PROCEDURE FOR VERIFICATION VALIDATION AND CERTIFICATION OF THE REQUIREMENTS OF THE PO 12.3 ON THE RESPONSE OF WIND FARMS IN THE EVENT OF VOLTAGE DIPS

VERSION 3

November 2007
INDEX

1. PURPOSE
2. FIELD OF APPLICATION
3. DEFINITIONS AND ABBREVIATIONS
4. VERIFICATION PROCESS
   4.1. GENERAL VERIFICATION PROCESS
   4.2. PARTICULAR VERIFICATION PROCESS
   4.3. WTG TYPE
   4.4. WIND FARM TYPE
5. VERIFICATION AND CERTIFICATION BODIES
   5.1. THE TECHNICAL VERIFICATION COMMITTEE
   5.2. THE ACCREDITED CERTIFIER: FUNCTIONS
6. TEST PROCEDURE
   6.1. TEST EQUIPMENT
   6.2. TESTING OF WTGS
      6.2.1. Test conditions for model validation
      6.2.2. Test conditions for direct observance of P.O.12.3. Particular process.
   6.3. FACTS TEST
7. MODELS VALIDATION PROCESS
   7.1. WTG MODEL
   7.2. FACTS MODEL
   7.3. VALIDATION CRITERIA
8. PROCESS FOR SIMULATING WIND FARMS
   8.1. TOPOLOGY OF ELECTRICAL SYSTEM
      8.1.1. Wind farm and FACTS devices
      8.1.2. Medium/high voltage transformer
      8.1.3. Evacuation line
   8.2. EQUIVALENT ELECTRICAL GRID
      8.2.1. Data of the nodes and passive elements of the grid equivalent
      8.2.2. Data of the synchronous generator and its excitation system
      8.2.3. Load power
      8.2.4. Fault reactance
   8.3. EVALUATION OF RESPONSE TO VOLTAGE DIPS
9. MEASUREMENT TECHNIQUES
   9.1. CLASSIFICATION OF ZONES DURING THE DIP
   9.2. METHODOLOGY FOR CALCULATING POWER
10. REFERENCES
11. APPENDIX: STANDARD REPORT FORM
1. PURPOSE

The purpose of this document is to provide a procedure for measuring and assessing the response of wind farms in the event of voltage dips. This procedure must ensure the uniformity of tests and simulations, the precision of measurements and the assessment of the response of wind farms in the event of voltage dips. The requirements for the response to dips are specified in the electrical system Operational Procedure 12.3.

2. FIELD OF APPLICATION

Voltage dips are sudden falls in voltage, mainly caused by faults in the grid. Voltage dips are random events and may be described in terms of the level of the voltage during the dip and its duration. A fault may also cause a phase jump in the voltage wave. Different types of dips may therefore be specified to assess the response of a wind farm.

This document contains:

- The testing and measurement procedures for the individual response of a WTG or FACTS device in the event of voltage dips.
- The validation procedures for computer models of WTGs or FACTS devices based on the measurements recorded in the field tests.
- The procedures to check compliance of wind farms with the response requirements in Operational Procedure 12.3.

In order to issue certified reports in each of the procedures described above, the laboratory must be accredited according to the ISO/IEC 17025 standard, or certification bodies accredited according to EN45011 standard.

These verified reports will be the technical basis that allows the Ministry of Industry and Commerce or any delegated authority to check compliance according to the fourth additional disposition of Royal Decree 436/2004, relating to the continuity of supply during voltage dips.

The creation of a Technical Verification Committee is proposed, in order to verify and follow the compliance with this procedure. The specific works of this committee are specified in section 5.1 of this document.
3. DEFINITIONS AND ABBREVIATIONS

The following definitions are used in this document:

**WTG:** a system for converting the kinetic energy of wind into electrical energy.

Note: the WTG includes the wind turbine, the mechanical transmission system, the electrical generator, the control system and all its power systems (which may include electronic converters, reactive compensation systems, transformer, etc).

**WTG terminals:** the point of the WTG identified by the supplier as the point for connecting the WTG to the power collecting system (IEC 61400-21).

**Accredited certifier:** public or private entity, that exists for the purpose of establishing conformity - which is voluntarily solicited by a specific company, product, process, service or person - with the requirements defined in norms or technical specifications in accordance with the Royal Decree 2200/1995

**Accredited certifier:** public or private company, with legal entity, accredited by ENAC, or any other accreditation body with a mutual recognition agreement, according to the standard EN 45011, for the certification of compliance of the wind farms with requirements of response stated in Operational Procedure 12.3.

**Technical Verification Committee:** grouping of representatives of the different agents that participate in the execution and operation of wind farms, whose mission is to supervise and follow compliance with the present procedure.

**fundamental component:** component with the fundamental frequency (IEC 61000-4-30).

**wind farm configuration:** the electrical characteristics of the wind farm that define its behaviour within the grid. This includes the WTGs, the power lines (overhead and underground), the transformers and any other element, which may influence the electrical performance of the wind farm.

**continuity of supply of a WTG during a voltage dip:** the capability of a WTG to remain connected to the electrical system during a voltage dip, complying with Operational Procedure 12.3.

**nominal current of a WTG (I_n, A):** the WTG’s line current when the WTG is operating at the nominal power with nominal voltage and frequency.
**reactive current of a WTG:** net reactive current \((I_r, A)\) obtained each period as:

\[
I_r = I^+ \cdot \text{sen}(\phi)
\]

where:

\(I^+\): is the magnitude of the fundamental component of the positive sequence of the current in (A)

\(\phi\): angle between the fundamental component of the positive sequence of the voltage and the current (rad).

**total current:** net current \(I_{tot}\) (A) obtained each period as:

\[
I_{tot} = I^+
\]

where:

\(I^+\) is the magnitude of the fundamental component of the positive sequence of the current in (A)

**FACTS (Flexible AC Transmission System) device:** system based on power electronics and other static devices whose purpose is to improve the control of electrical transmission systems in AC and improve its power transmission capability. This device may be used to compensate for the effects of voltage dips in electrical installations. In this document this term is used to designate installed electrical equipment in a WTG, wind farm or the grid connection point.

Note: There are various systems for this on the market, such as, for example, dynamic voltage restorers (DVRs), static synchronous compensators (STATCOMs), static VAr compensators (SVCs), etc.

**dip duration:** in a three phase system, a dip starts when the voltage \(U_{ef(1/4)}\) of one of the phases drops below the dip threshold and ends when the voltage \(U_{ef(1/4)}\) in all of the channels measured, is equal to or higher than the dip threshold (IEC 61000-4-30).

**net active energy:** active energy obtained from the numerical integration of the active power in a given period of time.

**net reactive energy:** reactive energy obtained from the numerical integration of the active power in a given period of time.

**voltage dip:** a temporary voltage reduction at a point in the electrical power grid below the dip threshold (IEC 61000-4-30).
Note 1: Typically, a dip is associated with the start and end of a short-circuit in the grid.
Note 2: A voltage dip is an electromagnetic disturbance characterized by two parameters, the voltage and the duration of the dip. Furthermore, a fault can produce a phase jump in the voltage wave, although its characterization is more complex because it depends on the ratio between the angle of the grid impedance and the angle of impedance of the fault.

**accredited laboratory:** entity accredited according to UNE EN ISO/IEC 17025, to perform field tests in WTG and/or FACTS, granted by ENAC or another accreditation company with which ENAC has signed an agreement of mutual recognition. This accreditation can be extended for the completion of corresponding simulations by the same laboratory.

**Accredited laboratory:** entity accredited by ENAC, or any other accreditation body with a mutual recognition agreement, according UNE EN ISO/IEC 17025 standard, for making field test of WTGs and/or FACTS, or for the validation of computer models of WTGs or FACTS, based on the measurements registered in the field tests

**endorsed laboratory:** institution that complies with the requirements fixed by the accredited certifier for the completion of only the wind farm simulations required in this document and which receives the corresponding guarantee by this same accredited certifier.

