Cigre Science & Engineering

Volume N°8, June 2017

Innovation in the Power Systems industry

Engineers and specialists worldwide exchange information and state-of-the-art world practices to enhance knowledge related to power systems in CIGRE's latest publication.

New members join the Editorial Board
Utilizing smart meter data for electricity fraud detection
International industry practice on modelling and dynamic performance of inverter based generation in power system studies

CIGRE © 21, rue d'Artois, 75008 Paris - ISSN : 1286-1146

Cigre Science & Engineering

Volume N°8, June 2017

Journal edited by CIGRE

President	Rob STEPHEN
Technical Council Chairman	Mark WALDRON
Secretary General	Philippe ADAM / philippe.adam@cigre.org

Editorial Committee

Chief Editor	Konstantin O. PAPAILIOU	
Editors	Pouyan POURBEIK	Erli FIGUEIREDO
	Nikos HATZIARGYRIOU	Rob STEPHEN
	Pierre ARGAUT	Christian FRANCK
	Xidong LIANG	

Copyright registration	N° 008, June 2017 1286-1146 CIGRÉ

© Copyright CIGRE

Conseil International des Grands Réseaux Electriques
International Council on Large Electric Systems
21 rue d'Artois - 75008 Paris - France
Tel : 33 (0)1 53 89 12 90
http://www.cigre.org

"The author(s) of papers published in the CIGRE Science and Engineering Journal, are granted permission to post a PDF copy of their paper, as published in the journal, for self-archival purposes on their own personal websites, or similar outlets (e.g. researchgate.com). This permission is granted with the following restrictions, requirements, and understanding:
1. CIGRE is the copyright owner of all articles. Please see the CIGRE copyright statement for details. The articles cannot be disseminate for commercial use (i.e. for payment, etc.).
2. A clear reference must appear where it is posted stating that "The paper may also be downloaded for free from the source CIGRE. Goto: http://www.cigre.org/Menu-links/Publications/CIGRE-Science-Engineering. Then click to download the <Month/Year> Issue of the CIGRE Science and Engineering Journal. The paper appears on pages <page numbers>.
3. The paper can only be posted on the author(s) website after it has been published and released through the CIGRE website."

Submission Procedure http://www.cigre.org/Menu-links/Publications/CIGRE-Science-Engineering

International industry practice on modelling and dynamic performance of inverter based generation in power system studies

Gustav Lammert[1*], Koji Yamashita[2*], Luis David Pabón Ospina[3],
Herwig Renner[4], Sergio Martínez Villanueva[5], Pouyan Pourbeik[6],
Florin-Emilian Ciausiu[7], Martin Braun[1,3]

[1]University of Kassel, Kassel, Germany
[2]CRIEPI, Kanagawa, Japan
[3]Fraunhofer IWES, Kassel, Germany
[4]Graz University of Technology, Graz, Austria
[5]Red Eléctrica de España, Alcobendas, Spain
[6]PEACE-PLLC, Flower Mound, USA
[7]Tractebel ENGIE, Bucharest, Romania

On behalf of CIGRE C4/C6.35/CIRED

Abstract

The increasing penetration of Inverter Based Generation (IBG) over the last years has led to much effort on the development of IBG models for power system dynamic studies. CIGRE and CIRED established the joint working group CIGRE C4/C6.35/CIRED: "Modelling and dynamic performance of inverter based generation in power system transmission and distribution studies" with the aim of collecting the present best practices in the industry on modelling of IBG for power system dynamic studies, with the focus on photovoltaic systems. For that purpose, a questionnaire was distributed to utilities and system operators around the world. This paper summarizes some of the key findings about: 1) the studied power system; 2) the used IBG models (RMS and EMT models); and 3) the type of the performed studies. This survey supports utilities and system operators as well as research institutes and academia to benchmark their approach against the prevailing international industry practice.

1. Introduction

Presently, many regions around the world are seeing ever increasing penetration of Inverter Based Generation (IBG), such as type 3 and 4 wind generation systems and PhotoVoltaic (PV) generation. The dynamic characteristic of IBG is different from conventional synchronous generators, and so this ever increasing penetration of IBG means that the dynamic performance of the power system following disturbances may change. Therefore, analyses of the high penetration levels of IBG require much focus on the type of the IBG models being used in power system dynamic studies.

There are many levels of models used for all types of power equipment. At one end of the spectrum are stability models, sometimes also referred to as positive sequence or Root Mean Square (RMS) models. At the other end of the spectrum are very detailed equipment level Electro-Magnetic Transient (EMT) based models. However, since all models have limitations, the selection of the model type is crucial based on the objectives of the study to be performed with the model. Therefore, the adequate model type could change depending on the type of power system dynamic study and the system conditions to be studied.

Static load models are still widely used around the world, except in North America [1], where reliability standards now mandate that dynamic load models be used at

---

*gustav.lammert@uni-kassel.de or koji.yamashita.jp@ieee.org

KEYWORDS

Electro-Magnetic Transient (EMT) models, model survey, PhotoVoltaic (PV) system models, power system stability, Root Mean Square (RMS) models.

least when studying heavy summer loading conditions [2]. Thus, because most of the PV generation in many regions around the world is connected to the distribution level, such as medium and low voltage networks, it is more likely that negative static load models are being used in many countries for the representation of IBG.

RMS models for IBG have been developed over the last years for generation connected at the bulk electric system level that is, at the transmission level. Two industry working groups were established, one within the Western Electricity Coordinating Council (WECC) [3] in North America, and another within the International Electrotechnical Commission (IEC) [4], in order to develop generic models of different types of IBG for power system dynamic studies. Some of those models have been already implemented in widely used commercial power system analysis software tools [5], [6]. However, these generic models are still not widely used yet by the industry, especially in Europe, as they are still relatively new. With respect to IBG, connected at the medium and low voltage distribution level (e.g. residential PV), there are still no widely accepted aggregated dynamic models. In this context, the most recent work has been done by WECC [7], but it is presently under review and discussion for further changes. Some of this is driven by new grid code requirements that need to be considered in the development of generic models for IBG, e.g., the changing IEEE 1547 standard in North America or the newly proposed German grid code for the high voltage network VDE-AR-N 4120. This might be another reason that generic models for IBG are not widely used yet.

