

Chapter 2

Problem Definition

Abstract An overview of grid connection methodologies of offshore wind power plants (OWPPs) and harmonic challenges related hereto were given in the preceding chapter. The scope and deliverables from this Industrial Ph.D. project are presented in this chapter, based on the overview in Chap. 1. This chapter furthermore defines the approach, limitations and thesis outline.

2.1 Background

OWPPs can be characterized as a power electronic device (PED) rich grid, as described in the preceding chapter. The Ph.D. project is expected to develop a deeper understanding on how the PEDs and associated control systems interact (from a harmonic perspective) with each other and with the passive electrical components in the OWPPs, such as the extensive submarine cabling.

The purpose is to meet a necessary need to develop and strengthen DONG Energy Wind Power's (DEWP's) in-house competencies with regard to electrical system modelling and analysis of large OWPPs employing PEDs in the transmission system, such as the Static Compensator (STATCOM) and the voltage-sourced converter high-voltage direct current (VSC-HVDC, hereafter denoted HVDC for brevity).

By achieving a better understanding of the complexity of how such actively controlled systems interact with each other, seen from a harmonic perspective, it will be possible to make a better and more cost-efficient design of e.g. harmonic filters, reactive compensation etc. This will eventually enable DEWP to optimise the overall electrical infrastructure in modern OWPP incorporating a number of power electronic devices (PEDs), which is of key importance for timely grid connection of the OWPP.

Furthermore, the attained knowledge enables DEWP to give relevant input during the grid code compliance process of an OWPP. The project will enable DEWP to get the right information for e.g. the HVDC system in due time during the

design of an OWPP and will lead to lowering the risks in each of DEWP's OWPP projects. Additionally, the project aids DEWP define technical requirements to potential suppliers and increase the in-house competencies required for optimised OWPP design,

2.2 Research Objectives

This Industrial Ph.D. project will mainly focus on investigating the best possible way(s) to perform harmonic stability studies in HVAC and HVDC grid connected OWPPs. The project aims at gaining new insight, methods and models, which will contribute to achieve a better understanding of the harmonic stability phenomena in OWPPs. Eventually, the knowledge and applicable models expected to be derived within the project will enable the involved parties (e.g. the OWPP developer and the power electronic device (PED) vendors) to improve e.g. the filter design and in general ensure a high degree of reliability of future OWPPs where PEDs are widely applied.

In order to achieve the above-mentioned goals, the following main objectives are defined as:

- To obtain knowledge of the modular multi-level cascaded converters (MMCCs) for wind power integration (HVDC and STATCOM).
- **Develop and validate appropriate models of the PEDs, including the MMCCs.**
 - In time and frequency domain, where found applicable.
 - Conduct field measurement campaign for model validations.
- **Investigate OWPP harmonic stability issues** for frequencies above the fundamental frequency with widespread use of active PEDs.
 - Compare different stability assessment methods **in time and frequency domain.**
- **Develop a best practice for harmonic stability assessment in OWPPs.**

2.2.1 Formulation of Specific Research Questions

In order to meet the main objectives stated in the above, the following research questions have been formulated:

1. What is the state-of-the-art for the MMCC technology for HVDC and STATCOM systems?

2. Is it possible to develop generic yet detailed models of the WTGs, HVDC and STATCOM systems for harmonic studies in OWPPs?
 - a. What are the required modelling details?
 - b. How are PEDs typically controlled?
 - c. How can the developed models be evaluated?
3. How is the harmonic stability in OWPPs currently evaluated?
4. What is the state-of-the-art harmonic instability mitigation means applied in the OWPPs nowadays?
 - a. Can these mitigation means be applied in OWPPs with PEDs in the transmission system?
5. What are the advantages/limitations of using a time or frequency domain approach in the evaluation of harmonic stability in OWPPs?
 - a. What are the pros/cons using the two domains?
 - b. Is there a correlation between the results obtained in the two domains?
 - c. Is it possible to utilise the advantages of each of the domains in the stability assessment?
 - d. Taking into account the above questions, is it possible to derive a procedure for evaluation of the harmonic stability in OWPPs with PEDs in the transmission system, which can be applied in the design phase of future OWPPs?

2.3 Approach and Methodology

The methods which will primarily be applied in this Industrial Ph.D. project include literature study and theoretical analysis, measurement data acquisition and post-processing, component modelling and validation and finally power system simulations and analysis based on the developed models.