**wind farm:** a group of several WTGs at a specific site with one single grid connection point, which owns an administrative authorization and a definitive registry code as special regime.

Note: A wind farm is made up of WTGs, electrical lines connecting them and the transformer sub-station for connecting the wind farm to an electrical energy transport or distribution grid, together with all of the power systems in it, up to the grid connection point (transformers, reactive compensation systems, FACTS, etc).

**net active fundamental power:** active power obtained each period as:

\[ P = 3 \cdot U^+ \cdot I^+ \cdot \cos(\varphi) \]

where:
\( U^+ \) is the magnitude of the fundamental positive voltage sequence component.
\( I^+ \) is the magnitude of the fundamental positive current sequence component.
\( \varphi \) existing angle between the positive sequence component of the voltage and the current.

**apparent power assigned to a WTG:** apparent power \( (S_n) \) of a WTG when operating at its assigned power and at nominal voltage and frequency (IEC 61400-21).
assigned reactive power of a WTG: three phase reactive power \((Q_n)\) of a WTG when operating at its assigned power and at nominal voltage and frequency.

net reactive fundamental power: reactive power obtained each period as:

\[
Q = 3 \cdot U^+ \cdot I^+ \cdot \text{sen}(\varphi)
\]

where:

\(U^+\) is the magnitude of the fundamental positive voltage sequence component.
\(I^+\) is the magnitude of the fundamental positive current sequence component.
\(\varphi\) existing angle between the positive sequence component of the voltage and the current.

nominal registered power of a WTG: declared active power \((P_n)\) that the WTG can supply in its terminals under normal working conditions.

developer or generation company: legal entity that either owns a wind farm, or has delegated powers to subject the wind farm to the verification process.

grid connection point: a node in the transport or distribution grid used to transmit the power produced by the wind farm.

test point: any point between the terminals of the element to be tested and the grid connection point as long as it includes less than or equal to the number of elements equivalent to those in a wind farm (sub-station transformer, step-up transformer for the elements to be tested, medium and high voltage lines).

WTG power collecting system: an electrical system which takes the energy produced by a WTG and supplies this to an electrical power transport or distribution grid (IEC 61400-21).

reference voltage \((U_{ref})\): threshold of tolerance of \(U_{res} \pm 3\%\), to guarantee that overlapping among the areas defined in O.P. 12.3 does not occur, which allows the consumption of active and reactive power to be determined.

effective voltage updated every quarter of a cycle \((U_{ef(1/4)})\): value of the effective voltage measured in a period and updated every quarter of a cycle (IEC 61000 - 4 -30)

nominal voltage of a WTG \((U_n \text{ kV})\): the designated or identified voltage between phases of the WTG at the terminals (IEC 61000-4-30).

residual dip voltage \(U_{res}\): the minimum value of the voltage \(U_{ef(1/4)}\) recorded during the dip (IEC 61000-4-30).
dip threshold: voltage value specified for detecting the beginning and end of the dip (IEC 61000-4-30). OP 12.3 specifies 0.85 pu as the dip threshold.

ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>WTG</td>
<td>Wind Turbine Generator</td>
</tr>
<tr>
<td>HV, MV, LV</td>
<td>High Voltage, Medium Voltage, Low Voltage</td>
</tr>
<tr>
<td>CNE</td>
<td>Comisión Nacional de Energía (National Energy Commission)</td>
</tr>
<tr>
<td>TVC</td>
<td>Technical Verification Committee</td>
</tr>
<tr>
<td>GCP</td>
<td>Grid Connection Point</td>
</tr>
<tr>
<td>TP</td>
<td>Test Point</td>
</tr>
<tr>
<td>OP</td>
<td>Operational Procedure</td>
</tr>
<tr>
<td>PVVC</td>
<td>Procedure for Verification Validation and Certification</td>
</tr>
<tr>
<td>REE</td>
<td>Red Eléctrica de España (Spanish Electrical system operator)</td>
</tr>
<tr>
<td>CS</td>
<td>Energy Collecting System</td>
</tr>
<tr>
<td>3φ, 2φ</td>
<td>Three phase, Two phase</td>
</tr>
<tr>
<td>MITYC</td>
<td>Ministry of Industry Tourism and Trade</td>
</tr>
</tbody>
</table>
4. VERIFICATION PROCESS

The end purpose of this procedure for measuring and evaluating the response of wind farms in voltage dips is to certify its conformity with the response requirements specified in Operational Procedure 12.3 for the electrical system.

Generally, the certification process includes the following verifications of specified requirements:

- Verification that the wind farms do not disconnect as a consequence of voltage dips in the GCP associated with correctly cleared short circuits according to the voltage time curve indicated in the OP 12.3.

- Verification that the power and energy consumption (active and reactive) in the GCP, for balanced and unbalanced faults, are less than or equal to the levels marked in OP 12.3.

Figure 1 shows the verifying process flow diagram, which may be completed by executing two optional processes:

- General verification process.
- Particular verification process.
Figure 1. Flow chart of the stages of the verification process.

The owner of the wind farm to be verified will be able to choose between the general and particular processes. If it is necessary to follow the general process the manufacturer is obligated to supply the model for new wind farms as well as existing ones.
4.1. GENERAL VERIFICATION PROCESS

The general verification process consists of verifying that the wind farm does not disconnect and that the requirements stated in the OP 12.3 are met, by means of the completion of the following actions:

1. WTG and/or FACTS test
2. WTG and/or FACTS simulation
3. Wind farm simulation

Upon satisfactory execution of these actions the following reports will be obtained:

(1) ACCREDITED TEST REPORT

It includes the field test and the corresponding measures that allow the response of the WTG and FACTS during a voltage dip to be verified.

For FACTS, laboratory tests could be accepted, if the manufacturer demonstrates that the conditions are similar to those which present themselves in the field, provided that the certifier does not have a contrary opinion. When the FACTS is included in the WTG, the tests carried out are those of the WTG itself.

Upon completion of this stage, a verification of the completed tests will be carried out and an ACCREDITED TEST REPORT (1) will be issued by the accredited laboratory with the format included in ANNEX I. For FACTS and in the case of laboratory tests, the results will also be verified and accepted by an accredited laboratory.

(2) ACCREDITED REPORT OF MODEL VALIDATION

In accordance with the measurement criteria described below in this document, a simulation model will be produced whose validity must be confirmed by the measurements recorded and accredited in the field tests. These validation criteria are set by comparing these measurements with those from the reproduction of the tests in simulation. The validation criteria are given in Section 7 of this document. Upon completion of this stage, an ACCREDITED REPORT OF MODEL VALIDATION will be issued by the accredited laboratory, be it the same or a different one that carried out the field tests.

The accredited reports of model validation are classified as:
- type 2.A for WTGs
- type 2.B for FACTS
(3) VERIFIED WIND FARM SIMULATION REPORT

The simulation models of all dynamic elements of the wind farm (WTGs and/or FACTS), once their validation reports have been obtained, will be integrated inside a wind farm simulation model. Using this model, a wind farm simulation will be carried out evaluating the response of the wind farm in the GTP as it is described in the section 8. From the results of the simulations, the endorsed laboratory will produce a VERIFIED WIND FARM REPORT (3).
4.2. PARTICULAR VERIFICATION PROCESS

As alternative to the general procedure, it will be possible to obtain the direct wind farm verification, by testing the dynamic elements of the wind farm and without having to carrying out computer simulations. In this case, the conditions in the field test will be harsher than those that would have to be endured in the event of a voltage dip in the GCP, as indicated in OP 12.3 and it is required in the General Process of Verification.

The requirements that the WTG should meet during the field tests for this particular process are indicated in the section 6.2.2 of this document.

4.3. WTG TYPE

A type of WTG is defined as one that possesses the ACCREDITED TEST REPORT, as a result of the pertinent tests and simulations.