In October 2013, CIGRE and CIRED established the new Joint Working Group (JWG) CIGRE C4/C6.35/CIRED: “Modelling and dynamic performance of inverter based generation in power system transmission and distribution studies”, to look at some of these evolving issues. One of the tasks of the JWG is to identify the present industry practice on modelling of IBG, with the focus on PV systems, for power system dynamic studies. For that purpose, a comprehensive questionnaire was developed and distributed during the spring of 2015 to 63 utilities and system operators in 21 countries on five continents. This paper summarizes some of the key findings from 45 responses to the survey, which have been received by the summer of 2016.

The aim of this paper is not necessarily to recommend the application of any specific dynamic model for a specific power system dynamic study, but, rather, to identify what dynamic models are presently applied and to provide some fundamental information on their use. Based on the key findings and observations, this paper states a clear message for the necessity and importance of the use of IBG models.

2. Survey

2.1. Organization

The original questionnaire that was distributed consists of four categories, whereas this paper focuses on the results of the two main categories. The main categories and the corresponding questions are listed in Table I. Further results of the original questionnaire can be found in [8].

Category 1 is about the characterization of the studied power system and gives a basic, but comprehensive, overview of the analyzed grids. The participants of the survey describe the overall system they study, e.g., the system connectivity, the installed capacity of their generation and the highest percentage of the penetration level of IBG.

Category 2 describes the type of model that is used by the utility and system operator for a specific type of power system dynamic study. In this category two types of models are distinguished, namely RMS and EMT models. A detailed comparison between RMS and EMT models is given in Section 3. Furthermore, category 2 refers to 14 different types of studies, including well known phenomena such as frequency, voltage, transient and small-signal stability. In this context, it should be noted that the evaluation of voltage fluctuations at steady state is not considered as long-term voltage stability.

2.2. Participants

Potential survey participants were identified by the JWG members and contacted via e-mail. The considered utilities and system operators were either Transmission System Operators (TSOs), or utilities and system operators that operate both, transmission and distribution systems. However, Distribution System Operators (DSOs) were not considered for this paper, because most of them replied that they do not perform power system dynamic studies.

No.	Category	No.	Question
1	Characterization of the studied power system	1.1	What system is the model intended to be used for (transmission/distribution/both)?
		1.2	What is the system connectivity (isolated small grid/interconnected grid)?
		1.3	What is the main purpose of the power system dynamic study?
		1.4	What is the total generation capacity?
		1.5	What is the total inverter based generation capacity?
		1.6	What is the highest percentage of penetration level of inverter based generation?
2	Type of model used for a specific type of power system dynamic study		What type of model do you use for a specific type of power system dynamic study?
		2.1	Frequency stability (large system)
		2.2	Short-term voltage stability (seconds)
		2.3	Short-circuit provision from inverter based generation
		2.4	Low voltage ride-through
		2.5	High voltage ride-through
		2.6	Transient stability with balanced faults
		2.7	Transient stability with unbalanced faults
		2.8	Long-term voltage stability (minutes)
		2.9	Small-disturbance angle stability
		2.10	Unintentional islanding
		2.11	Transients including switching transients
		2.12	Control system interactions (high frequency)
		2.13	Control system interactions (low frequency)
		2.14	Protection coordination

Table I: Survey categories and questions

As depicted in Table II, the questionnaire was sent to 63 utilities and system operators around the world between spring 2015 and summer 2016. Out of these 63 contacted utilities and system operators, 45 replied to the JWG. Hence, the response rate of 71 % was reached. The 45 received questionnaires from utilities and system operators came from 21 countries on five continents.

Participants	Total
Sent questionnaires to utilities and system operators	63
Received questionnaires from utilities and system operators	45
Response rate from utilities and system operators [%]	71
Received questionnaires from continents	5
Received questionnaires from countries	21

Table II: Survey participants and response rate

It should be noted that software vendors, consultancies, research organizations and academia are out of scope and only responses from utilities and system operators were considered for the survey. Out of the 45 received questionnaires, 35 came from TSOs, and 10 came from utilities and system operators that operate both, transmission and distribution systems.

3. Type of models

3.1. RMS models

RMS models are mainly used to study power system stability for large interconnected systems, this includes electromechanical oscillations (small-signal stability), as well as rotor-angle stability of synchronous generators and voltage and frequency stability [9]. Phasor simulation methods are used when only the magnitude and phase of the voltages and currents are of interest. It is not necessary to solve all the differential equations resulting from the interaction of R, L, and C elements. Hence, the network is simulated with fixed complex impedances instead of differential equations [10]. RMS simulation tools consider phenomena with a bandwidth of typically 0.1 to 3 Hz, since the network model's fidelity diminishes rapidly for phenomena with frequencies significantly outside of this range. However, the control loops modeled on individual power plants may cover phenomena up to 10 Hz. Another commonly used terminology for RMS type models is to call them “positive-sequence stability” models. In essence, such models assume a perfectly balanced network and consider only the positive sequence components of all phenomena.

Converters are included in RMS programs using their averaged models. They provide the behavior of the converter ignoring fast switching transients and any control with very small time constants compared to the time steps and the phenomena considered. For instance, in stability analysis there is usually no need to model the inverter in detail since its transients are much faster than the dynamics being studied. Therefore, only the fundamental frequency outputs of the converter are modelled, which are mainly reflected in the electrical control model. Due to this averaged representation, the modelling of different technologies of IBG can be unified using sub-models for each basic component according to their characteristics.

3.2. EMT models

When the phenomena to be studied are significantly outside of the range of fidelity of RMS models (for example studying electro-magnetic transients, or sub-synchronous torsional interactions, etc.), then EMT simulation software should be used, together with detailed equipment specific models. EMT analysis programs solve the differential-algebraic equations of a three phase electrical network [11]. This distinction means that EMT analysis is capable of representing electro-magnetic transients (hence the name EMT), the frequency dependence of network components (e.g. change in transmission line resistance/reactance with frequency), harmonics, unbalanced networks, power electronic devices, including the switching transients as well as the detailed controls and protection systems.

Users need to be careful on the selection of the type of models between RMS and EMT. RMS models usually do not include the inner current control loops of the converter, the detailed phase-locked loop model and various other details of the converter. Nevertheless, RMS simulations are much faster to execute than EMT and are thus dominant for specific types of power system dynamic studies.