2.3.1 Literature Study and Theoretical Analysis

Theoretical analysis is a suitable method during the study of the PEDs used in the WTGs and in the transmission system. The study will include the working principle of the state-of-the-art type 4 WTGs, the MMCC HVDC and the MMCC STATCOM, on their topology and control methodology. The state-of-the-art review on the MMCC technology includes both previous work in academia and especially what is offered by relevant vendors, as this is relevance to OWPP developers such as DEWP. The review will focus on the topology of relevant converter systems and on the structure of the applied control system.

A fundamental understanding of the time and frequency domains must be obtained in order to assess their application for harmonic stability studies in OWPPs. This will be achieved by reviewing the existing methods used in the industry as well as academic contributions.

A review on the typical modelling of the internal OWPP cable collecting grid and the external power system (in HVAC grid connected OWPPs) enables the Ph.D. student to develop and implement a suitable model in the simulation tool(s).

2.3.2 Measurement Data Acquisition and Processing

One of the main advantages of being an Industrial Ph.D. project is the possibility to conduct field measurements on commercial power system components.

Two measurement campaigns have been conducted within the current project as described in the following.

MMCC STATCOM located at the grid connection point of London Array OWPP

A long term harmonic measurement campaign has been conducted at the CleveHill onshore substation, connecting London Array OWPP to the transmission system. Four STATCOMs are located at CleveHill substation, and measurements were made on one of these. The purpose of the measurement data is foremost to obtain real life knowledge of the STATCOM and for model development and evaluation.

The STATCOM measurement could furthermore be used to gain in-depth knowledge on how such a MMCC based PED acts a harmonic source. This could then be transferred into a harmonic emission model of the STATCOM. The 1 month duration of the campaign was therefore selected in order capture a large number of operating conditions of the STATCOM, the OWPP and the external grid, as each of these will have an impact on the harmonic emission of the STATCOM.

As described in Sect. 2.1, the main scope of this project is the evaluation of the harmonic stability phenomena in OWPPs; hence the evaluation of the harmonic emission is suggested for future work, see Sect. 14.6.

The obtained measurements are considered a significant contribution from this work, as there is no previously public available high-resolution measurements data on an actual STATCOM. The measurements have also been utilised in improving the author's knowledge on MMCCs, which is needed for detailed STATCOM modelling as well as for evaluation of the model.

Measurements at National Renewable Energy Laboratory (NREL), Colorado, US

The author has had the pleasure of being employed as a guest researcher at the National Wind Technology Center (NWTC) at NREL as part of the Ph.D. project. The NWTC commissioned an advanced grid simulated test system during the author's stay at the research facility. The grid simulator (referred to as Controllable Grid Interface, CGI) is capable of supporting multiple types of grid compliance tests,

including low and high-voltage fault ride-through (LVRT and HVRT, respectively), frequency response, and voltage support for WTGs and other types of renewable energy sources and storage units (a system description is given in Chap. 7).

According to the author's knowledge, the CGI shown in Fig. 7.3 is a modified version of ABB's SVC Light (PCS 6000) [1].

Tests on a commercial multi-megawatt sized type 4 WTG connected to the CGI for both normal and abnormal operating conditions (e.g. LVRTs of various types and durations) were realised during the author's three stays at NREL. The test results were found to provide a useful source of information on how commercial PEDs are controlled and how they respond to e.g. a full single-phase fault at their terminals. The test data was furthermore used to develop suitable generic models of the PEDs for harmonic stability studies as described in the following.

2.3.3 Component Modelling and Validation

When the relevant knowledge of the above mentioned PEDs is defined and described in the theoretical analysis, it will be transferred into simulation models intended for harmonic stability studies in OWPPs. The models will be validated by comparison of simulation results with measurement data in the time domain.

The acquisition of detailed generic models of the PEDs (especially the STATCOM and the HVDC) enables one to gain further insight on e.g. the MMCC's working principles, which might not have been possible by the literature study alone. Having these models is deemed valuable to DEWP, as it enables the company to acquire relevant information and specify relevant requirements related to harmonic stability in the early stages of the negotiations with possible PED vendors.