In order to avoid having to repeat field tests, for WTGs of the same manufacturer, of similar characteristics and components, a WTG TYPE is defined as that which includes WTGs that meet the following specifications:

- Electrical generator with the same design specifications:
  - Nominal power ±25%
  - Same type
  - Same stator connection voltage (only asynchronous WTGs)
  - Transformation ratio ±20% (only asynchronous WTGs)
  - Same number of poles

- Electronic converter(s), if existing, with the same hardware and specifications to withstand voltage dips.

- Transformer short circuit voltage percentage, based on the assigned power of the WTG, within a range of ±20% of the value shown on its data plate. This point will not apply to WTGs without transformers connecting them to the medium voltage circuit.

- Compensation system with the same properties and technology and with an assigned reactive power equal to or greater than that of the WTG being tested.

- Nominal registered power for the WTG (Pn, MW) within a range of ±25% of the value for the WTG being tested.

- Specific software for complying with the continuity of supply and voltage dip requirements, including protections and control. This software will be endorsed by the manufacturer.

1 The generator type must be: asynchronous with winding rotor or short-circuited rotor or synchronous with independent excitation or permanent magnets.
If an update the software takes place, that may affect the programming code for the response to voltage dips, the manufacturer will declare these modifications and will verify that they do not affect the compliance of the solution to voltage dips. The manufacturer has to submit the simulations and additional information considered necessary. The accredited certifier will produce the corresponding report on the compliance of the changes proposed to the WTG.

The ACCREDITED TEST REPORT (1) and the ACCREDITED MODEL VALIDATION REPORT (2.A) will be valid for any other WTG considered to be within its type category.

Whenever a group of WTGs share a common MV/LV transformer, it is possible to carry out a single field test of said WTG group, which would be treated as a single unit. It is necessary for this, that at the moment of the test, all of the turbines comply individually with the requirements set on Table I on operation point.

Each WTG group may be treated as a single unit to the effect of validating an equivalent model (section 6.2.1) or tested according to the particular procedure for compliance with P.O. 12.3 (section 6.2.2).

4.4. WIND FARM TYPE

The response to voltage dips of many of the wind farms connected to the Spanish electrical system is similar when they are comprised of WTGs of the same type and when the electrical properties up to the GCP meet a series of common requirements.

A wind farm is considered a WIND FARM TYPE if it possesses the VERIFIED WIND FARM REPORT (section 4.1 (3)) according to the general process for pertinent tests and simulations. In order to avoid unnecessarily simulating wind farms similar to those included in the category of WIND FARM TYPE, a wind farm will be accepted as valid (and therefore with VERIFIED WIND FARM REPORT (3)) whenever it can be declared as belonging to a certain WIND FARM TYPE. A wind farm cannot be considered to be a WIND FARM TYPE unless it has completed all the pertinent tests and simulations.

The definition of WIND FARM TYPE will be proposed by the owner of the wind farms to be verified, accepted previously by accredited certifier, and will include at least the following data:

- The normalized short circuit impedance\(^2\) of all of the electrical elements (transformers and lines) between the medium voltage side of the wind farm and the GCP.

---

\(^2\) The base magnitudes will be the nominal power of the wind farm and the voltage level of the GCP
- Connection group of the transformers and neutral of the electric system between the MV side of the wind farm and the GCP.

- The assigned power of the reactive compensation systems in ratio to the registered power of the wind farm.

- WTGs of the wind farm type

The validation criteria of the given parameters for which a wind farm can be considered to belong to a WIND FARM TYPE, are the following:

- The normalized short circuit impedance\(^3\) of the wind farm in a margin of ±20% of the defined magnitude for the wind farm type.

- Connection group of the transformers and neutral: the wind farm should have equal connection groups and neutral as those defined in the wind farm type.

- The assigned power of the reactive compensation systems in ratio to the registered power of the wind farm greater than or equal to that of the wind farm type.

- The relative quantity\(^4\) of WTGs of the same type or belonging to that type must be identical to those in the wind farm type.

The accredited certifier will verify that each new wind farm belonging to the same owner meets the configuration on wind farm type defined by him.

The VERIFIED WIND FARM REPORT (3), in the category of wind farm type will only be valid for wind farms meeting the following requirements:

- The WTGs and/or FACTS must have a ACCREDITED TEST REPORT (1). It will also be necessary for the WTGs to have an accredited model certification report (2.A). The FACTS devices must have a accredited model validation report (2.B).

- The electrical characteristics are within the tolerances and specifications indicated in the definition of wind farm type.

---

\(^3\) The base magnitudes will be the nominal power of the wind farm and the voltage level of the GCP.

\(^4\) The relative quantity will be the quotient between the number of the WTGs of the same type (or belonging to the type) with respect to the total number of WTGs in the wind farm.
Wind farm type simulation will be carried out only once and will be done with the characteristics and topology indicated by the owner whose wind farms are to be verified, using validated models for all dynamic elements inside the wind farm (WTGs and/or FACTS).

All those installations that meet the above requirements will directly receive a verified wind farm simulation report without needing additional simulations. Each installation that is not within the wind farm type category must carry out a specific simulation of the wind farm.

5. VERIFICATION AND CERTIFICATION BODIES

5.1. THE TECHNICAL VERIFICATION COMMITTEE

A specific TECHNICAL VERIFICATION COMMITTEE (TVC) will be created, that will supervise the execution of this PVVC and will make decisions and propose appropriate correction mechanisms in the specific topics mentioned in this document. In general terms the TVC will be comprised of and governed by statutes created for this purpose.

All of the wind energy sector representatives will participate in this body: the electrical system operator, REE; WTG and FACTS manufacturers; wind farm promoters and test laboratories.

In general terms, the functions of this TVC will be at least the following:

- To follow the correct application of this PVVC.
- To arbitrate in the event of disagreement and based on specific elaborated reports.

Which are specified as:

(1) To propose the criteria for the validation of the laboratories that produce the VERIFIED WIND FARM VALIDATION REPORTS (3).
(2) To include the pertinent modifications of the present PVVC in accordance with the obtained results. Once modified it must be presented to the Subdirección General de Energía Eléctrica of the MITYC.
(3) To assist in the completion of the functions of the accredited certifiers and more specifically, to arbitrate in the case of disagreement (in the most anonymous and confidential manner possible), on modifications to established WTG types, FACTS and wind farms.

The statutes for the specific operation of this TVC will determine the internal operation, the issuing of reports and the election of representatives with highest precision.
5.2. THE ACCREDITED CERTIFIER: FUNCTIONS

The accredited certifier has the task of ensuring that the aforementioned documents for the verification and validation of compliance of a wind farm with the requirements set in the OP 12.3 comply with what is established in this document and subsequently certify it. If the conditions are not met, a report specifying the reasons for this non compliance must be produced.

The accredited certifier will sign an agreement with the petitioner in which economic considerations, timeline and compromises of the signatories will be established.

The accredited certifier will also endorse the laboratories that carry out the wind farm simulations based on corresponding accredited reports and certified models, on the basis of the criteria defined by the TVC.

In case of variations on the established types, the accredited certifier will:

1. Approve that the modifications proposed by the manufacturers are within the WTG type certificates available and do not affect the requirements set in OP 12.3.
2. Approve changes in the type or configuration of FACTS in such a way that they do not affect the type described in the FACTS’ ACCREDITED MODELS VALIDATION REPORT (2.B)
3. Approve the wind farm type proposed by the promoter and to determine if the wind farms to be validated fit this type.

The accredited certifier will periodically check the effect of the configuration changes to the initially produced certificate, when needed. If differences are observed, the Certifier will issue a corresponding report to the Subdirección General de Energía Eléctrica, which will determine the action to be taken.

The certification process will be the following:

- Reception of the petition of the corresponding certification, together with the documents specified in this PVVC. The petitioner must identify the contact person for later steps.
- Checking of documentation and issuing of the corresponding acknowledgement of receipt.
- Opening the file, assigning the corresponding code and initiating the processing, if the information is valid according to this PVVC.
- Issuing the invoice.
- Producing the pertinent confidential reports prior to certification, based on the present documentation and the controls that are considered necessary.
Any additional information that is considered necessary to complete the certification will be required of the petitioner, as well as any appropriate correcting actions for the completion of the requirements of this PVVC.