EMT models may also be required under the following special system conditions (where RMS time-domain simulation programs may not be accurate or suitable anymore):

- Weak system conditions (with a very low short-circuit ratio)
- Detailed inverter and collector system design
- Detailed equipment and system interaction studies
- Unbalanced faults (note that many RMS models are positive sequence models)

4. Results

4.1. Category 1: Characterization of the studied power system

Question 1.1 (What system is the model intended to be used for (transmission/distribution/both)?) in this category is about the type of power system that is studied. For this paper only utilities and system operators that perform studies with either the transmission system only, or with both, the transmission and the distribution system, were considered. Out of the considered participants, 78 % perform transmission system studies only, whereas 22 % perform studies for both, the transmission and the distribution system.

Question 1.2 (What is the system connectivity (isolated small grid/interconnected grid)?) analyzes the system connectivity. Out of the considered participants, 87 % of the utilities and system operators operate an interconnected grid. Furthermore, there are 9 % of the utilities and system operators, which operate both, an interconnected and an isolated small grid. This is the case for countries that also consist of islands. Just 4 % of the survey participants perform studies with an isolated small grid only.

Question 1.3 (What is the main purpose of the power system dynamic study?) in this category is about the predominant studies that utilities and system operators usually perform and the results are shown in Figure 1. The participants could select between different types of studies given in category 2 in Table I. The results indicate that the utilities and system operators mainly perform stability studies, such as frequency stability (study 2.1) with 89 %, short-term voltage stability (study 2.2) with 89 % and transient stability with balanced faults (study 2.6) with 89 %. It should be noted that recently announced

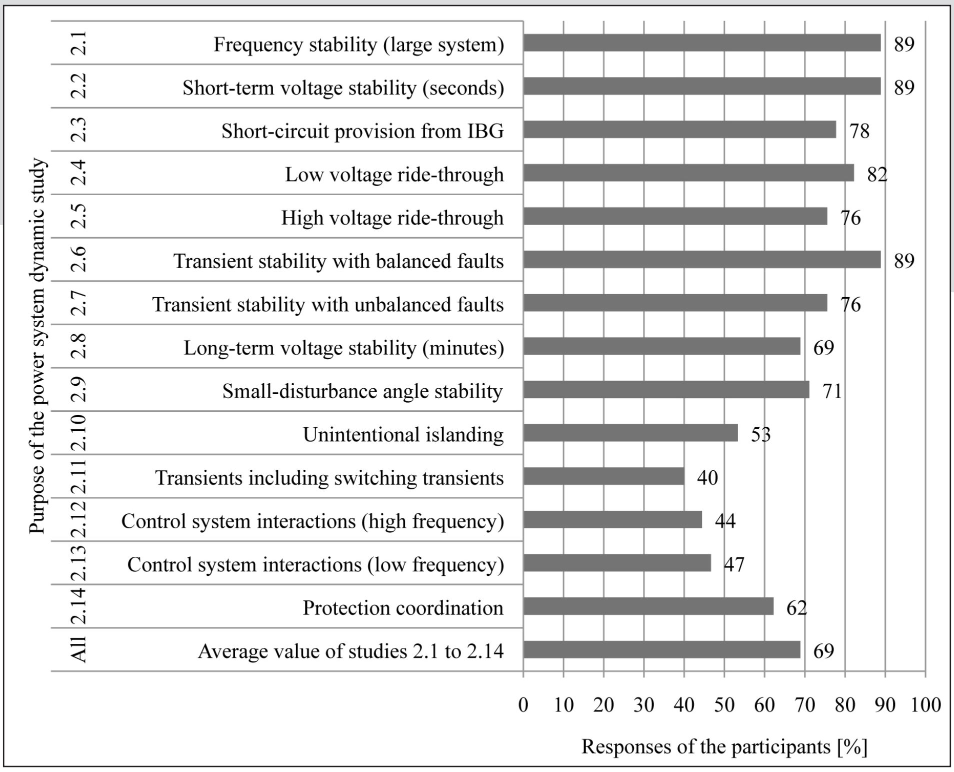

Figure 1: Question 1.3: What is the main purpose of the power system dynamic study?

grid code requirements for IBG, like low voltage ride-through (study 2.4), are also very common with 82 %. Other power system dynamic studies, such as transients including switching transients (study 2.11) with 40 %, control system interactions (studies 2.12 and 2.13) for high frequencies with 44 % and low frequencies with 47 % as well as unintentional islanding (study 2.10) with 53 % are less commonly performed by the utilities and system operators. However, even for the less commonly performed studies it should be noted that almost every second utility and system operator performs these types of studies. The main observation of the results is that 69 % of the participants perform the listed power system dynamic studies (studies 2.1 to 2.14), as seen in the last row of Figure 1.

Question 1.4 (What is the total generation capacity?) analyzes the size of the system regarding the installed generation capacity. The average value of the system sizes of all of the utilities and system operators is about 50 GW. The system size starts with 84 MW grids and ranges over large-scale power systems with 780 GW.

Question 1.5 (What is the total inverter based generation capacity?) is about the amount of installed IBG. The average value of installed IBG of all of the participants is about 5 GW, which is 10 % of the average value of the total installed generation capacity. However, there are also utilities and system operators with no IBG and a few with a high amount of IBG of about 44 GW.

Question 1.6 (What is the highest percentage of penetration level of inverter based generation?) investigates the penetration level. The results to this question are depicted in Figure 2 as a box plot. The present penetration level is calculated considering the values given by questions 1.4 and 1.5, and therefore represents the installed capacity. The main characteristics of the box plot shown in Figure 2 are: the median, shown as the black bar inside the grey box; the 25 %- and 75 %-quantile, represented as the top and the bottom of the grey box; and the min. and max. value, depicted as the whisker. The results can be interpreted as follows. The median of all of the utilities and system operators reaches 12 %. The min. and max. values are 0 % and 57 %, respectively. This means there are some of the utilities and system operators with no IBG, and some of the utilities and system operators reach a high share of IBG with 57 %.

