Activities of the Joint Working Group CIGRE C4/C6.35/CIRED: Modelling and Dynamic Performance of Inverter Based Generation in Power System Transmission and Distribution Studies

On behalf of CIGRE C4/C6.35/CIRED

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***Abstract*—This paper presents the recent activities of the Joint Working Group CIGRE C4/C6.35/CIRED. Specifically, the characteristics of Inverter Based Generation (IBG) is compared in detail with the characteristics of synchronous generators used in conventional power plants. In this context, the main differences are identified as: 1) the inertia; 2) the fault current provision; 3) the synchronization capability; and 4) the fixed internal voltage source. Those characteristics are provided by synchronous generators, but they are not easily provided by IBG. In order to overcome these differences grid code requirements for IBG need to be updated and thus, IBG units also have to provide ancillary services. Moreover, the paper presents the characteristics of IBG from the protection point of view. The internal and external protection of IBG is described in detail and examples are given.**

***Index Terms*—Ancillary services, grid code requirements, PhotoVoltaic (PV) generation, power system stability, protection, dynamic models, Electro-Magnetic Transient (EMT) models, Root Mean Square (RMS) models.**

I. Overview of the Joint Working Group (JWG)

A. Background of the JWG

Over the past decades, Inverter Based Generation (IBG), such as Wind Turbine Generators (WTGs) and PhotoVoltaic (PV) systems, have spread around the world to cope with governments' commitment for increasing the share of renewable energies to deal with the global warming and other environmental problems. In the past, power system dynamics and security were determined by the characteristics of (large) synchronous generators connected to the transmission system level. However, nowadays the impact of IBG and their specific characteristics can no longer be neglected.

With low penetration of IBG, its impact on power system security and adequacy is negligible. Yet today some Transmission System Operators (TSOs) are facing operational situations with a penetration level of IBG reaching over 50 % of the total generation [1]. This increasing penetration of IBG has started to affect power system adequacy and security. This is due to the displacement of conventional large synchronous generators and their stabilizing controls. Most of the existing IBG technologies in the grid do not always have the same features as synchronous generators. This led to the improvement of grid codes around the world requiring now that new installations of IBG contribute to the grid operation with ancillary services such as voltage and frequency control [2].

To assess power system security, power system dynamic studies have played an important role for many years. Such studies have been performed by the power system planners and operators by means of numerical models. To this aim, tailored dynamic models of the elements in the system have been developed taking into account the physical phenomena to be investigated. Thus, synchronous generators and the associated controls models for different applications are available over many years. Yet there are no generally accepted generic models for IBG that can be used in power system dynamic studies around the world. In fact, 35 % of the utilities and system operators still use negative load models to represent IBG in power system dynamic studies [1]. According to the results of the questionnaire survey performed by this Joint Working Group (JWG) [1], [3], the reasons for this approach are the lack of:

- Model requirements of IBG for specific power system phenomena
- Well-validated detailed IBG models
- Widely accepted generic IBG models
- Widely accepted range of IBG model parameters
- Specific grid code requirements
- Information about the power system
- Agreed methodology for the aggregation of distributed IBG units
- Knowledge and experience of IBG operation in power systems

Many efforts have been made in the past by modelling experts to establish generic Root Mean Square (RMS) type models through organizations like the International Electrotechnical Commission (IEC), or the Western Electricity Coordinating Council (WECC). Some of those generic models have been already implemented in widely used commercial power system analysis software tools [4], [5]. However, the activities of the former focus on the development of generic models for wind generation only. But these generic models are not widely used by industry yet, especially in Europe, as they are still relatively new. Equally with regard to IBG connected to the medium and low voltage distribution levels, e.g., residential PV systems, there are still no widely accepted aggregated dynamic models [1].

B. Objective of the JWG

The goal of the JWG is to review and report on the latest developments in IBG models for power system dynamic studies, both of individual as well as aggregated units, with a special focus on PV systems. The Technical Brochure (TB) provides some guidelines for the selection of the appropriate IBG model and its required functions, according to the type of power system dynamic study and the system characteristics.