The issues that are not addressed in this PVVC will be regulated by the specific guidelines of each accredited certifier.
6. TEST PROCEDURE

This section specifies the conditions and validity criteria for field tests as well as defining the equipment needed to carry out this test. It also specifies the measurements required to determine the typical properties of the WTG or FACTS response to dips.

The procedures described in this section are valid for WTGs and FACTS devices of any power with a three phase connection to an electrical grid.

The measurements will be used to check the typical parameters for the response to voltage dips throughout the operating intervals of the WTG or FACTS device tested.

The properties measured are only valid for each WTG type. Variations in the configuration that could affect its response to voltage dips will affect their type classification and will require another test.

6.1. TEST EQUIPMENT

The use of test equipment including a voltage dip generator using an inductive divider (Figure 2) is recommended. This figure shows a single line diagram of the voltage dip generator located among the power collecting system SC and the equipment to test (WTG or FACTS).

Figure 2. Voltage dip generator equipment
This voltage dip generator must meet at least the following requirements:

- The function of the impedance $X_1$ is to limit the short circuit current contributed by the electrical network in which the test is carried out. It may represent a combination of reactances or transformers and will be of such value that the short circuit power in the test point, TP, is greater than or equal to 5 times the registered power of the WTG or FACTS being tested.

- The impedance $X_2$ will be adjusted in such a way that the voltage at TP is the same as that for the three-phase and two-phase faults (see section 6.2)

- In the branch where the impedance $X_2$ is found, there must be a switch that operates in such a way as to generate three-phase and isolated two-phase voltage dips.

- Impedance $X_3$ will be the following may be a transformer or a combination of reactances and transformers. The impedance $X_3$ will take the one of the following values:
  
  - Without step-up transformer: $X_3 = 0$
  - With step-up transformer there are two cases:
    
    a. $X_3$ will take the value of the short circuit impedance of the transformer.
    b. $X_3$ will take the value of the short-circuit impedance of the step-up transformer in normalized value with a tolerance of ±20%

- If additional transformers are used, in the position of reactance $X_3$, these may have any transformation ratio and will have the same connecting group as the step-up transformer of the WTG or FACTS (if any exists).

In the case of dip generators that do not have the inductive divider, it is necessary to check that the residual voltages in the magnitude and argument in the three phases are similar to those that result from simulating or testing three and two-phase short circuits with an inductive divisor as defined in this document.

The equipment described in this section only applies to the WTG field testing.
6.2. TESTING OF WTGS

The definition and conditions in which the WTG test will be carried out will depend on the objective that is sought with the test. Therefore, the tests may be:

- Tests for validating the simulation model (general verification process).
- Tests for direct observance of the OP 12.3 (particular verification process)

The following are the characteristics common to both tests.

For each of the two cases, the complete WTG should be tested in the field and the test should be carried out considering the following operation points (Table I)

<table>
<thead>
<tr>
<th>PARTIAL LOAD</th>
<th>FULL LOAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>registered active power</td>
<td>Power factor</td>
</tr>
<tr>
<td>10%-30% Pn</td>
<td>0.90 inductive -0.95 capacitive</td>
</tr>
<tr>
<td>&gt;80% Pn</td>
<td>0.90 inductive -0.95 capacitive</td>
</tr>
</tbody>
</table>

The accredited laboratory will confirm that neither a particular moment for the short circuit and later clearance, nor a power factor that would be especially favorable to the permanency of the WTG coupled during the voltage dip, have been chosen.

The test must be carried out using the dip generator to apply three-phase and isolated two-phase faults that cause voltage dips in the affected phases whose properties, based on Operational Procedure 12.3, are specified below. The specified properties of the voltage dip are independent of the response of the WTG being tested. This is achieved by obtaining the dip through a test with the WTG disconnected from the dip generator ("no load test" from now on). In the on-load test the adjustment of the impedances will be the same as in the no load test.

The test equipment limits the short circuit power, which causes voltage variations during the application of the short circuit that may be important. In order to specify uniform test conditions, the test is categorised by the value of the residual voltage resulting from the no load test.

Four categories of test must be carried out in the procedure (Table II)
Table II. Test categories

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>Operating Point</th>
<th>DIP TYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PARTIAL LOAD</td>
<td>THREE PHASE</td>
</tr>
<tr>
<td>2</td>
<td>FULL LOAD</td>
<td>THREE PHASE</td>
</tr>
<tr>
<td>3</td>
<td>PARTIAL LOAD</td>
<td>TWO PHASE ISOLATED</td>
</tr>
<tr>
<td>4</td>
<td>FULL LOAD</td>
<td>TWO PHASE ISOLATED</td>
</tr>
</tbody>
</table>

As a result of the test, the ACCREDITED TEST REPORT (1) will be produced in accordance with the format that is included in ANNEX I.

6.2.1. Test conditions for model validation

The WTG test conditions for validating the model are the following:

- **Point of measurement**: for the validation of the WTG or FACTS model, the point of measurement may or may not coincide with the testing point. The model to be validated will include all the elements downstream of the point of measurement. For example if a test is chosen with the test and measuring points in MV, the dynamic behaviour of the WTG plus the step-up transformer will be validated. However, if the test is carried out in MV and the measure point is in LV only the WTG model will be validated.

- **Test characteristics**
  - For each of the four test categories described in Table II, it will be proven that the minimum voltage $U_{ef}$ (1/4) registered during the no load test of the fault phases is less than 90%. Subsequently and without modifying the configuration of the dip generator, the load test will be carried out, in which the voltages and currents in the point of measurement will be registered.
  - Of each test category the time series of voltage and current in the first block of three consecutive tests without disconnection will be recorded. These data series will be used to validate the simulation model later on.

The validity of the test will subsequently be carried out in section 7.3 where it will be proven that the voltage and current levels at the point of measurement are more severe in the field test than during the wind farm simulation procedure.

In the particular case of asynchronous WTGs, without dynamic compensation (or FACTS devices that act during the dip), the accredited certifier will decide whether it is necessary to carry out the field test of this kind of WTG depending on information supplied regarding the electric parameters and dynamic characteristics of the mechanical part that influence the behaviour of the machine during the voltage dip.
6.2.2. Test conditions for direct observance of P.O.12.3. Particular process.

WTG test will be accepted as valid for direct observance of OP 12.3 as stated in section 4.2 of this document (particular verification process) when for each of the four test categories on Table II, the following requirements are met:

(1) Guarantee of continuity of supply

The WTG is not disconnected during the application of the voltage dip in three consecutive tests in the same category (see Table II). If at least one disconnection occurs in this test sequence (the first three consecutive tests), the continuity of supply condition will only be considered valid, if the WTG does not disconnect in the four following tests in the same category. If a disconnection occurs in this last series of tests, the test will be considered invalid.

(2) Operation point

An essential condition of each test category is that the active and reactive power recorded before the voltage dip test (see Table I), are within the interval that defines partial load and full load.

(3) Residual voltage level and time during the no load test

For tests carried out in each of the categories with the WTG disconnected (no load test) the dip residual voltage $U_{res}$ recorded in the no load test for the phases in fault must be proven to be lower than the following values and the time less than or equal to the one specified below:

<table>
<thead>
<tr>
<th>Type of dip</th>
<th>Residual dip voltage $U_{res}$</th>
<th>Voltage tolerance $U_{TOL}$</th>
<th>Dip duration (mseg)</th>
<th>Time tolerance $T_{TOL}$ (mseg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>THREE PHASE</td>
<td>$\leq(20%+U_{TOL})+3%$</td>
<td>$\geq(500-T_{TOL})$</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>ISOLATED TWO PHASE</td>
<td>$\leq(60%+U_{TOL})+10%$</td>
<td>$\geq(500-T_{TOL})$</td>
<td>50</td>
<td></td>
</tr>
</tbody>
</table>

(4) Conditions of power and energy exchange at test points

The necessary voltage and current measurements for the subsequent power and energy calculations (active and reactive), as indicated on OP 12.3, will be registered at the test point TP.