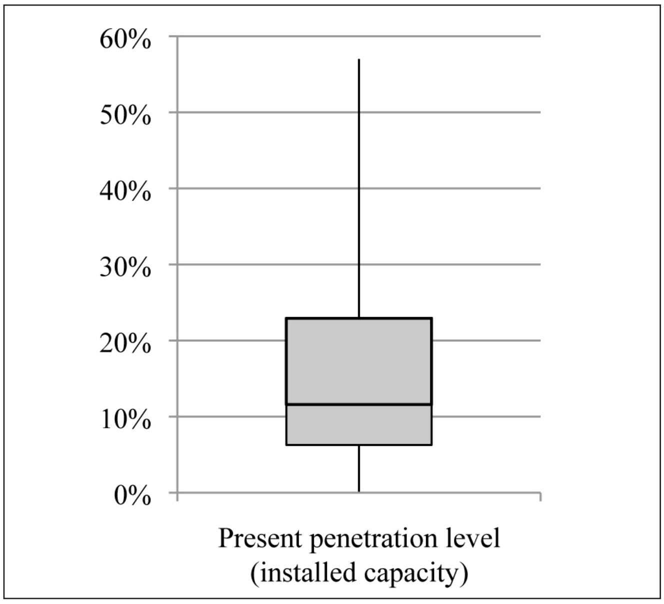

Figure 2: Question 1.6: What is the highest percentage of penetration level of inverter based generation?

4.2. Category 2: Type of model used for a specific type of power system dynamic study

Category 2 is about the type of model that is used for a specific type of power system dynamic study. The results for this category are divided into three parts. Part 1 analyzes whether an IBG model or a negative load model is used. If an IBG model is applied, a further distinction is made between RMS and EMT model, which is investigated in part 2. Part 3 is similar to part 2 while the focus is on the expected application of RMS and EMT models in the future. For all of the three parts, the answers were separated into 14 different power system dynamic studies, as shown in Table I. The results are discussed below.

Part 1 (distinction between IBG model and negative load model) describes a fundamental decision by the utilities and system operators, whether they represent IBG with an associated model or with a negative load model. The results of this distinction are depicted in Figure 3. It can be seen that for 13 out of 14 studies the participants decide for the IBG model instead of the negative load model. Only for transients including switching transients (study 2.11) the participants prefer the negative load model. Furthermore, the studies 2.1 to 2.7 in Figure 3 show that the application of IBG models is predominant (about 75 % in average) compared to the negative load model (about 25 % in average). For the studies 2.8 to 2.14 except 2.11 the share of the negative load model increases, whereas for study 2.11 it exceeds the IBG model. The main finding of the results is that 35 % of the utilities and system operators still use the negative load model for power system dynamic studies, as seen in the last row of Figure 3.

Part 2 (distinction between RMS and EMT model) deals with the decision of utilities and system operators with the type of IBG model that is used for a specific type of power system dynamic study. The results of the comparison between RMS and EMT models are presented in Figure 4. In general it can be concluded that in the studies 2.1 to 2.10 and 2.13 as well as 2.14 RMS models are predominant. Only for transients including switching transients (study 2.11) utilities and system operators prefer the EMT model instead. For control system interactions (high frequency) (study 2.12) the participants apply equally both, RMS and EMT models with 50 %, respectively. It should

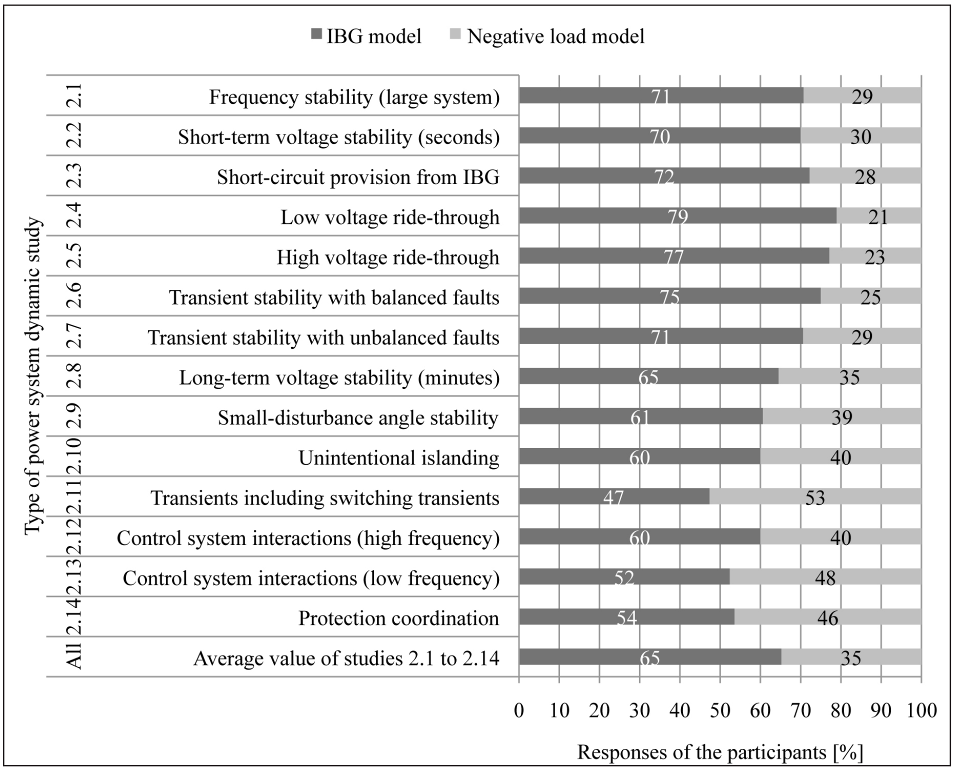

Figure 3: Question 2: What type of model do you use for a specific type of power system dynamic study? Distinction between Inverter Based Generation (IBG) model and negative load model.

be noted that for stability studies, such as frequency stability (study 2.1), voltage stability (studies 2.2 and 2.8) and rotor angle stability (studies 2.6, 2.7 and 2.9), RMS models are widely (about 90 % in average) used by the utilities and system operators. Furthermore, for power system dynamic studies that analyze transients, like unintentional islanding (study 2.10), transients including switching transients (study 2.11), control system interactions (high and low frequency) (studies 2.12 and 2.13) as well as protection coordination (study 2.14), the share of EMT models used by the utilities and system operators is considerable increased. The main observation of the results is that 78 % of the participants apply RMS models (if they use IBG models at all (refer to Figure 3)) instead of EMT models for power system dynamic studies, as seen in the last row of Figure 4.

