance-based dynamic analysis are summarized as follows:

Unique challenges for TSOs/power plant developers: It can be seen from Fig. 4 that the lack of the automated impedance measurement toolbox is one of most significant challenges for TSOs/power plant developers. The impedance measurement tools have been developed, both in simulation software and hardware, for measuring impedances of single or a few IBRs [7]-[10]. However, TSOs/power plant developers are dealing with large and complex electrical systems that may include thousands of IBRs, which imposes more stringent requirements on the time efficiency of the automated impedance measurement tools. A recent attempt can be found from Aalborg University and TenneT TSO that has developed the impedance measurement toolbox and tested in a multi-terminal HVDC system [8], as shown in Fig. 14. NERL [9] as well as ERCOT [10] have also developed similar toolboxes that are tested in wind power plants. Yet, more efforts are still expected to further improve the computational efficiency and accuracy.

Fig. 4 indicates another challenge for TSOs/power plant developers, which is the difficulty of verifying the accuracy of the impedance measurement. This challenge arises because TSOs/power plant developers work with black-boxed simulation models of IBRs, as the IBR vendors cannot disclose the control algorithms of IBRs due to intellectual property (IP) concerns. Consequently, TSOs/power plant developers cannot theoretically derive the impedance models to check with the measured results. A few TSOs/power plant developers have asked IBR vendors to provide black-boxed, theoretically-derived impedance models for cross-validation with the measured impedances [11]. However, this requires IBR vendors to have adequate expertise in impedance modeling of IBRs, and hence, it is still not a common practice at the current stage.

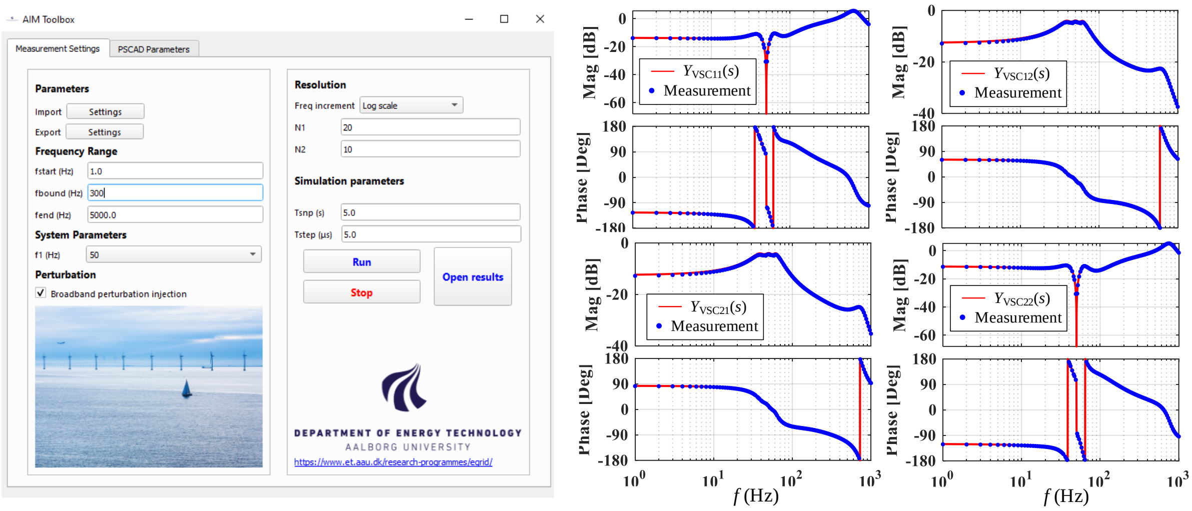


Fig. 14. Graphical user interface (GUI) and part of test results of the impedance measurement toolbox developed in [8]..

Unique challenges for IBR vendors: Based on Fig. 5, the lack of impedance specifications poses a significant challenge for IBR vendors. Given the fact that the impedance matrix of IBR can be simplified to a SISO form in the high-frequency range, its real part is required to be non-negative by some grid codes for the guarantee of high-frequency stability [12]. However, there are currently no specifications for impedance matrix of IBR in the low-frequency range, where its original MIMO form should be adopted for stability assessment. This is mainly due to the lack of relationship between the low-frequency stability margin and the dynamic properties of impedance matrix, which makes it difficult to establish the impedance specifications. Moreover, the missing of such a direct link also poses a challenge for IBR vendors in obtaining analytical insights into controller design from the impedance-based dynamic analysis, as indicated by Fig.5.

Common challenges: It can be seen from Figs. 4-5 that TSOs/power plant developers and IBR vendors have expressed their concerns in using impedance-based dynamic analysis for multi-IBR systems. This concern can be further broken down into two questions: 1) how to aggregate impedance models of IBRs, and 2) how to deal with multiple operating points of a complex electrical system, which are indicated by Q11-Q12. The industry's responses to the former question, as given by Fig. 12(b), suggest that they are skeptical to the capability of aggregated impedance model of multiple IBRs in reflecting the control interactions therein. Further, their response to the latter question reflects a lack of an appropriate method for dealing with multiple operating points, i.e., they either attempt to cover as many operating points as possible, or select multiple operating points based on practical experiences or operational guidelines, but are not sure if the selected operating points can cover the worst-case scenarios, as illustrated in Fig. 13(b).

