SHORT CIRCUIT CONTRIBUTION OF NEW GENERATING UNITS CONNECTED WITH POWER ELECTRONICS AND PROTECTION BEHAVIOUR

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DEFINITIONS

Power Electronics Based Generation (PEBG) or Power Electronic Interfaced Generators (PEIG): Generators, which are connected to the network through power electronic converters e.g. Wind Farms, Photovoltaic Plants etc.

Wind Turbine Generator Type I: Type I is a squirrel cage induction generator connected directly to the step up transformer. The turbine speed is fixed (or nearly fixed) to the electrical grid frequency. It generates real power, when the turbine shaft rotates faster than the electrical grid frequency creating a negative slip (positive slip and power is motoring convention).

Wind Turbine Generator Type II: Type II is a wound rotor induction generator with a variable resistor in the rotor circuit. This can be accomplished with a set of resistors and power electronics external to the rotor with currents flowing between the resistors and rotor via slip rings. The variable resistors are connected into the rotor circuit and can control the rotor currents in order to keep constant power even during variable wind speed conditions.

Wind Turbine Generator Type III: Type III is a variable speed asynchronous wound rotor generator which has a three phase AC field applied to the rotor from an AC to DC to AC converter, the power source for which is the generated voltage. In contrast with Type II, this design adds variable frequency AC excitation (instead of simply resistance) to the rotor circuit. The additional rotor excitation is supplied via slip rings by a current regulated, voltage-source converter, which drives the rotor currents. This rotor-side converter is connected back-to-back with a grid side converter, which exchanges power directly with the grid.

Wind Turbine Generator Type IV: Type IV is an AC generator in which the stator windings are connected to the power system through an AC to DC to AC converter. This turbine type offers a great deal of flexibility in design and operation as the outp.u.t of the rotating machine is sent to the grid through a full-scale back-to-back frequency converter. The turbine is allowed to rotate at its optimal aerodynamic speed.

Photovoltaic Generator (PVG): Refers to the total of all PV strings of a PV power supply system, which are electrically interconnected. A PV string is a circuit in which PV panels are connected in series, generating power in DC voltage and current. An inverter is needed in order to connect the PV to the grid.

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SUMMARY

This document analyses the potential impact on the main line protection functions used in transmission network with high penetration of PEIG.

Currently implemented operating algorithms in protection devices are designed for synchronous generation short circuit contribution. As PEIG short circuit contribution is highly influenced by the control of the power electronic converters developed in positive and negative sequence reference frame, its consequences to protection equipment could be different from traditional synchronous generation short circuit contribution.

The short circuit contribution of Type III and Type IV wind turbines' generators is presented in this document. PVG and HVDC links short circuit contribution is similar to Type IV wind turbines, as they are fully driven by converters directly connected to the network. Therefore, Type IV wind turbines explanation can be applied to PVG and HVDC links.

The potential impact on Line Differential Protection (ANSI code 87L), on Distance Protection (21) and on Directional Ground Overcurrent Protection (67N) in case if high PEIG penetration is analysed, they are the commonly implemented protection functions in the electrical transmission protection schemes.

For the support of the edition of present report, a related questionnaire had been structured by the ENTSO-E Protection Equipment subgroup's (SG) members and distributed to the SG TSOs, in order to gather information about the state of the PEIG penetration in the individual transmission networks and about the actual impact on the currently implemented protection systems.

The document finally gives recommendations for the protection systems in cases of high penetration of PEIG.

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1 INTRODUCTION

Renewable energy is leading an increase of PEIG in the transmission networks. Wind farms or Photovoltaics plants which are usually connected to grid through power electronics, HVDC links and STATCOMS, constitute a challenge for protection engineers as their behaviour differs from synchronous generation in terms of short circuit contribution, which can lead to incorrect operation of protection devices.

This document has been developed by ENTSO-E Protection Equipment SG and it is intended to present the impact of PEIG in protection devices algorithms' behaviour under short circuit conditions in cases of high penetration of PEIG.

A brief introduction to Type III and IV wind turbines and Photovoltaic Generation theory and characteristics is presented in Chapter 2.

Chapter 3 is a short technical explanation of the main line protection functions commonly used in transmission protection schemes.

Chapter 4 analyses and focuses on the short circuit contribution of Type III and Type IV wind turbines.

Chapter 5 analyses the potential impact of short circuit contribution of the Type III and Type IV wind turbines in the performance of the protection functions.

In Chapter 6, the main findings of the related questionnaire are presented. This questionnaire includes main issues about the PEIG in the TSO's networks, about practices applied and about problems detected, when high penetration of PEIG is identified in the network.

Finally, Chapter 7 summarizes the conclusions and recommendations applied to protection systems when high PEIG is present in the network.

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2 PEIG: TYPE III AND TYPE IV WIND TURBINES AND PHOTOVOLTAIC GENERATION

PEIG is usually associated to renewable sources of energy. High percentage of wind power is generated with PEIG and therefore connected to grid through power electronics.

Wind turbines are usually classified in four types for the technology they use for frequency control:

- **Type I** are squirrel-cage induction generators directly connected to grid with a step-up transformer.
- **Type II** are wound rotor induction generators, which control rotor speed with a variable resistor.
- **Type III** turbines are double feed induction generators, whose rotor are connected with a back to back to power grid.
- **Type IV** turbines are synchronous generators whose stator is connected to the grid by a back to back converter.

As Type I and Type II wind turbines do not utilize power electronics, they will not be discussed in this document.

Since Type III and Type IV wind turbine generators have power-electronic-type converters connected directly to the grid, so they will be analysed as they are in the scope of this document.