Part 3 (distinction between RMS and EMT model in the future) analyzes in the same way as part 2 (distinction between RMS and EMT model) the type of IBG model that is used by the utility and system operator, with the difference that part 3 is focused on the expected application of RMS and EMT models in the future. The results are shown in Figure 5. At the first sight, it can be seen that RMS models are still prevailing compared to EMT models. The majority of the participants use RMS models for 11 out of 14 power system dynamic studies. Only for transients including switching transients (study 2.11) as well as control system interactions (high and low frequency) (studies 2.12 and 2.13) EMT models are predominant. It should be noted that for stability studies, such as frequency stability (study 2.1), voltage stability (studies 2.2 and 2.8) and rotor angle stability (studies 2.6, 2.7 and 2.9), RMS models are still widely used (about 75 % in average) by the utilities and system operators. Furthermore, similar to Figure 4, for power system dynamic studies that analyze transients, like unintentional islanding (study 2.10), transients including switching transients (study 2.11), control system interactions (high and low frequency) (studies 2.12 and 2.13) as well as protection coordination (study 2.14), the share of expected EMT models in the future used by the participants is considerable increased. The main finding by analyzing the results is that 63 % of the participants apply RMS models instead of EMT models for power system dynamic studies in the future, as seen in the last row of Figure 5. By comparing the results, the last row

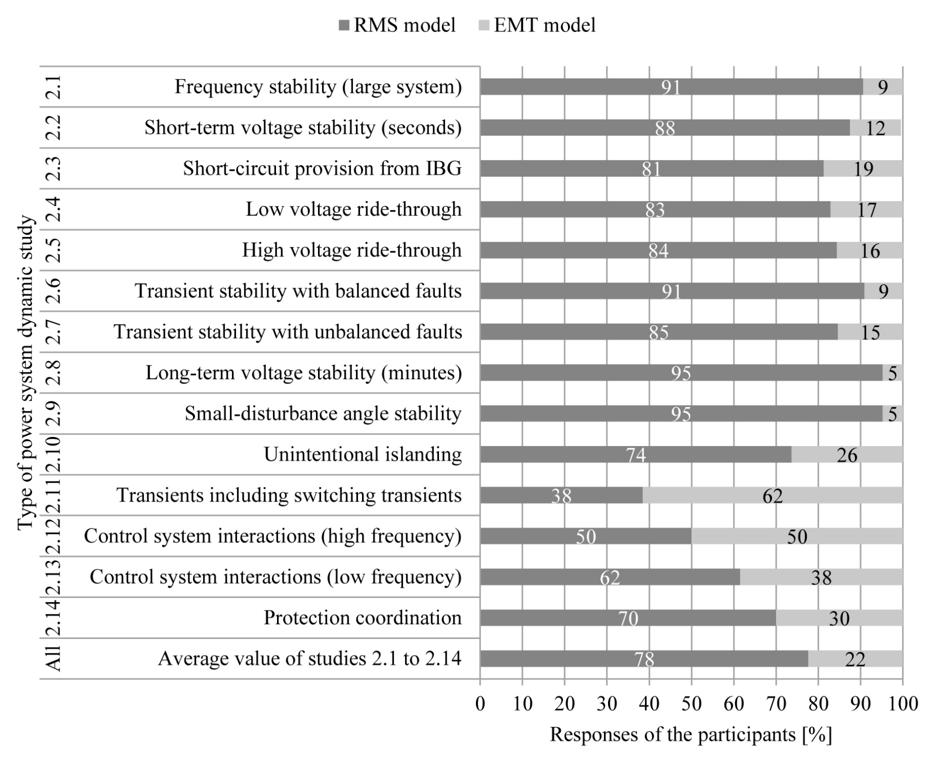

Figure 4: Question 2: What type of model do you use for a specific type of power system dynamic study? Distinction between Root Mean Square (RMS) and Electro-Magnetic Transient (EMT) model.

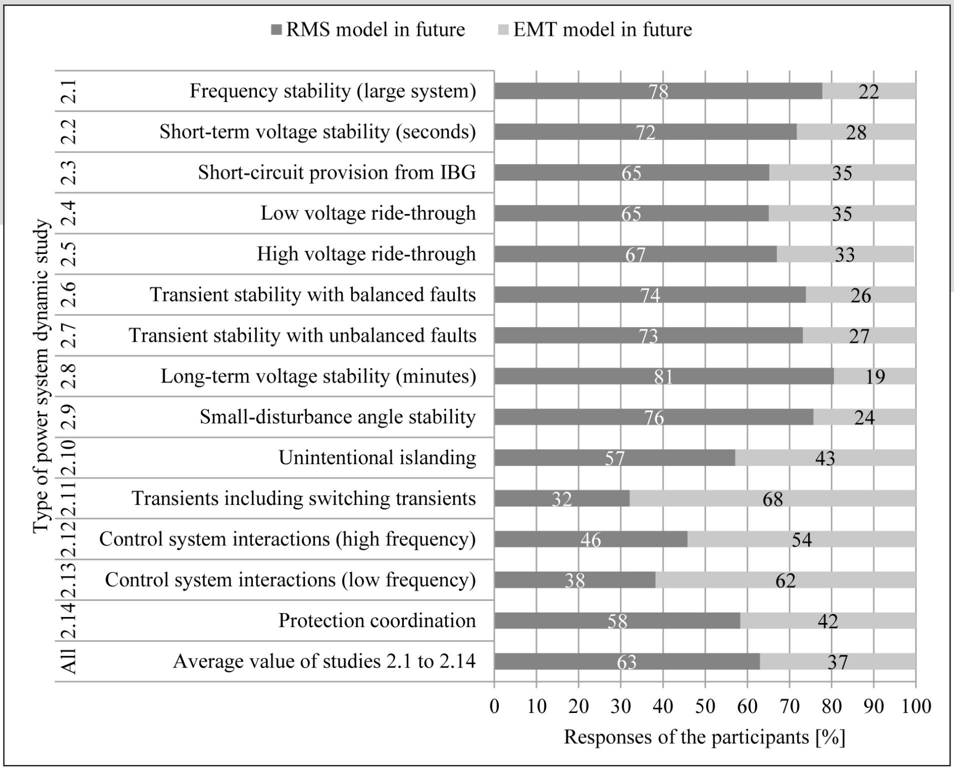

Figure 5: Question 2: What type of model do you use for a specific type of power system dynamic study? Distinction between Root Mean Square (RMS) and Electro-Magnetic Transient (EMT) model in the future.

of Figure 5 with the last row Figure 4, it is important to mention that the share of EMT models used for power system dynamic studies will increase in the future from 22 % to 37 %.