If the WTGs installed in a given wind farm are capable of meeting the requirements set in OP 12.3 for two-phase dips, with the test conditions defined in this section 6.2.2., it will not be necessary to carry out a simulation of a two-phase short circuit at the GCP.
Also, if the WTGs installed in a given wind farm are capable of meeting the requirements set in OP 12.3, (with reduced reactive power consumption) with the test conditions defined in this section 6.2.2., it will not be necessary to carry out a simulation of a three-phase short circuit at the GCP.

To use this particular process for three-phase dips:

- The reactive power consumption in zone A (see zone characterization during voltage dips, section 9.1.) must not be greater than 15% of \( P_n \) for every 20 ms. In zone B, this value must not exceed 5% of \( P_n \) for every 20 ms.

- During the period between the fault clearance starting time (\( T_3 \), see section 9) and \( T_3 + 150 \) ms it must be verified that the net reactive current consumption at the test point in each cycle (20 ms) must not be greater than 1.5 times the current at nominal power, even when the voltage has reached 0.85 p.u. within that period.

The mean value of the current measurements carried out in zone B of the dip, according to section 9.1, will be used to verify compliance with the requirement on the ratio between the reactive part of the current during the dip and the total current (section 4.1 of OP 12.3).

**6.3. FACTS TEST**

The test of a FACTS device is performed in order to establish its dynamic response and to allow validation and verification of a simulation model. The test is never performed in order to check continuity of supply.

Generally, a full size FACTS device or a scalable module will be tested in a laboratory and will include all the associated control and power elements. The test characteristics and validity are the following:

- Only two of the test categories are necessary: THREE-PHASE AND ISOLATED TWO-PHASE. In each of them, the overload capacity of the device during the voltage dip will be proven. The initial load is not considered to be relevant to the test. For each of the test categories, the minimum voltage \( U_{\text{ef}(1/4)} \) registered during the dip in the phases in fault in the no load test must be shown to be less than 90%.

- Three time series for instantaneous voltage and current in each phase for each test category will be recorded. These time series will subsequently be used to validate the simulation models of these devices.
If the FACTS device can not be tested at full size or if there is not a scalable module, a laboratory test will be allowed that includes the real time control elements that act on a real time simulator of the power section of the FACTS device. The characteristics and validity of this test are the same as in the general case.

Different tests will be also allowed -tests performed by the manufacturers- provided that they adjust to established international regulation and reproduce the dynamic response of the device during a voltage dip, and are also accepted by the accredited certifier.

7. MODELS VALIDATION PROCESS

7.1. WTG MODEL

The validation of the WTG model requires the following steps:

1. The instantaneous voltage and current values in each phase at the test point are recorded and rms values determined for the fundamental harmonic of these variables, as well as the values of the active and reactive power according to the calculation procedure described in Section 9.2 of this document. This is carried out for each of the three data series recorded in the four test categories specified in this PVVC (three-phase and two-phase faults at partial and full load).

2. The manufacturer's WTG model must be used by the endorsed or accredited laboratory to reproduce each of the tests carried out in the field in the computer system, by including the properties and configuration of the test bench and the electrical grid in which the test was carried out. In order to compare the field test measurements with the results of the simulation model, the latter should be, on the one hand, as detailed as possible and, on the other, sufficiently manageable to allow for the integration of the electrical system simulation programs. The same computer model must be used to compare the four test categories.

3. The results of the simulation model must be the same instantaneous variables as those recorded in each of the four field tests. The integration step should be equal to or less than the time interval for the sampling frequency in the measurements recorded during the field tests. The rms values of the fundamental harmonic of these variables are determined from the simulation values of voltage and current in each phase, as well as the active and reactive power values, as described in point 1 of this section.

Compliance with the validation criteria will result in the issuing of a ACCREDITED TYPE MODEL VALIDATION REPORT 2.A by the accredited laboratory.
7.2. FACTS MODEL

The validation process for FACTS devices in the wind farm (except those in the WTG, with which it must be jointly tested) will be the same as that described in the above points in section 7.1, and will also be applicable to the laboratory tests described in section 6.3. Compliance with the validation criteria will result in the issuing of a ACCREDITED TYPE MODEL VALIDATION REPORT 2.B by the accredited laboratory.

7.3. VALIDATION CRITERIA

A WTG or FACTS model will be considered validated when, for 85% of each of the data series corresponding to the first block of consecutive tests without disconnection (section 6.2.1), the difference between the values of the following variables measured in the field test and those measured in the computer platform does not exceed 10%:

- The rms value of the fundamental harmonic voltage in each phase.
- The rms value of the fundamental harmonic current in each phase.
- The active and reactive three-phase power.

The calculation of this index $\Delta x(\%)$, is understood to be the ratio between the absolute value of the difference of the measurements recorded in the field $x_{\text{med}}$ and those obtained in the computer platform $x_{\text{sim}}$ with respect to those recorded in the field multiplied by 100. The rms values calculated at least each quarter cycle with an integration window of one cycle must be compared.

$$\Delta x(\%) = \left| \frac{x_{\text{med}} - x_{\text{sim}}}{x_{\text{med}}} \right| \cdot 100 \leq 10\%$$ (1)

Once the simulation model has been validated, the accredited laboratory will provide a physical copy of the simulation model with the accreditation seal, the properties of the WTG tested (Table I.1 of Appendix I) and the properties of the computer tools that allow it to be used. The model stored on this physical medium may be used in as many wind farm simulations as necessary with any accredited laboratory.

The TVC may decide that these criteria need modification depending on the obtained results.
8. PROCESS FOR SIMULATING WIND FARMS

To carry out the wind farm simulation study, a tool must be used that allows the components of the electrical system to be modelled by phase, since dynamic studies with balanced and unbalanced faults will be carried out. This tool must be able to use the validated WTG model without needing to make modifications to it.

8.1. TOPOLOGY OF ELECTRICAL SYSTEM

In order to carry out wind farm simulations, an electrical configuration as described in Figure 3 will be used, which must contain at least the following elements:

- Wind farm and facts devices.
- Medium to high voltage step-up transformer.
- Evacuation line (AT - PCR).
- Grid equivalent.

Figure 3. Single-line schematic of the layout of the electrical system.

All of the groups of WTGs connected through electrical power circuits will be connected to the medium voltage (MV) point. If additional loads or other wind farms are connected between the high voltage (HV) point and the grid connection point (GCP), those additional loads or wind farms will be taken out of the simulation, in order to avoid any modification of the equipment that connects to the GCP (transformers and lines).
8.1.1. Wind farm and FACTS devices

In the wind farm simulation process, validated WTG and/or FACTS models will be used. Figure 3 shows a parallel connection for the FACTS in the medium voltage (MV) node; however, serial type connections are also possible although they are not shown.

Generally, a wind farm will include any WTG, FACTS and existing reactive compensation devices, cables, step-up transformers (LV/MV) and internal lines. The internal layout of the wind farm used in the simulation will be accepted as valid for verifying other wind farms included in the type category (section 4.4).

Particularly, a wind farm might be represented by only one equivalent WTG provided that all WTGs in the wind farm are of the same type. If the wind farm contains more than one type of WTG, aggregation might still be valid if each equivalent WTG represents a grouping of WTGs connected to the same power equipment and belonging to the WIND FARM TYPE configuration selected by the owner in the actual wind farm.

8.1.2. Medium/high voltage transformer

The electrical properties of the MV/HV transformer used in simulating the wind farm are:

- Ratio of medium (kV) / high (kV) voltages.
- Apparent nominal power $S_n$(MVA).
- Connection group.
- Power of losses in the short circuit test $P_{cc}$(kW).
- Power of losses in the no load test $P_o$(kW).
- Short circuit voltage in $U_{cc}$(%).
- No load current $I_o$(%).