C. Missing capabilities of IBG and grid code requirements

The final TB of this JWG identifies and categorizes the difference in characteristics between small-scale IBG connected to MV/LV grid with a set of minimum requirements in grid code, and conventional large synchronous generators connected to HV grid with the standard generation controllers. These differences between IBG and synchronous generators are the major focus of this paper and therefore, explained in detail in the following sections.

In this context, the final TB will provide a complete as possible list of IBG functions together with the corresponding model components required to provide these functions.

D. Selection of type of IBG model

Moreover, the TB investigates two types of models: Electro-Magnetic Transient (EMT) and RMS type models. The benefits and limitations of each type of model are presented, along with the functionalities that need to be implemented by each model depending on the type of power system dynamic study performed.

EMT models are identified to be more accurate and provide higher detail in power system dynamic studies. Furthermore, they are more complex, requiring advanced modelling details and knowledge of the components, and are unsuitable for large-scale studies (with hundreds or thousands of units of IBG) due to the computational cost.

On the contrary, RMS models are computationally more efficient, allowing to perform large-scale studies, and are easier to create abstract generic models. Nevertheless, RMS models have been identified in this TB as inadequate to model accurately IBG in situations of:

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

It is up to the power system engineer to know the scope of application and to be aware of possible model limitations.

E. Selection of IBG functionalities

The final TB has catalogued the components and functions that need to be included in the IBG model, depending on the power system phenomena to be studied, as already partly introduced in [6]. 25 functions are classified into three categories:

1) Internal inverter control
2) Inverter protection
3) Grid supporting capability

The classification is not unambiguous; yet, it gives a first impression about the relevance of the functionalities with regard to different power system stability studies. The necessity of each functionality is examined for the following five power system phenomena:

a) Frequency deviation
b) Large voltage deviation
c) Small but longer voltage deviation
d) Small disturbance (analysis)
e) Unintentional islanding

For example, the maximum power point tracking, also known as MPPT, is necessary to be modelled for c), while it is generally unnecessary for a), b), d) and e).

Some representative power system dynamic simulation studies are also illustrated in the final TB to bridge the power system phenomena with the types of the power system dynamic studies. For example, frequency deviation is relevant to transient stability as well as frequency regulation studies. Large voltage deviation is relevant to short-term voltage stability, transient stability, fault current and Low Voltage Ride-Through (LVRT) as well as High Voltage Ride-Through (HVRT) studies, etc.

F. Control block diagram for each functionality

In the final TB, the model components representing the control block diagrams are further classified into:

1) Local/component level control
2) Plant level control

This classification is based on the the required capabilities as they are different between small-scale IBG, e.g., residential PV systems, and large-scale IBG, e.g., PV plants.

Furthermore, there is a difference between RMS type and EMT type models. The high-level control block diagrams of the model components are usually the same both for RMS and EMT, but the low-level controls and electrical interface circuits are usually different and the levels of detail for RMS model is very much limited.

G. Aggregation of IBG

Aggregation methodologies for IBG, and specifically PV systems, are presently underdeveloped. The TB reviews one of the most advanced and recent aggregation methodologies, proposed by WECC in [7]. This methodology is categorized into:

1) Steady-state representation for power flow and simplified short-circuit studies
2) Dynamic simulation representation for dynamic power system studies which includes disconnection of IBG units in LV network

The TB of this JWG asserts that the different IBG requirements are most likely to be regulated separately in MV and LV networks and thus, the power flow representation for the aggregation of IBG should be performed depending on the voltage level. The TB also sorts out the future technical challenges emphasizing the importance of the balance of the model accuracy levels between IBG models and load models.

H. Model validation of IBG

Another topic that is covered by the TB is the present validation methodologies of IBG used by the industry. Although the relevant work is still ongoing within IEC activities, the TB focuses more on the available measures for model validation, such as the test facilities for representing the LVRT and the power swing oscillation, and on the example model validation following system faults in the real transmission network. The general model validation iterative procedure is also provided in the TB.