5. Discussion

5.1. Negative load model

From the results it is remarkable that still 35 % of the utilities and system operators use negative load models for the representation of IBG in power system dynamic studies. According to the results of the questionnaire survey, the following reasons may explain this approach:

- **Lack of model requirements of IBG for specific power system phenomena:**

  As the penetration level of such IBG technologies increases, various aspects of power system stability and dynamic performance in the grid may change. Therefore, requirements that address the necessary functionalities that need to be modeled of IBG for specific power system phenomena need to be developed. These functionalities include various aspects, such as control, protection and the capability of IBG. Considering these requirements, utilities and system operators can select specific models for each power system phenomenon.

- **Lack of well-validated IBG models:**

  In recent years there has been much effort on the development of validated models for IBG. This work has been primarily related to wind generation. Now, further attention is starting to be devoted to PV systems and other technologies. In general, there is still a lack of well-validated and generally accepted dynamic simulation models, particularly for distributed PV systems, for the use in power system dynamic studies.

- **Lack of widely accepted generic models for IBG:**

  Usually utilities and system operators do not create their own (user-written) models. They request validated models from manufacturers, either proprietary or adjusted generic models. This request poses two main disadvantages: 1) the manufacturer wants to keep the confidentiality of their proprietary user-written model; and 2) the extra effort for the manufacturer for tuning the parameters of the generic model including the validation of the simulations against the field measurements. Thus, the importance of developing reliable and flexible generic models for different technologies and manufacturers of IBG should be noted. Advantages of generic models are: vendor and manufacturer independent, grid code compatible, public model structure (control block diagram), software simulation tool independent, etc. For some technologies, like wind generation, these models are already being widely used, however, the latest generic models had only recently been developed at the time the questionnaire survey was conducted.

- **Lack of widely accepted range of model parameters for IBG:**

  Although widely accepted generic models are provided, the control model parameters are crucial for power system dynamic studies. Because many grid codes do not define the detailed specification/characteristics of the inverter control, the control model parameters could be different depending on the manufacturer of the inverter. Even if the control model parameters of one inverter can be identified through validation, it is almost infeasible to identify the parameters of all inverters connected to the power system. Therefore, a set of realistic control model parameters need to be provided.

- **Lack of grid code requirements:**

  Due to the lack of grid code requirements in the past, specifying detailed control functionalities of IBG, the approach of using negative load models for power system dynamic studies was justified. However, with the development of new grid codes, certain functionalities of IBG are required (e.g. voltage control, frequency response etc.) and therefore, the negative load model is not adequate anymore.

- **Lack of information about the power system:**

  The aforementioned increased penetration level of IBG also makes system operation, both for TSOs and DSOs, more challenging than in the past. Already, in some areas the consumers' demand is mostly covered by generation which is connected directly to the distribution system. TSOs routinely run time-domain simulations to assess the stability of the power system. Models, which are currently used to represent distribution systems, are only based on a limited amount of information, generally related to the high voltage network.

- **Lack of agreed methodology for the aggregation of IBG:**

  Present trends towards the integration of an increasing range of IBG technologies, widely differing in size and number, poses serious concerns in the industry on how to represent these new technologies in power system dynamic studies. There is not only a lack of validated dynamic computer models of individual distributed generating technologies, such as distributed PV systems, fuel cells, micro turbines etc., but also there is no agreed methodology on how to represent or aggregate the enormous number of distributed generation, embedded in very low voltage grids, for power system dynamic studies, focusing on both, local (distribution level) and widespread (transmission level) studies.

5.2. Necessity of IBG models

The high penetration level of IBG has resulted in the displacement of conventional synchronous generators. Therefore, the impact of IBG on the dynamic performance of the system increases. The dynamic characteristic of IBG is different compared to synchronous generators, and with proper control system design and functionalities of modern IBG technologies, they can provide many of the same or even better services (e.g. voltage control, frequency response etc.). None the less, they do need to be modeled differently and properly. Therefore, the development of the proper computer simulation models for IBG with such additional functionalities is vital for power systems analyses.

Moreover, DSOs have a representation of their networks and have details about connected consumers and producers to some extent. However, the limited data is generally not suitable for dynamic simulations for either the distribution or the transmission system or, at least, has not been used for that purpose in the past, due to the high level of detail. From the point of view of the DSOs, time-domain simulations may also now be necessary to assess, e.g., protection system behavior, distribution network automated operation, unintentional islanding of part of distribution systems including IBG, voltage issues, etc. For these types of power system dynamic studies detailed IBG models are needed.

Therefore, the necessity of IBG models should be clarified for each type of power system dynamic study. A few examples are given as follows:

- **Frequency stability (refer to study 2.1 in Table I):**

  Frequency stability studies often involve looking at the frequency response of the grid to a large disturbance, such as the loss of the largest generating unit (or facility) on the system and assessing if the resulting frequency response of the system is stable and avoids under frequency load shedding. Such studies are typically performed using RMS (positive-sequence) simulation models and tools.

- **Short-circuit provision from IBG (refer to study 2.3 in Table I):**

Short-circuit studies are performed, typically by protection engineers, to identify the setting for protection relays as well as to assess the capability of existing (or new) circuit breakers to be able to withstand and interrupt the short-circuit levels that will be seen on the network during fault conditions. Such studies are typically performed in EMT tools and other software tools specifically designed for short-circuit studies. Thus, appropriate models of IBG are needed in such tools.