8.1.3. Evacuation line

The electrical properties of the evacuation line from the high-voltage point to the grid connection point (GCP) to be used in the process of wind farm simulation are:

- Voltage level (kV).
- Power transmission capacity (MW).
- Cross section of conductors.
- Resistance $R_{AC}$ (50 Hz - 20° C) ($\Omega$/km).
- Reactance $X_{AC}$ (50 Hz) ($\Omega$/km).
- Susceptance ($\mu$S/km).
- Length and number of circuits in the line.
8.2. EQUIVALENT ELECTRICAL GRID

The rest of the electrical grid that does not belong to the wind farm being studied must be modelled so that the fault clearance at the grid connection point reproduces the usual voltage profile in the Spanish electrical system - a sudden increase on the clearing of the fault and a slower recovery afterwards. Said profile will be considered fixed and independent of the geographic location of the wind farm to be studied.

In order to simulate the equivalent electrical grid, a dynamic system has been chosen consisting of one node in which the equivalent dynamic model of the UCTE (UCTE node) is modelled, along with another node in which an equivalent model reflecting the dynamic characteristics due to the hypothetical closest electrical grid (RED node) and a third that represents the GCP (GCP node). Said nodes are separated by impedances of predetermined values in a way in which the typical voltage profile of the Spanish electrical system is reproduced. In this way, it is guaranteed that all of the wind farms are tested, by simulation, for short-circuits with equal characteristics.

The UCTE equivalent includes a synchronous generator (Generator 1) of an apparent power that reflects a realistic value for the interconnected apparent power and therefore the inertia of the UCTE system. Said generator is modelled in 20 kV bars with a step-up transformer. The demand of the UCTE system is modelled as a load in the equivalent node of said system.

In order to considerate the dynamic side of the equivalent of the closest grid, a synchronous generator has been included (Generator 2) and a demand. The generator (Generator 2) is modelled in 20 kV bars with a step-up transformer and the demand is modelled as a load in 20 kV bars connected to the RED node through a transformer.

The properties of the equivalent electrical grid must include at least the following elements represented in figure 4:
8.2.1. Data of the nodes and passive elements of the grid equivalent

In accordance with the nomenclature considered in Figure 4, the following data are considered.

Nodes:

For the GCP node, the base voltage is considered to be the nominal voltage of the grid to which, in reality, the connection node to the corresponding grid belongs.

For the UCTE node, as well as the RED node, the same base voltage will be taken as that assigned to the GCP node.

Lines:

“π” models with the fixed characteristics indicated in Figure 4 will be used. Said resistance, reactance and susceptance characteristics will be expressed in per unit values with base power of 100 MVA Additionally, it will be considered that the corresponding values indicated in Figure 4 are already expressed in the base voltage of the extreme nodes, independently from the nominal voltages of the same nodes. This will guarantee that the voltage dip and the recuperation profile are always the same independently from the actual voltage of the GCP node.
Transformers:

Simple reactances with the fixed characteristics indicated in Figure 4 will be used. Said reactances are expressed in per unit values with a base power 100 MVA and base voltage of 20 kV. All of the transformers are considered to be part of the connection group YNd11.

8.2.2. Data of the synchronous generator and its excitation system

Generators 1 and 2 must have the active and reactive production values indicated in Figure 4.

The parameters needed to correctly model the synchronous generator 1 for the UCTE equivalent, as well as the synchronous generator 2 of the RED equivalent, are the same with the exception of the inertia constant. Said values are indicated in Table V, in per unit with machine base and with unsaturated characteristic values. Additionally, the model to be used must not consider magnetic saturation:

Table V. Data of the generators.

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn (generator 1)</td>
<td>400,000 MVA</td>
<td>Apparent nominal power of the generator (MVA)</td>
<td></td>
</tr>
<tr>
<td>Sn (generator 2)</td>
<td>2,000 MVA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Un</td>
<td>20</td>
<td>Nominal Voltage between phases (kV)</td>
<td></td>
</tr>
<tr>
<td>T'do</td>
<td>5,0 s</td>
<td>Transient, open-circuit time constant d-axis (s)</td>
<td></td>
</tr>
<tr>
<td>T''do</td>
<td>0,038 s</td>
<td>Subtransient, open-circuit time constant d-axis (s)</td>
<td></td>
</tr>
<tr>
<td>T'qo</td>
<td>0,65 s</td>
<td>Transient, open-circuit time constant q-axis (s)</td>
<td></td>
</tr>
<tr>
<td>T''qo</td>
<td>0,075 s</td>
<td>Subtransient, open-circuit time constant q-axis (s)</td>
<td></td>
</tr>
<tr>
<td>Xd</td>
<td>2,1 p.u.</td>
<td>Synchronous, d- axis reactance (p.u)</td>
<td></td>
</tr>
<tr>
<td>Xq</td>
<td>2,0 p.u.</td>
<td>Synchronous, q- axis reactance (p.u)</td>
<td></td>
</tr>
<tr>
<td>X'd</td>
<td>0,25 p.u.</td>
<td>Transient, d- axis reactance (p.u)</td>
<td></td>
</tr>
<tr>
<td>X'q</td>
<td>0,45 p.u</td>
<td>Transient, q- axis reactance (p.u)</td>
<td></td>
</tr>
<tr>
<td>X''d = X''q</td>
<td>0,21 p.u.</td>
<td>Subtransient, d- axis and q-axis reactance (p.u)</td>
<td></td>
</tr>
<tr>
<td>Xl</td>
<td>0,16 p.u</td>
<td>leakage reactance (p.u.)</td>
<td></td>
</tr>
<tr>
<td>H (generator 1)</td>
<td>4,5 s</td>
<td>Inertial Constant (s)</td>
<td></td>
</tr>
<tr>
<td>H (generator 2)</td>
<td>3,0 s</td>
<td>Inertial Constant (s)</td>
<td></td>
</tr>
</tbody>
</table>

The data needed for the excitation systems of both synchronous generators are those included on Table VI (see figure 5).
It will be assumed that the generators are under a constant mechanical torque at all times, which makes it unnecessary to model the speed regulators or the respective turbines.

### 8.2.3. Load power

With regard to the load, independently for each one, the active part must be modelled as a constant current ($P(v) = P_1V$) and the reactive power as a constant impedance ($Q(v) = Q_1V^2$).

Where $P_1$ and $Q_1$ are the load values corresponding to a voltage of 1 p.u. Said values are calculated from the initial load values $P_0$ and $Q_0$ corresponding to the initial node voltage $V_0$. If $V_0$ is expressed in p.u. then:

\[
P_1 = \frac{P_0}{V_0} \cdot (p.u)
\]

\[
Q_1 = \frac{Q_0}{V_0^2} \cdot (p.u)
\]

The values $V_0$ for the nodes of the module will vary slightly depending on the current operation point and whether or not the wind farm is modelled at the GCP node, as well as the working regime. Therefore it will be necessary to make a load distribution considering its own particular effects.
• The generation node “Generator 1” will be the balancing node \((V, \delta)\) with the data:
  o \(V=1,042\) p.u. (generator 1 voltage instructions)
  o \(\Delta=0^\circ\) (angle reference)

• The generation node “Generator 2” will be considered as a PV node with the data:
  o \(P=1600\)MW (generated power)
  o \(V=1.042\) p.u. (voltage instructions for generator 2)

• The remaining nodes will be considered to be PQ nodes with fixed power loads in its active and reactive parts.

Once the load distribution is completed, the reactive power of the generators will be able to vary slightly, however, it is most important that voltage instructions are maintained at the generation bars (20kV).

8.2.4. Fault reactance

For the dynamic simulation of a balanced fault, a three-phase fault at the GCP will be simulated, with a ground reactance reference of \(8.4034\times10^{-3}\) p.u. with a 100MVA base. Said reactance is such that the voltage at the GCP node falls to 0.2 p.u. in the moment in which the fault clears (500 ms).