II. Characteristics of IBG

A. IBG technologies and modelling challenges

Renewable Energy Sources (RES) mainly consists of IBG. A power inverter, or inverter, is an electric energy converter that converts Direct Current (DC) to single-phase or polyphase Alternating Current (AC). This technology represents 100% of the total for the PV systems and an appreciable and increasing percentage of WTGs. Furthermore, inverter technology has also extended its influence area in hydro plants. The inverter provides the interface between the grid and a so called prime mover (energy source), which is the primary energy source to be transformed into electricity. Although the inverter technologies may be similar to all devices, an appreciable difference may exist related to the prime mover features, thus influencing at least the inverter control. The response and achievable performance of the combined system depends both on the capability of the inverter and the capability of the prime mover.

For example, PV systems have no inertia, mechanical or thermal process. Therefore, nearly real time regulation is possible, limited only by inverter capabilities and inverter control reaction time (for the whole chain, including measurement time of relevant quantities, such as voltage, frequency, etc., the theoretical reaction time may be some milliseconds or shorter). There is no inherent energy storage (due to missing inertia) and thus, no possibility to support the system in case of underfrequency (unless additional storage devices are foreseen or unless the generation is curtailed by several percent of the available active power).

In terms of simulation models for IBG the following challenges and requirements can be highlighted:

- Recently a lot of new capabilities for IBG have been required in grid codes, some of them are still at the definition stage, according both to DSOs needs and TSOs needs. Those capabilities have to be represented in each model.
- Specific capabilities are already available on the market, e.g., simulation of inertia, even if obtained by additional devices, e.g., energy storage systems. However, they are not described in detail in any standard in terms of algorithms, performance, implementation, compliance assessment, etc., making it difficult to develop appropriate and generic models.
- Standardized methods for voltage and frequency measurements, reaction times of control loops etc. are also not defined in standards and, if present, operation is according to the manufacturers approach and design choices.
- From a “model definition” perspective, it is very important to be aware of all the “natural” features of IBG, and the “additional” ones.
- The scope of application (area of validity) of any given model has to be defined.

Many capabilities of IBG such as Fault Ride-Through (FRT) capability have been required as the RES spreads. It can be considered that the starting point of the advanced requirements is the difference of characteristics between synchronous generators and IBG. In other words, there are some capabilities which the synchronous generators have but the IBG do (did) not have. This paper clarifies the major differences of characteristics between synchronous generators and the initial IBG technology and gives sufficient explanation where the capabilities of the IBG come from.

B. Comparison of IBG with synchronous generators

IBG, before adding additional functionalities according to the grid code requirements, will differ in its behaviour from large synchronous generators. It is noted that the term “IBG” used hereafter in this section only denotes IBG with minimum functionalities and with no advanced capability. It is also noted that the term, “synchronous generator” which is used denotes large synchronous generators in conventional power plants connected to the high voltage network and which are assumed to be replaced with IBG. The main difference of characteristics between IBG and synchronous generators are summarized in Table I.

The most important differences between IBG and synchronous generators are further described in the following points:

1) Rotating mass/inertia:
Inverters do not have a rotating mass component, i.e., there is no inherent inertia. The prime mover behind the inverter might have the inertia, but its "usage" has to be achieved via the inverter controls and the inverter size because all IBG technologies are limited in terms of maximum current through the power electronics device, as well as maximum voltage. To use the real available inertia, if any, of the "prime mover", a significant oversize of the inverter may be necessary. Moreover, synthetic inertia cannot be considered completely equivalent to the inertia provided by conventional synchronous generators which are directly connected to the grid as measuring devices and control introduce delays in how the synthetic inertia reacts to events in the grid. The typical scheme for representing the synthetic inertia captures the Rate Of Change Of Frequency (ROCOF) and increases or decreases the IBG output so that the frequency change is mitigated. This concept enables the reduction of the mismatch between the mechanical output and the electrical output when ROCOF is not zero. However, the synthetic inertia concept of modifying the control dependent on the measured ROCOF cannot be considered completely equivalent to the inertia provided by conventional synchronous generators. But it should be noted that other concepts are under discussion at present. In general, inverters act as a current source and new concepts are suggesting that modifying the control in such a way that the inverters can also act as a voltage source and thus provide an instantaneous response (see also 4)).
2) Fault current contribution:
Inverters lack inductive characteristics that are associated with rotating machines. The classical fault circuit current contribution expected from synchronous machines does not apply (as caused by law of constant flux in rotating machines). Instead, a fault circuit contribution is possible by means of inverter control. However, this contribution is typically limited to slightly above 1 p.u. current (limited overload capability of semiconductor valves), even if all the active power supplied to the network is reduced to zero and all the current which is able to flow through the valves without damaging them is turned into reactive power, which would not be sufficient enough for the correct operation of the present protections. Of course, a certain oversized IBG unit would help to also reduce this gap on traditional synchronous generators. If the voltage at the Point of Common Coupling (PCC) during a fault is very low, the phase angle of the current injected by the IBG may be ill defined, which means, the expected fault current is unlikely to be provided no matter how oversized the IBG unit is.
3) Synchronization torque capability:
The synchronous generators have the synchronizing torque capability which is a very important factor for rotor angle stability. The synchronizing torque index is proportional to the internal induced voltage of the synchronous generator and the equivalent synchronous generators and/or the angle difference between the synchronous generators and the equivalent synchronous generator. Such generators can automatically change their active power output so as to mitigate the angle deviation/oscillation. For IBG it might be required to have the synchronizing torque capability in the future. However, it is not easy to achieve it because the angle difference between the IBG and the synchronous generator needs to be measured or observed all times including in the case of the disconnection of a synchronous generator which consists of the equivalent synchronous generator.
4) Constant voltage source:
The voltage induced in the windings of a synchronous generator is larger than the grid voltage. Moreover, this internal induced voltage is independently regulated from the grid voltage. It will cause increasing reactive current injection shortening the electrical distance between the fault point and the internal induced voltage source when the grid voltage sags and hence typically contributes positively to network stability. IBG usually does not have such an inherent internal voltage source. The current that can be provided to the grid during a voltage sag is dominated by the IBG control behaviour and typically limited to 1 p.u.

In the case of high penetration of IBG, which means conventional synchronous generators are replaced with IBG, functionalities which the conventional generators have and which IBG does not have, will be lost and the system stability could be affected. In order to cope with this, such functionalities have been required by IBG through updating grid codes. It should be noted that the aforementioned advanced functionalities and capabilities could require an upgrade of the IBG unit.

C. Ancillary services of IBG

Because of the flexibility of the inverter control, IBG units may be required either, from the technical standards and/or from grid codes, to provide some additional capabilities for grid support, among them:

- Zero-sequence current injection
- Reactive current control calculated by mean of power factor input
- Maximum reactive current injection
- Reactive current level depending on voltage depth

Table II shows the most relevant requirements of capabilities for IBG from EU Regulation 2016/631 [8] establishing