Active Component Modelling in the Time Domain

Generic, yet detailed electromagnetic transient (EMT) models of the following actively controlled PEDs have been developed and implemented in the simulation tool PSCAD/EMTDC:

- WTG (normal as well as abnormal operating conditions).
- CGI (normal as well as abnormal operating conditions).
- MMCC STATCOM.
- MMCC HVDC.

The measurement data obtained within the project will be used to evaluate the developed models of the WTG, the CGI and the STATCOM. Based on the reflections presented in Chap. 3–6 it is considered that the validated model of the MMCC STATCOM can be transferred to the generic MMCC HVDC.

Harmonics in power systems are considered a steady-state operating condition [2] The model evaluation of the WTG and the CGI during abnormal operating conditions might therefore appear to be unnecessary in relation to this research

project. However, the evaluation has been included in the work presented in this report due to the following considerations:

- Provides in-depth insight of the operating characteristics of commercial PEDs, which was proven very useful in the modelling and further evaluation of the PEDs.
- Active filtering is typically used in the direct chain of the WTG's current control system, as described in Chap. 10. Hence, the active filtering might impede the dynamic response of the WTG during e.g. faults. Having validated generic models of the WTG (without any active harmonic filtering) during faults enables the researcher to evaluate the dynamic impact of these filters by simply adding the active filtering described in Chap. 10 into the already validated model and compare the results. This is suggested for future work.
- A Cooperative Research and Development Agreement (CRADA) was signed between NREL and DEWP in order for the author to be employed as a guest researcher at NREL. Deliverables from the CRADA include both modelling and evaluation of the PED models. Thus, the modelling and validation of the abnormal operating conditions was a prerequisite for the establishment of the CRADA.

Active Component Modelling in the Frequency Domain

As defined in Sect. 2.1, the main focus of this research project will be on the evaluation of the frequency domain with regard to the time domain method. Linearized models of the PEDs therefore need to be developed and implemented in a suitable simulation tool (in this work DigSILENT PowerFactory and MatLab).

Passive Component Modelling

The relatively complex structure of converter rich OWPPs with extensive submarine cabling possesses modelling challenges (especially for time domain simulations using EMT programs (EMTPs)). Therefore, suitable methods for representation of the OWPP and the external power system (in HVAC connected OWPPs) must be devised.

2.3.4 Power System Simulations

Simulations studies are useful in order to investigate and understand possible phenomena related to harmonic distortion in an OWPP with the possible employment of PEDs in the transmission system. The investigation at system level will be done on basis of the validated models and will be carried out in both time and frequency domain. As defined in Sect. 2.1, the main focus will be on the evaluation of the frequency domain with regard to the time domain. The electrical system considered in this work is presented in Fig. 2.1. Figure 2.1a shows a generic overview of an aggregated OWPP. An export cable connects the OWPP to one of the three external systems shown in Fig. 2.1b.