For the dynamic simulation of an unbalanced fault, an isolated two-phase fault at the GCP node will be simulated, with a reactance between phases such that the phase-ground voltage of the phases in the fault, in the GCP node, fall to 0.6 p.u. in the moment in which the fault clears (500 ms).

The voltage at connecting node during the balanced fault and subsequent recovery can be observed in the following figures:

In the case of a three-phase balanced fault simulation, the fault is applied when the voltage of one of the phases is at a peak.

In the case of an isolated two-phase fault simulation, the fault is applied when the voltages of the phases in which the fault will be simulated coincide. The fault will clear through an automatic switch that opens at a zero crossing of the current.
Figure 6. Voltage in a connection node during the balanced fault and fault recovery.

Figure 7. Voltage in a connection node during the balanced fault and fault recovery. (detail of the first 2 s)
8.3. EVALUATION OF RESPONSE TO VOLTAGE DIPS

The final part of the simulation procedure consists of the strict evaluation of the wind farm’s response to voltage dips. Once the electrical system, its associated dynamic elements and the starting conditions before simulation have been defined, a fault can be applied to the grid connection point for the four test categories (see Section 6.2).

Once the initial conditions are adjusted at the WTG terminals, for which the active generated power correspond to the full or partial-load and the reactive power is zero, the conditions indicated in Section 8.2.3 will be considered to be the initial conditions prior to the simulation.

Once the simulations have been carried out, the fulfilment of the following requirements must be proven for each test category:

(1) **Continuity of supply**

During the simulation, it must be shown that the wind farm withstands the specified dips in the test procedure without disconnection. To carry out these simulations, it is necessary that the simulation model includes the protections internally, which determine the triggering of the WTG in case of voltage dips and return the resulting disconnection signal.

If the entire wind farm (without aggregation) is simulated, the simulated installation guarantees the continuity of supply if the number of machines remaining connected during the dip is such that the loss of generated active power does not exceed 5% of the power previous to the fault. If an equivalent wind farm (with aggregation) is used, the triggering of the WTG will determine the continuity of supply for the complete wind farm.

(2) **Voltage and current levels at the WTG terminals**

After checking the voltage level during the no load test, the voltage and current values in each phase for the four categories described above must be measured and recorded during the load tests (WTG connected during the short circuit).

The field test will be considered valid when, during the simulations of the wind farm at the GCP, it is found that:

The calculated residual voltage levels at the test point $V_{RES,PE_SIM}$ (WTG terminals or step-up transformer if included in the test) are greater than or equal to those recorded in the field test $V_{RES,PE_TEST}$ minus a 2% tolerance.

$$V_{RES,PE_SIM} (pu) \geq (V_{RES,PE_TEST} (pu) - 0.02)$$

(3)
- The calculated current levels at the test point (WTG terminals or step-up transformer if included in the test) for each phase during the simulation are lower than those recorded in the field test. This requirement will be confirmed for the maximum values registered in zones A and C (see definitions of zones in section 9.1).

(3) Exchanges of active and reactive power as described in OP 12.3 which is calculated according to the calculation method in Section 9.2 of this document. The average value of the current measurements in zone B of the voltage dip defined in section 9.1 will be considered in order to verify the compliance with the requirement for the ratio between the reactive component current during the fault and the total current (Section 4.1 of OP 12.3).

In the wind farm simulation, it must be shown that neither a specific beginning or clearance point for the voltage dip, nor a power factor for the WTGs, which are especially favourable for the compliance with the requirements set in the OP 12.3 have been chosen.

For existing wind farms, if during the simulation, the voltage remains above 85% of the nominal voltage of the machine at all times, the WTGs can be represented through a simplified model and the necessary relays that disconnect the machine when the fixed conditions for the protection limitations occur. The simplified models will be modelled according to their technology:

- Asynchronous speed generators
- Asynchronous generators with dynamic slide control.
- Double-feed induction generators: designed from a simplified model that considers at least the electric dynamic of the rotor in order to determine the trip of the machine in case of overcurrents.
- Synchronous generator with total converter: modelled a constant current source.
9. MEASUREMENT TECHNIQUES

Both in the field tests and in the simulation procedure, all of the records of voltage and current sampled for each phase must be carried out at a sampling frequency (or equivalent integration step) of at least 5 kHz. For each test, the instant values of voltage and current recorded must include at least the 10 seconds prior to the beginning of the dip and at least 5 seconds after T_4. In the registered values prior to the fault, the frequency will be determined that is going to be used as starting data for determining the U_{rms(1/4)}.

9.1. CLASSIFICATION OF ZONES DURING THE DIP

O.P. 12.3 defines three zones during the voltage dip, as shown in Figure 8, that are classified as a function of the dip threshold and of the residual voltage of the dip:

The typical points on the voltage U_{ef(1/4)} are determined as follows:

- **Instant of start of dip (T_{1})**: the instant in which the voltage U_{ef(1/4)} of one of the phases falls below the dip threshold (IEC 61000-4-30).

- **Instant of the end of dip (T_{4})**: the instant in which the voltage U_{ef(1/4)} in all of the channels measured is equal to or greater than the dip threshold (IEC 61000-4-30).

- **Instant of start and end of the bottom of the dip (T_{2} and T_{3})**: the instants T_{2} and T_{3} are determined from the voltage values U_{ef(1/4)} measured.

![Figure 8. Classification of the voltage dip in the field test.](image-url)
Because during the voltage dip the residual voltage may be modified by the reactive power exchanges, a distinction will be made between the calculation for $T_2$ (start of the bottom of the dip) and $T_3$ (end of the bottom of the dip).

The point $T_2$ is determined by the calculation of a reference voltage $U_{\text{ref1}}$ as shown in Figure 8, such that at all times the value of $U_{\text{ref1}}$ does not differ by more than 3% from the voltage reached at the start of the bottom of the dip $U_{\text{res1}}$.

Similarly, the point $T_3$ is determined by the calculation of a reference voltage $U_{\text{ref2}}$ (see figure 8), such that at all times the value of $U_{\text{ref2}}$ does not differ by more than 3% from the voltage reached both at the end of the bottom of the dip $U_{\text{res2}}$.

$U_{\text{ref1}}$ and $U_{\text{ref2}}$ will be determined by an algorithm which detects changes in the $U_{\text{ef(1/4)}}$ voltage slope measured with great accuracy to correctly determine dip zones.

Once the values of $U_{\text{ref1}}$ and $U_{\text{ref2}}$ as well as the associated times $T_1$, $T_2$, $T_3$ and $T_4$ are obtained, areas A, B and C are considered as:

- Zone A: all of the values of voltage $U_{\text{ef(1/4)}}$ between the instant $T_2$ and $T_2 + 150$ ms.

- Zone B: all of the values of voltage $U_{\text{ef(1/4)}}$ between the instant $T_2 + 150$ ms and $T_3$.

- Zone C: all of the values of voltage $U_{\text{ef(1/4)}}$ between the instant $T_3$ and the lesser of the following values, $T_4$ and $T_3 + 150$ms.

Once the zones have been obtained, the following calculated values are updated each period. Measuring equipment for obtaining the measurements will be according to IEC 61400-21 standard.

For the purpose of calculation, the first cycle from which the above values are calculated will that which is marked by the first value of $U_{\text{ef(1/4)}}$ after the start threshold of the dip.

**9.2. METHODOLOGY FOR CALCULATING POWER**

This section describes the method for calculating the active power, reactive power, reactive current and rms voltage values to be used to determine compliance with the response to voltage dips as specified in OP 12.3 of the electrical system. This method must be applied to both the field tests and to the simulations referred to in this document.

The method for measuring the instantaneous values of voltage, current and frequency must be carried out according to the standard IEC 61000-4-30: Electromagnetic compatibility (EMC). Part 4-30: Test and measurement techniques. Methods for measuring the quality of supply.
1. It is recommended that the frequency determined in the 10 cycles before the dip be used to calculate the phasor during the dip. The value of the frequency calculated per phase, f(Hz), allows the calculation window of the period to be determined for T(s), (T=1/f) and must remain constant throughout the test or simulation.