- **Low voltage ride-through (refer to study 2.4 in Table I):**

  To properly assess the actual low voltage ride-through capabilities of IBG, analyses have to be performed using detail vendor specific EMT type models and simulations. Furthermore, such simulations may be verified by factory tests of the equipment. It usually then suffices to translate the observed performance to simplified RMS models that will mimic the low voltage ride-through capabilities of the equipment for large-scale power system dynamic studies. Thus, both appropriate RMS and EMT models of IBG are needed.

- **Transient stability (refer to study 2.6 in Table I):**

  For bulk power system transient stability studies validated RMS (or positive-sequence) models are needed for IBG. However, in some cases EMT models may also be needed when investigating, e.g., the connection of a large IBG power plant to a very weak part of the power system.

- **Long-term voltage stability (refer to study 2.8 in Table I):**

  Long-term voltage stability is often analyzed using continuous power flow analysis, such as P-V or Q-V analyses. For such studies, the dynamics of IBG are often neglected, and a quasi steady-state model that respects the real and reactive power limits of the IBG is sufficient. If mid-term time-domain dynamic simulations are performed, then a suitable RMS (positive-sequence) IBG model is needed.

- **Unintentional islanding (refer to study 2.10 in Table I):**

  For this type of study, either an RMS or EMT model for the IBG is needed. Some anti-islanding protection systems utilize the harmonics of the voltage for the islanding detection and therefore, the EMT model for the IBG is the only option to analyze unintentional islanding. On the other hand, if the used anti-islanding protection system does not consider voltage harmonics and if the power systems model includes many IBG models, the RMS model for the IBG may be adequate to analyze unintentional islanding.

- **Protection coordination (refer to study 2.14 in Table I):**

  Many protection systems need to be coordinated. Depending on the type of protection systems to be studied, either an RMS or EMT model for the IBG is needed.

6. Conclusions

The aim of this paper is not necessarily to recommend the application of any dynamic model for a specific power system dynamic study, but, rather, to identify what dynamic models are presently applied and to provide some fundamental information on their use.

The main contributions and key findings of this paper are:

- **Prevalent type of power system dynamic studies:**

  The most dominant type of studies performed by TSOs are stability studies, such as frequency stability, short-term voltage stability and transient stability with balanced faults. This is done by 89 % of those who responded to the survey.

- **Prevalent type of model (IBG/negative load) for power system dynamic studies:**

  35 % of the utilities and system operators still use a negative load model for power system dynamic studies.

- **Prevalent type of model (RMS/EMT) for power system dynamic studies:**

  78 % of the utilities and system operators apply RMS models instead of EMT models for power system dynamic studies. EMT models are more likely to be used for various high-frequency transient studies (e.g. switching transients).

- **Prevalent type of model (RMS/EMT) in the future for power system dynamic studies:**

  63 % of the utilities and system operators expect to continue to apply RMS models instead of EMT models

in the future for power system dynamic studies. It is important to mention that the share of EMT models used for power system dynamic studies will increase in the future from 22 % to 37 %.

Based on the results of the questionnaire, the following reasons for the approach of the negative load model are identified:

- Lack of model requirements of IBG for specific power system phenomena
- Lack of well-validated IBG models
- Lack of widely accepted generic models for IBG
- Lack of widely accepted range of model parameters for IBG
- Lack of grid code requirements
- Lack of information about the power system
- Lack of agreed methodology for the aggregation of distributed IBG

Some reasons have been resolved mainly for models of wind generation. The IEC 61400-27-1 and 61400-27-2 standards under development are presently in the process of providing more refined generic wind turbine and generic wind power plant models and the procedures for validating those models. A standard range of parameters, similar to WECC [12], is also expected to be illustrated in the future IEC documents. The methodology for the aggregation of distributed IBG has been discussed in the WECC and is presently under review [7]. The second generation generic renewable energy system models, developed in the WECC, as well as the generic wind turbine models, developed in the IEC, are now implemented by several commercial software vendors and utilities and system operators start using these models for power system dynamic studies with IBG. None the less, much learning as well as technical challenges still remain, such as the methodology of the aggregation of distributed IBG considering the diversified control parameters, and therefore, further effort is needed.

In light of the observations of the survey, the necessity of the IBG model for the several representative power system dynamic studies is discussed highlighting the need of IBG models. Furthermore, the recommended type of model is also emphasized providing the approach of RMS or EMT model for IBG. It can be concluded that every type of model has advantages and disadvantages and the proper model type needs to be selected depending on the type of power system dynamic study and the system condition.

The results of the questionnaire emphasize the clear message for the necessity and importance of the use of IBG models. Furthermore, the final technical brochure of the CIGRE JWG C4/C6.35/CIRED will give guidance in selecting adequate models for IBG for specific power system dynamic studies.

With these contributions the paper supports utilities and system operators as well as research institutes and academia to benchmark their approach against the prevailing international industry practice.

7. Acknowledgement

The authors appreciate the support of their colleagues from the CIGRE JWG C4/C6.35/CIRED on “Modelling and dynamic performance of inverter based generation in power system transmission and distribution studies”, who contributed in many different, but always useful ways to this paper. In particular the authors acknowledge the contributions of the following members (in alphabetical order): Ab Halim Bin Abu Bakar (MY), Robert Adams (AU), Petros Aristidou (GB), Igor Aronovich (IL), Babak Badrzadeh (AU), Matteo Barbieri (IT), Jens C. Boemer (US), Nicola Cammalleri (IT), Jose Carvalho Martins (PT), Alberto Cerretti (IT), Kevin Chan (CH), Ettore T. De Bernardinis (IT), Herivelto de Souza Bronzeado (BR), Vincent Debusschere (FR), Luming Ge (CN), Irina Green (US), Andrew Halley (AU), Garth Irwin (CA), Stanko Jankovic (DE), Karim Karoui (BE), Lidija Korunovic (RS), Jin Ma (AU), Paolo Mattavelli (IT), Thomas McDermott (US), Jovica V. Milanović (GB), Marta Molinas (NO), David Mvura (ZA), Ziming Song (GB), Roberto Turri (IT), Stanislav Utts (RU), Thierry Van Cutsem (BE), Klaus Vennemann (DE), Eknath Vittal (US), Xinhui Wu (US), Changjiang Zhan (GB) and Lingzhi Zhu (CN).