TABLE I
MAJOR EXISTING AND/OR POTENTIAL DIFFERENCES BETWEEN IBG AND SYNCHRONOUS GENERATORS

Characteristic	Relevant phenomena	Synchronous generator	IBG with minimum functionality	IBG with advanced capability/feasibility
Rotating mass/inertia◇	Frequency stability	Yes	No	Yes, depends on prime mover, operating point, storage, direction of frequency deviation
Frequency response capability	Frequency stability	Yes	No	Yes, depends on prime mover, operating point, storage, direction of frequency deviation
Limited frequency sensitive mode	Frequency stability (overfrequency)	Yes	No	Yes, depending on prime mover
Constant voltage source◇	Voltage stability	Yes	No, if connected to the grid	Yes, but isolated system is required
Grid voltage support (steady state)	Voltage stability	Yes	No	Yes, (large-scale IBG units) with reactive power compensators (shunt capacitor, SVC, etc.)
Reactive power support (V-Q steady state)	Voltage stability/support	Yes, according to PQ-capability	No	Yes, according to PQ-capability
Reactive power support (reactive current control during incidents)	Rotor angle stability	Yes	No	Yes, usually during faults IBG units may be able to provide a reactive current injection with some delay
Synchronization torque capability◇	Rotor angle stability	Yes	No	Yes, but almost infeasible
Damping torque capability (power oscillation damping capability)	Rotor angle stability	Yes, damper windings and PSS	No	Yes, power oscillation damping functionality
Loss of synchronism	Rotor angle stability/protection	Yes	No	Not applicable
Fault ride-through capability	Rotor angle transient stability	Yes	No	Yes, depending on prime mover
Harmonic emission	Power quality	No	Yes, supra-harmonics	–
Harmonic voltage reduction	Power quality	Yes, for low order harmonics	No	Yes, if active filter algorithms are implemented
Fault current contribution◇	Protection, limit voltage decline	Yes	No	Yes, but contribution is limited to around 1 p.u.
Control response capability	Voltage and frequency stability	Fast, depending on the time constants involved	Inverter itself fast, possible limitations due to measurement delay	Not applicable
Overload capability (up to few seconds)	Misc.	Yes	Limited depending on semiconductor devices	Yes, but IBG needs to be oversized significantly
Maintenance	Misc.	Regularly	Inverter itself low, prime mover depends	Not applicable

◇Explained in detail in Section II-B.

Network Code Requirements for Generators (NC-RfG) and from the IEEE 1547 Standard [9]. Because it is more likely that IEEE 1547 and UL 1741 [10] will dramatically evolve, the possible future requirements for IEEE 1547 [11] are also introduced in this table.

D. Protection of IBG for power system dynamic studies

An inverter's protection may be distinguished into two main classes, internal and external. This classification has nothing to do with the physical location of the protections.

- Internal protection:

Internal protections are primarily to assure the safety of the inverter itself, may be not in accordance with relevant standards of protection relays and are applied by the manufacturers. Internal protections are generally suggested to be inserted in inverter models, in such a way they do not affect IBG capabilities and requirements. Each IBG type has its own type of internal protections focused on avoiding damage to the inverter itself. These internal protections are also known as generator protections (i.e. nothing to do with interface protection). Some examples of inverter internal protections are:

TABLE II
ANCILLARY SERVICES OF IBG DEFINED IN GRID CODES AND STANDARDS

Requirement	EU 2016/631 [8]	IEEE 1547 [9]	IEEE 1547 (future) [11]
Frequency control (over/under) by means of active power (P(f))	×		×
Voltage control by means of reactive power (Q(V))	×	(×)	×
Voltage control by means of active power (P(V))			×
Synthetic inertia	(×)		
Rate Of Change Of Frequency (ROCOF) immunity	×	(×)	×
Fault Ride-Through (FRT) low and/or high voltage	× (LVRT only)	(×)	×
Anti-islanding detection methods	× (ROCOF)	×	×
Dynamic voltage support during faults and voltage dips	(×)		(×)
Power oscillation damping	(×)		
Black start capability	(×)		
Capability of islanding operation	×		
Automatic disconnection with abnormal voltage	×		×
Automatic connection with active power recovery speed	×	×	×
Constant power at low voltage	×		
Constant power at low frequency	×		

× denotes one or more classes/categories of the IBG are required.
() denotes a non-mandatory requirement.

- Reduction of maximum inverter current when the DC voltage exceeds a certain limit
- Limitation of inverter current's variation rate after a fault
- Limitation of total reactive current
- Manual PV field shutdown with emergency stop
- PV field insulation detection
- DC Overcurrent protection
- Over/under voltage protection
- Over/under frequency protection

It should be noted that "Limitation of inverter current's variation rate after a fault" and "Limitation of total reactive current" are generally categorized into control instead of protection. Because their control functions can operate for protection purposes as well as for control purposes, they are treated as the internal protection in this paper and the final TB of the JWG.