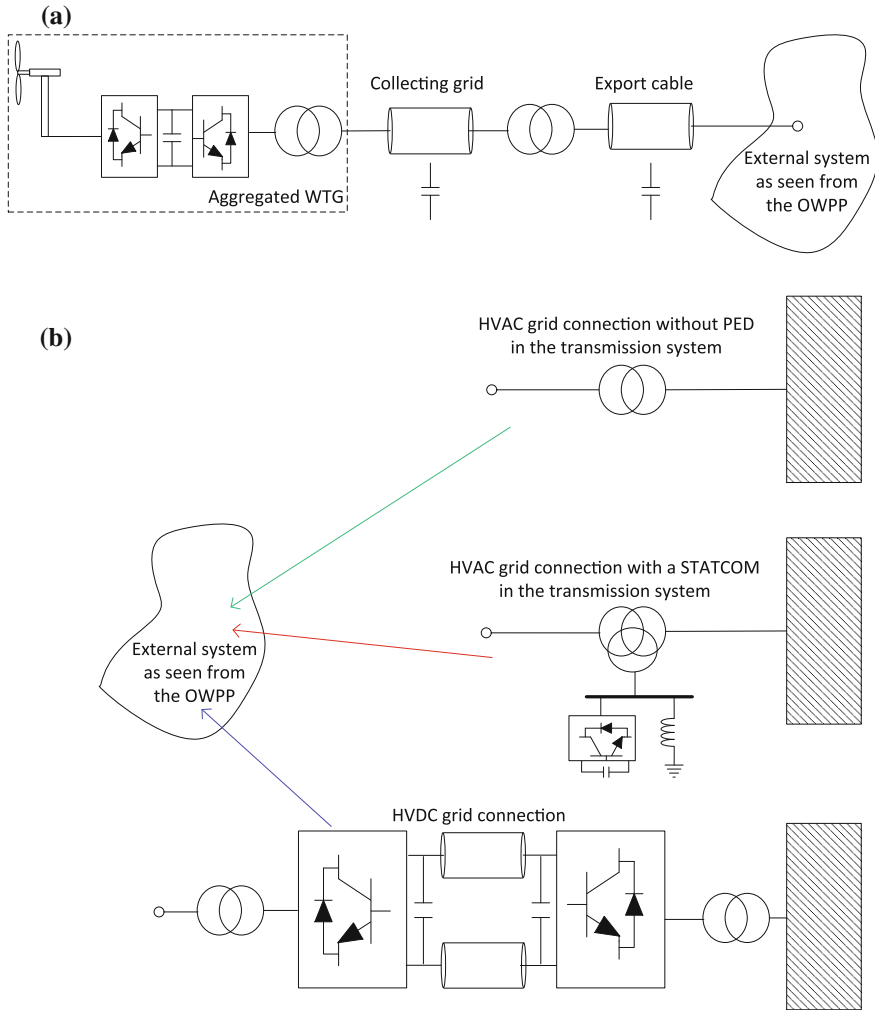


Fig. 2.1 a Simplified single line diagram of generic OWPP. b HVAC grid connections without and with PEDs in the external system

2.3.5 Project Flowchart

The approach defined in Sect. 2.3.1–2.3.4 can be visualised using a flowchart, as presented in Fig. 2.2, which provides a good overview of the different processes. It should be noted that the applied approach in this work does not exactly follow the flow indicated in Fig. 2.2, as e.g. the theoretical analysis of the PEDs and the harmonic stability was done throughout the project time frame. Furthermore, the experience gained during e.g. the WTG and the CGI modelling was transferred to