2. Using a sampling frequency f_s(Hz) that is constant and greater than 5 kHz, the number of samples N must be determined for each calculation window as the even and integer number nearest to the product of the period of the window by the sampling frequency T*f_s.

3. Using the N samples of the instantaneous values of phase voltage u(n) and of phase current i(n), the complex values of these magnitudes are determined for the fundamental harmonic using the following expressions:

\[
U_1 = \frac{\sqrt{2}}{N} \cdot \sum_{n=0}^{N-1} u(n) \cdot e^{-j \frac{2\pi n}{N}} \quad I_1 = \frac{\sqrt{2}}{N} \cdot \sum_{n=0}^{N-1} i(n) \cdot e^{-j \frac{2\pi n}{N}}
\]  

(4)

4. The values of the three-phase active P and reactive Q powers are calculated using the magnitude and argument of the complex values from expression (4) for each of the three phases. In the calculation process of the active and reactive power, only the positive sequence component of the voltage (U^+) and current (I^+) whose values are determined by the phase values according to expression (5) will be considered:

\[
U^+ = \frac{1}{3} \cdot (U_{1A} + U_{1B} \cdot e^{\frac{j2\pi}{3}} + U_{1C} \cdot e^{-\frac{j2\pi}{3}})
\]

\[
I^+ = \frac{1}{3} \cdot (I_{1A} + I_{1B} \cdot e^{\frac{j2\pi}{3}} + I_{1C} \cdot e^{-\frac{j2\pi}{3}})
\]

(5)

where:

I_{1A,B,C}: the complex expression corresponding to the rms value of the fundamental component of the current (A) in phases A, B and C each period.

U_{1A,B,C}: the complex expression corresponding to the rms value of the fundamental component of the phase-neutral voltage (V) in phases A, B and C each period.

The three-phase active and reactive power expressions will be obtained from the positive sequence component of the voltage and current as

\[
P = 3 \cdot U^+ \cdot I^+ \cdot \cos(\phi)
\]

\[
Q = 3 \cdot U^+ \cdot I^+ \cdot \sin(\phi)
\]

(6)
where:

\( U^+ \): the magnitude of the positive sequence component of the voltage in (V).

\( I^+ \): the magnitude of the positive sequence component of the current in (A).

\( \varphi \): the angle between the positive sequence component of the voltage and the current (rad).

5. The value of the reactive current and total current referred to in OP 12.3 are determined using the following expressions:

\[
I_r = I^+ \cdot sen(\varphi) \tag{7}
\]

\[
I_{tot} = I^+ \tag{8}
\]

6. The rms value of the voltage of each phase \( U_{rms} \) is determined using the expression:

\[
U_{rms} = \sqrt{\frac{1}{N} \sum_{n=0}^{N-1} (u(n) - \bar{u})^2} \quad \bar{u} = \frac{1}{N} \sum_{n=0}^{N-1} u(n) \tag{9}
\]

The average value of the voltage in the period \( \bar{u} \) shows the continuous component recorded in the period.

7. The values described in points 3 to 6 must be calculated by moving the calculation window each quarter of a period, while maintaining the number of samples \( N \) constant (4 records per period).

The laboratory may increase the sampling frequency or the number of times the data window is moved each period in order to increase precision of the measurement.

8. For both the balanced and unbalanced faults, the three-phase power must be calculated using the algebraic sum of each phase as described in point 4 of this section.
10. REFERENCES

O.P. 12.3: Requirements for response in the event of voltage dips in wind farms.

UNE-EN ISO/IEC 17025: General requirements for the competence of testing and calibration laboratories.


IEC 61400-21: Measurement and evaluation of supply quality properties of WTGs connected to the grid.
11. APPENDIX: STANDARD REPORT FORM

The standard WTG field test report form is shown below, including the technical specifications of the WTG tested, and the registered power and energy values during the three-phase and two-phase faults.

Table I.1. Data for the WTG tested.

<table>
<thead>
<tr>
<th>WTG field test report</th>
</tr>
</thead>
<tbody>
<tr>
<td>Report number:</td>
</tr>
<tr>
<td>WTG name (make and model):</td>
</tr>
<tr>
<td>Date of WTG manufacture:</td>
</tr>
<tr>
<td>Test location and date:</td>
</tr>
<tr>
<td>Manufacturer:</td>
</tr>
</tbody>
</table>

Technical specifications of the WTG

| Type, make and model of the electrical generator |
| Registered nominal power Sn (kVA) | Nominal voltage (V): |

| Type, make and model of the electronic converter |
| Nominal power (kW): | Nominal voltage (V): |

| Type, make and model of the LV/MV transformer |
| Nominal power (kVA): | Voltage ratio (V): V1/V |
| Connection group |
| Short-circuit voltage (%) |

Control type (make and model if relevant)

Control software version

Date of ACCREDITED TEST REPORT

Table I.2.- Energy and power registry. Three-phase faults, general process

<table>
<thead>
<tr>
<th>THREE-PHASE FAULTS</th>
<th>OP 12.3 REQUIREMENTS</th>
<th>RESULT</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZONE A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net consumption Q &lt; 60% Pn (20 ms)</td>
<td>-0.6 p.u.</td>
<td></td>
</tr>
<tr>
<td>ZONE B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net consumption P &lt; 10% Pn (20 ms)</td>
<td>-0.1 p.u.</td>
<td></td>
</tr>
<tr>
<td>Average I/Iิน</td>
<td>0.9 p.u.</td>
<td></td>
</tr>
<tr>
<td>ZONE C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net consumption Er &lt; 60% (150 ms)</td>
<td>-90 ms</td>
<td></td>
</tr>
<tr>
<td>Net consumption Ir &lt; 1.5 In (20 ms)</td>
<td>-1.5 p.u.</td>
<td></td>
</tr>
</tbody>
</table>
Table II.2.- Energy and power registry. Three-phase faults, particular process

<table>
<thead>
<tr>
<th>THREE-PHASE FAULTS</th>
<th>OP 12.3 REQUIREMENTS</th>
<th>RESULT</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZONE A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net consumption Q &lt; 15% Pn (20 ms)</td>
<td>-0.15 p.u.</td>
<td></td>
</tr>
<tr>
<td>ZONE B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net consumption P &lt; 10% Pn (20 ms)</td>
<td>-0.1 p.u.</td>
<td></td>
</tr>
<tr>
<td>Net consumption Q &lt; 5% Pn (20 ms)</td>
<td>-0.05 p.u.</td>
<td></td>
</tr>
<tr>
<td>Average I/I_{tot}</td>
<td>0.9 p.u.</td>
<td></td>
</tr>
<tr>
<td>Extended ZONE C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net consumption Ir &lt; 1.5 In (20 ms)</td>
<td>-1.5 p.u.</td>
<td></td>
</tr>
</tbody>
</table>

Table II.3.- Energy and power registry. Isolated two-phase faults

<table>
<thead>
<tr>
<th>TWO-PHASE FAULTS</th>
<th>OP 12.3 REQUIREMENTS</th>
<th>RESULT</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZONE B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net consumption Er &lt; 40% Pn (100 ms)</td>
<td>-40 ms*p.u.</td>
<td></td>
</tr>
<tr>
<td>Net consumption Q &lt; 40% Pn (20 ms)</td>
<td>-0.4 p.u.</td>
<td></td>
</tr>
<tr>
<td>Net consumption Ea &lt; 45% Pn (100 ms)</td>
<td>-45 ms*p.u.</td>
<td></td>
</tr>
<tr>
<td>Net consumption P &lt; 30% Pn (20 ms)</td>
<td>-0.3 p.u.</td>
<td></td>
</tr>
</tbody>
</table>

Power consumption is expressed in normalized value (p.u.) to the registered nominal power of the WTG tested. Energy consumption values are also expressed in normalized values of power by time unit in milliseconds (ms*p.u.)

The voltage and current levels registered in the test will be included in the report form, as well as the data obtained from the simulations.