Equally important, the authors would like to acknowledge the support of the colleagues from utilities and system operators around the world, who took the time to fill in the questionnaire and kindly shared their knowledge and experience.

The work of some of the authors was supported by the German Federal Ministry for Economic Affairs and Energy and the Projektträger Jülich GmbH (PTJ) within the framework of the project Netz:Kraft (FKZ: 0325776J) and DEA-Stabil (FKZ: 0325585A).

8. References

[1] *J. V. Milanović, K. Yamashita, S. Martínez Villanueva, S. Ž. Djokic and L. M. Korunović, "International Industry Practice on Power System Load Modeling," IEEE Transactions on Power Systems, pp. 3038-3046, August 2013.*

[2] *NERC Standard TPL-001-4, "Transmission System Planning Performance Requirements," January 2016, [Online]. Available: http://www.nerc.com/_layouts/PrintStandard.aspx?standardnumber=TPL-001-4&title=Transmission%20System%20Planning%20Performance%20Requirements&jurisdiction=United%20States.*

[3] *Western Electricity Coordinating Council (WECC) Renewable Energy Modeling Task Force, [Online]. Available: https://www.wecc.biz/PCC/Pages/MVWG.aspx.*

[4] *International Electrotechnical Commission (IEC) TC88 WG27, "Wind turbines - Electrical simulation models for wind power generation," [Online]. Available: http://www.iec.ch/dyn/www/f?p=103:14:0::::FSP_ORG_ID,FSP_LANG_ID:5613,25.*

[5] *R. Elliott, A. Ellis, P. Pourbeik, J. J. Sanchez-Gasca, J. Senthil and J. Weber, "Generic Photovoltaic System Models for WECC – A Status Report," in 2015 IEEE Power & Energy Society General Meeting, Denver, July 2015. pp. 1-5.*

[6] *G. Lammert, L. D. Pabón Ospina, P. Pourbeik, D. Fetzer and M. Braun, "Implementation and Validation of WECC Generic Photovoltaic System Models in DIgSILENT PowerFactory," in 2016 IEEE Power & Energy Society General Meeting, Boston, July 2016. pp. 1-5.*

[7] *P. Pourbeik, „Proposal for the DER_A model," Presentation at WECC meeting, November 2016.*

[8] *G. Lammert, K. Yamashita, L. D. Pabón Ospina, H. Renner, S. Martínez Villanueva, P. Pourbeik, F.-E. Ciausiu and M. Braun, "Modelling and Dynamic Performance of Inverter Based Generation in Power System Studies: An International Questionnaire Survey," in CIRED conference, Glasgow, 2017. (to be published)*

[9] *P. Kundur, Power System Stability and Control, Mc-Graw Hill, 1994.*

[10] *O. Ruhle and F. Balasin, "Simulations of Power System Dynamic Phenomena," in 2009 IEEE PowerTech, Bucharest, June-July 2009. pp. 1-6.*

[11] *H. W. Dommel, "Digital Computer Solution of Electromagnetic Transients in Single- and Multiphase Networks," IEEE Transactions on Power Apparatus and Systems, pp. 388-399, April 1969.*

[12] *Western Electricity Coordinating Council (WECC) Renewable Energy Modeling Task Force, "WECC solar PV dynamic model specification," September 2012, [Online]. Available: https://www.wecc.biz/Reliability/WECC%20Solar%20PV%20Dynamic%20Model%20Specification%20-%20September%202012.pdf.*

9. Biographies

Gustav Lammert received a B.Eng. degree in Electrical Engineering from the Baden-Wuerttemberg Cooperative State University, Mannheim, Germany, in 2010 and a M.Sc. degree in Renewable Energies and Energy Efficiency from the University of Kassel, Kassel, Germany, in 2013. He is now a Ph.D. student at the Department of Energy Management and Power System Operation, University of Kassel, Kassel, Germany. His fields of interest are power system dynamics and stability.

Koji Yamashita received the B.Sc. and M.Sc. degrees from Waseda University, Tokyo, Japan, in 1993 and 1995, respectively. Since 1995, he has been with the Department of Power Systems at the Central Research Institute of Electric Power Industry, Tokyo, Japan. He was a visiting researcher at Iowa State University, Ames, during 2006–2007.

Luis D. Pabón Ospina received his B.Sc. and M.Sc. degrees in Electrical Engineering from Universidad Pontificia Bolivariana, Medellín, Colombia. He received his M.Eng. degree from the University of Kempten, Kempten, Germany. He is currently working toward the Ph.D. degree at the group of Power System Control and Dynamics, Fraunhofer IWES, Kassel, Germany.

Herwig Renner holds a position as associate professor at Graz University of Technology. His main research work is in the area of power system dynamics and power quality. He is chairman of CIRED session 2 and active member in several CIGRE working groups.

Sergio Martínez Villanueva received the MS in Industrial Engineering from the Universidad Politécnica de Madrid, Madrid, Spain, in 2002. He joined Red Eléctrica de España (Spanish TSO) in 2005. Presently, he works in the Power System Reliability Department.

Pouyan Pourbeik (M'1993, SM'2002, F'2010) received his BE and PhD in Electrical Engineering from the University of Adelaide, Australia in 1993 and 1997, respectively. From 1997 to 2000 he was with GE Power Systems. From 2000 to 2006 he was with ABB Inc. From 2006 to March, 2016 he was with EPRI. From April, 2016 he is with Power and Energy, Analysis, Consulting and Education, PLLC.

Florin Ciausiu is a Power System Consulting Department Manager in Tractebel (Romania) and is having over 12 years' experience in power system studies. He holds a Ph.D. degree in Power Systems Electrical Engineering from the University Politehnica, Bucharest, Romania. His area of expertise includes coordination of power systems projects, such as transmission/distribution systems planning and operation, grid connection studies, interconnection studies, protection coordination studies or blackout studies.

Martin Braun received Diploma degrees in Electrical Engineering as well as in Technically Oriented Business Administration from the University of Stuttgart, Stuttgart, Germany in 2005 and a Ph.D. in Engineering from the University of Kassel, Kassel, Germany, in 2008. He is now Professor of the Department of Energy Management and Power System Operation at the University of Kassel, Kassel, Germany and head of the Department of Distribution System Operation at the Fraunhofer IWES, Kassel, Germany.