C. Gap between Academia and Industry

It is quite interesting to see from Figs. 12-13 that academia and industry hold quite different opinions on impedance-based dynamic analysis for multi-IBR systems. By comparing Fig. 12(a) and Fig. 12(b), it is found out that although both groups acknowledged that the control interactions of IBRs is the primary cause of inaccuracy of the aggregated impedance model, academia additionally identifies different operating points of individual IBRs as an important contributor, while industry attributes the inaccuracy to different controller and circuit parameters. This disparity may stem from the fact that academia often examines homogeneous multi-IBR systems, where IBRs have identical controller and circuit parameters, and thus fails to capture the impact of heterogeneous IBRs on the accuracy of impedance aggregation.

Moreover, Fig. 13(a) indicates that around 30% of academic researchers are confident to cover the worst-case scenarios by following certain guidelines, whereas this confidence is not agreed by the industry, as indicated in Fig. 13(b)

In a nutshell, the results of Figs. 12-13 clearly indicate the gap between understandings of academia and industry on the challenges with using impedance-based method, and highlight the importance of academia-industry collaboration in developing effective impedance aggregation methods for multi-IBR systems.

IV. Future Development of Impedance-based Dynamic Analysis

Based on the challenges identified in Section III and the response to Q5, several open issues with the impedance-based analysis method are summarized as follows, which are also outlined in Fig. 15. Addressing these issues require collaborative research and development efforts of academia and industry.

1) *Dynamic specifications for MIMO impedance matrix*: Control theories that can link dynamic properties of MIMO impedance matrix to low-frequency stability margin, and link the characteristics of each element of impedance matrix to specific controllers need to be developed. Such links would not only aid TSOs/power plant developers in developing clear specifications and requirements on the impedance matrix of IBRs, but also offer insights for IBR-vendors in shaping control dynamics of IBRs.
2) *Impedance measurement toolbox*: An automated impedance measurement toolbox with high measuring accuracy and high time efficiency should be developed and tested in large and complex electrical systems.
3) *Impedance-based analysis of multi-IBR system*: A solid theoretical framework of implementing impedance-based dynamic analysis should be developed for heterogeneous multi-IBR systems in complex electrical networks. This framework should be able to accurately aggregate impedance models of IBRs and address the challenges related to multiple operating points.

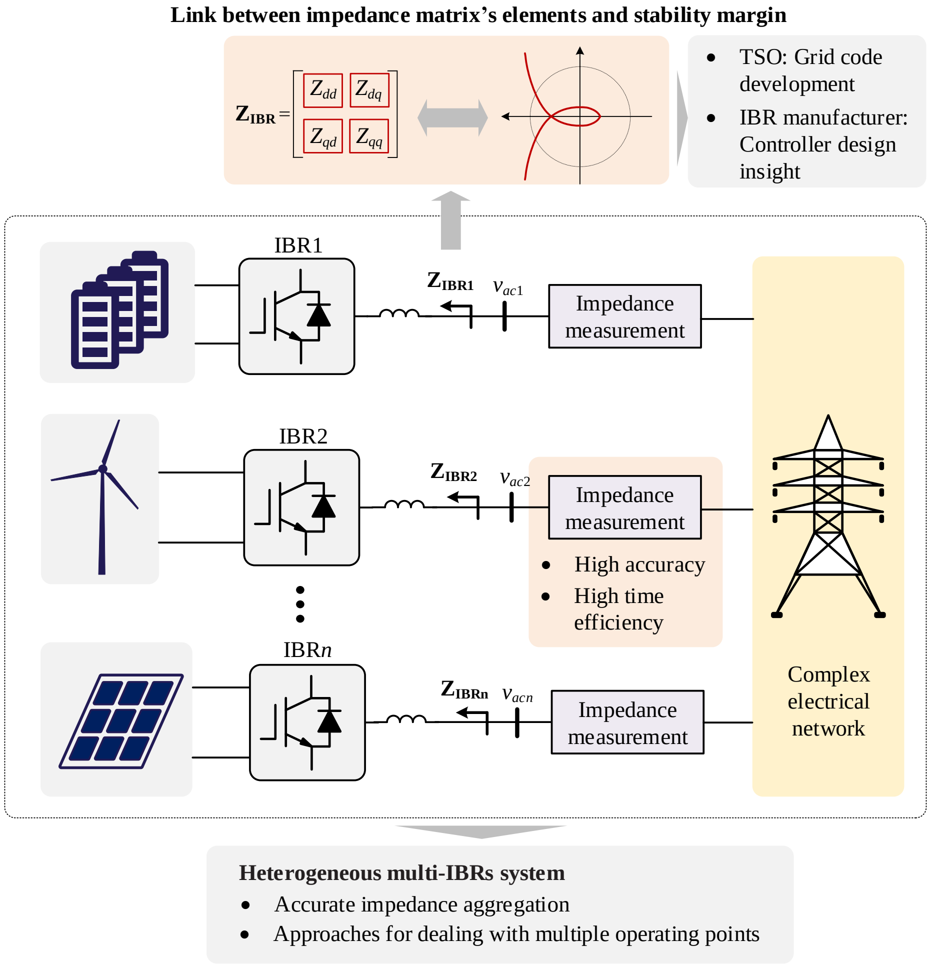


Fig. 15. Open issues with impedance-based dynamics analysis methods.

V. Conclusion and Future Action

The results of the survey on impedance-based dynamics analysis method have identified gaps and challenges faced by different stakeholders, based on which, several emerging topics in this direction are summarized. In the future, IEEE Task Force on Frequency-Domain Modeling and Dynamic Analysis of HVDC and FACTS will organize more technical activities to facilitate the collaborations between academia and industry in addressing the challenges, which can hopefully advance the technology for stability analysis of future power systems.

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