- External protection:
  External protection is required to serve a different purpose and considers the network. Physically, in some cases, the external protection may be the same as the internal inverter protection, but, despite this, they are not "monitoring" the inverter (internal), but the network (external). External protections, despite that they are physically inside the inverter control, may be modelled separately, in such way to allow changes in the models or different combination of different regulations without any change in inverter model. IBG units may have external protections to:
  - Detect uncontrolled local islanding situations and disconnect generators to shut down this island. This functionally is also known as "loss of main protection"
  - Reduce the power production from the generating plant to prevent an over-voltage situation in the network it is connected to
  - Assist the power system to reach a controlled state in case of voltage or frequency deviations beyond corresponding regulation values

  These protections (or combination of different elementary protection functions) are usually referred to as Interface Protection or Interface Protection System (IPS). The IPS is generally based on combinations of over/under voltage and over/under frequency protections. It is not the purpose of the interface protection system to:
  - Disconnect the generating plant from the network in case of faults internal to the power generating plant. Protection against internal plant faults or abnormal operation conditions, e.g., short-circuits, grounding faults, overloads, etc., is provided by other external protection relays coordinated with network protection, according to the system operator protection criteria.
  - Prevent damage to the generating unit due to incidents, e.g., short circuits, asynchronous reclosing operations, on the network. To avoid possible damage, the generating unit must have an appropriate immunity level.

  A good overview on external protection can be found in CIGRE TB 613 "Protection of Distribution Systems with Distributed Energy Resources" [12] and CIGRE TB 421 "The impact of renewable energy sources and distributed generation on substation protection automation" [13].

III. CONCLUSIONS

This paper provides an overview of the recent activities of the JWG CIGRE C4/C6.35/CIRED: "Modelling and Dynamic Performance of Inverter Based Generation in Power System Transmission and Distribution Studies". The content of this paper mainly focuses on one chapter of the TB, namely characteristics of IBG.

The characteristics of IBG is addressed and the differences between small-scale IBG units and synchronous generators are highlighted. The major differences are: 1) the inertia; 2) the fault current provision; 3) the synchronization capability; and 4) the fixed internal voltage source. Those four characteristics are provided by synchronous generators. However, they are not easily provided by IBG units. But many of the characteristics such as the frequency control capability the reactive power control capability can be provided by IBG. Because of the increasing functionalities of IBG, the IBG models need to be further extended.

Furthermore, this paper addresses the difference of the characteristics of IBG from a protection point of view. Compared to synchronous generators, IBG is more likely to be disconnected due to the high sensitivity of inverter protections. Because the operation of the inverter protection could result in the disconnection of the IBG, the inverter protection models play an important role for most of the power system dynamic studies. However, the primary source and its controls may often be neglected for dynamic stability analyses.

IV. Outlook

Moreover, the final TB of the JWG introduces the type of models which is used for specific power system dynamic studies, namely RMS model or EMT model. The selection of the model type (EMT or RMS) is very much dependent on the specific phenomena to be investigated. In this context, the selection of the model type with the necessary model element for each type of phenomenon is further discussed in the final TB.

Furthermore, the TB reviews the present industry practices and provides constructive recommendations for the development and use of IBG models in power system dynamic studies. It has been identified that the functions which need to be implemented by IBG models are different depending on the power system components, power system conditions, and type of dynamic study.

The TB does not recommend the application of any specific dynamic model for a specific power system dynamic study, but rather, identifies dynamic models which are applied and provides some fundamental information and guidance on their use. Based on the key findings and observations, this TB emphasizes the necessity and importance of the proper use of the various IBG models. The goal is to encourage utilities, system operators, research institutes and academia pay more attention to the selection of the necessary functionalities and of the type of IBG model when performing power system dynamic studies with embedded IBG.

The final TB of this JWG is expected to be published by the end of the year 2017 and can be accessed via e-CIGRE: https://e-cigre.org/.

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