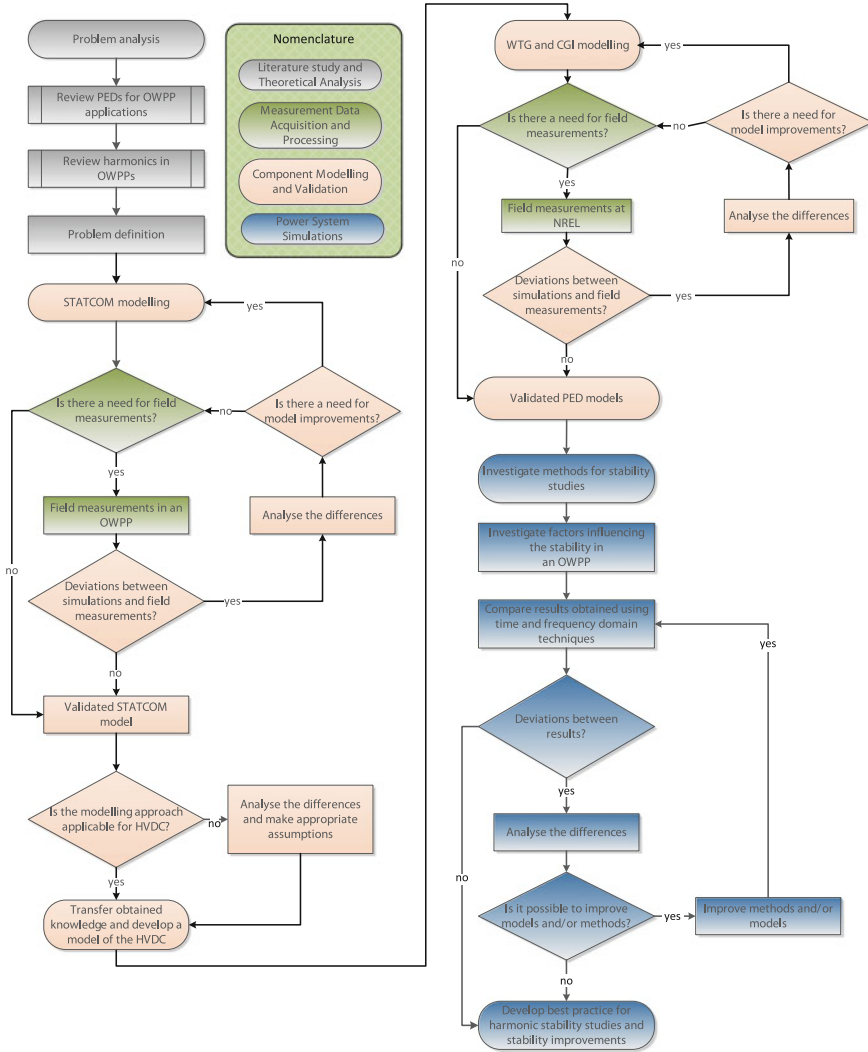


Fig. 2.2 Generalised project flowchart

the already developed STATCOM and HVDC models, which were then optimised and updated. Similarly, if any of the models were found insufficient in the model application process (the “blue process” in Fig. 2.2) in Fig. 2.2) they would be updated in the component modelling process. For example, if the STATCOM model was found insufficient in the model application process it would be updated in the modelling process. Then, the updated model would be directly transferred back and applied in the model application process. Including all of these iterations would significantly increase the complexity of Fig. 2.2.

The generalised flowchart in Fig. 2.2 is by the author and supervisors considered to provide a simplified, yet realistic overview of how the project was executed.

2.4 Limitations

A relatively thorough description of the limitations made within the 3 year research project is given in this section. The purpose of the description is:

- To demonstrate the author's awareness of the limitations made and their impact on the outcome of the project.
- To provide the reader with a framework to evaluate the soundness of the results obtained within the project (both on a scientific level and for industrial applications).
- To strengthen the foundations of future, related research projects which can take into account some of the limitations made here.
- To provide inspiration for future, related research projects with inspiration on what could be additionally included in their scope (in combination with the future work in Sect. 14.6).

The conscious specified limitations are:

- **London Array measurement campaign** (campaign description is given in Chap. 5)

- Measurement data was only collected at the tertiary winding of the onshore transformer (i.e. only at the STATCOM). Measurement data could have been collected offshore, in a few selected WTGs and/or at the offshore park transformer.

This was not done as offshore measurement campaigns are associated with high costs, required significantly more planning and execution time than was available. Furthermore, there are uncertainties regarding access to the WTGs due to weather conditions.

Extensive offshore field measurement campaigns have previously been conducted and post-processed in the previous Industrial Ph.D. project "Harmonics in Large Offshore Wind Farms" in DEWP [3].

- The application of the 1 month measurement campaign in this project was limited to validation of the developed EMT-like MMCC models. A more thorough evaluation of the STATCOM operating as a harmonic source is proposed as future work, using the measurement data.

- **Passive power system component modelling**

- An aggregated representation of the OWPP is used in this work, as it simplifies the modelling work.

OWPP aggregation is the standard approach in the industry for harmonic stability studies.

EMT-like simulations with detailed modelling of the full-scale converter (FSC) models in a converter rich grid such as an OWPP is by the author considered impractical due to significant time and calculation burden consumption.

A preliminary assessment of this approach was carried out using a full (real-life) OWPP model in DigSILENT PowerFactory.

The preliminary assessment indicates a good correlation between the impedance seen from the terminals of a specific WTG in the full model and to that of the aggregated WTG.

Results are not included since the applied models is for a real-life OWPP project.

The main scope of this work is the evaluation of the frequency domain approach related to the time domain.

Sensible to do the evaluation based on state-of-the-art harmonic stability procedure.

- Possible resonances in the external power system in the HVAC grid connected OWPP has been included using a frequency dependent network equivalent (FDNE). A look-up table of the grid impedance ($Z_{th}(f)$) provided by a TSO was used in the analysis. The exact implementation of the FDNE in the current version of PSCAD/EMTDC (v4.5) is not straightforward.

Could be achieved by using an auto regressive moving average (ARMA) model [4].

Requires a rational function description of $Z_{th}(f)$, which can be obtained using a system identification technique.

The next version of PSCAD/EMTDC (i.e. v4.6) includes an FDNE model in the main library.

The ARMA modelling requires a certain amount of coding in e.g. the FORTRAN language.

The author has in this work developed detailed equivalent models of the MMCCs using similar coding, and hence demonstrated the skills needed to model the ARMA.

A simplified FDNE is derived using a number of parallel RLC branches, which provides a relatively good correlation with the actual $Z_{th}(f)$ provided by a TSO.

This is considered appropriate as the main scope of this work is the comparison of the frequency and time domain harmonic stability methods using generic models.

- The inherent background harmonics in the HVAC grid connected OWPP has been omitted in the time domain model for simplicity.

The inclusion would have added to the overall harmonic distortion but it is presumed not to have an impact of the occurrence of instability. The evaluation of the background harmonics influence on the OWPP stability is proposed for future work.

- **PED modelling**

- The applied current control of the PEDs is realised in the rotating reference frame (RRF) only.

Additional harmonic controllers of e.g. the 5 and 7th in e.g. a nested structure or in separate RRFs have been omitted.

They will add additional challenges related to the harmonic stability [5].

- The voltage balancing of the sub-module (SM) voltages of the MMCCs is achieved using control strategies presented in the literature (see Chap. 6)

The control parameters were tuned by trial-and-error.

Complex analysis is needed to define the transfer function needed to analytically tune the controllers.

2.5 Thesis Outline

Table 2.1 on the following page shows an overview of the thesis, described more carefully in the following:

Part I Introduction and Problem Analysis

Part I has presented the background, motivation and scope of the Industrial Ph.D. project.

An overview of possible grid connection of remotely located OWPPs has been given in Chap. 1. Challenges related to harmonics in OWPPs have been also been described with main emphasis on the harmonic stability, as this is the topic of this Industrial Ph.D. project.

Table 2.1 Overview of the thesis

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This chapter has presented the scope and deliverables from this Industrial Ph.D. project. Furthermore, the chapter has described the applied methodology, limitations and the thesis outline.

Part II Power System Component Modelling and Evaluation

Part II of the thesis focuses on the modelling of the PEDs, the two measurement campaigns and evaluation of the developed models.

Chapter 3 presents and describes some of the various MMCC systems, which are commercially available and considered within the research project. The chapter presents a brief overview of the previous two- and three-level VSC-HVDC technologies.

Chapter 4 presents the detailed equivalent EMT based modelling technique developed within this project, which is capable to model the commercial MMCC STATCOM and MMCC HVDC systems considered in this work.

Chapter 5 describes the measurement campaign realised at the STATCOM, located at the onshore grid connection point of London Array OWPP.

Chapter 6 presents the time domain models of the MMCCs implemented in PSCAD/EMTDC. The low level control, ensuring the stabilisation of the distributed SM voltages in the MMCCs will be described and implemented in the STATCOM and the HVDC models. The evaluation of the STATCOM is presented based on

comparison with the measurement data obtained from London Array OWPP in Chap. 5.

The system description of the CGI and the commercial multi-megawatt sized type 4 WTG installed at the National Renewable Energy Laboratory (NREL) is presented in Chap. 7.

Detailed, generic EMT models of the CGI and the WTG are developed and implemented in PSCAD/EMTDC in Chap. 8.

The models are evaluated based on comparison with test measurement in Chap. 9.

Chapter 10 presents the frequency domain modelling of the PEDs.

Chapter 11 presented the methods used in this work for modelling the passive OWPP components (such as the cables etc.) in the time and frequency domains.

Part III System Studies and Conclusion

Part III of the thesis presents power system studies realised based on the developed models in Part II.

Chapter 12 presents the harmonic stability evaluation in OWPPs employing PEDs in the transmission system.

Chapter 13 presents a discussion of the findings and how to relate these to industrial applications.

Chapter 14 presents the concluding remarks and the list of publications realised within the confines of this Industrial Ph.D. project. Suggested future work is also outlined in Chap. 14.

2.6 Chapter Summary

This chapter has presented the scope and deliverables from this Industrial Ph.D. project. Furthermore, the chapter has described the applied methodology, limitations and thesis outline.

The scope of this project is to make a review of the state-of-the-art PEDs in OWPPs, to develop generic models of the PEDs in time and frequency domain, to conduct field measurement and apply the measurement data to validate the time domain models. Furthermore, the main scope is to conduct harmonic stability simulation studies in both the time and frequency domain and evaluate the results with respect to each other. Based on the findings of the analysis

The derivation of a recommendation on how to assess the harmonic stability in the OWPP design phase based on the simulation cases is expected to be made based on the findings in this research project.

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