PVG and HVDC links short circuit contribution is similar to Type IV wind turbines, as they are fully driven by converters directly connected to the network. Therefore, Type IV wind turbines explanation can be applied to PVG and HVDC links.

2.1 DOUBLY FED INDUCTION GENERATOR (WIND TURBINE TYPE III)

In Doubly Fed Induction Generators (DFIG), the stator is directly connected to the grid and the rotor is connected to the grid by back to back converter as show in FIGURE 1.

Using rotor current regulation is possible to control the machine's slip and therefore electromagnetic torque.

This connection allows the generator to operate within a wide range of axis speed, and therefore presents the advantage of the possibility of working at variable speed, giving a good damping against wind speed variations.

Referring to the here below schema

FIGURE 1: Doubly fed induction generator

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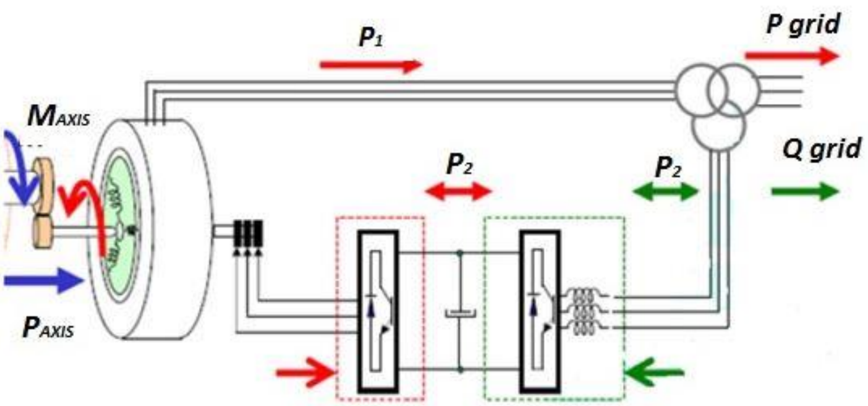


FIGURE 1: Doubly fed induction generator [1]

Following equations are valid:

$$P_{AXIS} = P1 + P2$$

$$P2 = sP1$$

Where:

$$P_{AXIS} = Power\ received\ by\ turbine's\ blades$$

$$P1 = Power\ transmited\ in\ stator's\ side$$

$$P2 = Power\ transmited\ in\ rotor's\ side$$

$$s = machine\ slip, [0,1]\ when\ undersynchronism\ conditions, [-1,0]\ when\ oversynchronism$$

This system allows using small power converters as just a little part of power is transferred between rotor and grid.

During severe short circuits the voltage in the stator decrease and due to magnetic coupling between stator and rotor, high voltages and currents could be induced in the rotor and consequently on the converter.

These overvoltage and overcurrent cannot be withstood by the converter. In order to protect the Back to Back converter, DFIG generators usually implement two protection systems, DC Chopper and Crowbar (see Fig.2).

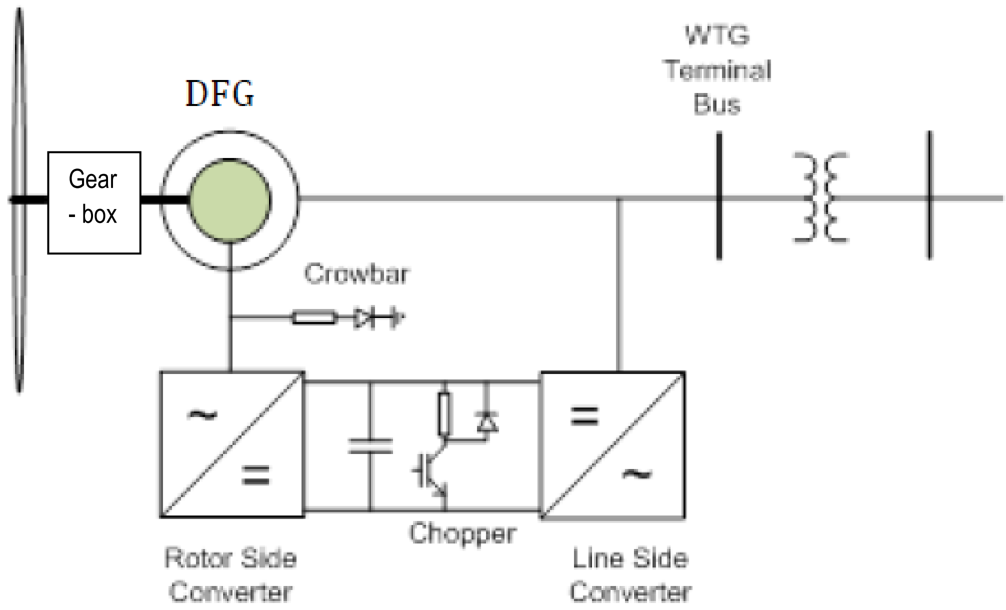
- **DC Chopper:** A barking resistor is installed in parallel to the DC converter capacitor.

In case of severe grid fault, the DC chopper will limit overvoltages in DC link, and these resistances will dissipate the energy that cannot be delivered to the grid due to the short circuit.

- **Crowbar:** Resistors driven by thyristors are installed on rotor side.

During severe grid voltage dips, high overcurrent will be induced in the rotor. In order to prevent this overcurrents flowing through converter, crowbar thyristors are triggered, allowing most of short circuit overcurrent flow through crowbar instead of converter [2].

FIGURE 2 shows how DC-chopper and crowbar are connected in a doubly fed induction machine.



As mentioned in [2] reference, the behaviour of Type III DFIG wind turbines depends on the fault severity. Three cases of severity are known:

- **Very severe faults where the crowbar is applied and not removed:** In this case, the DFIG provides the fault current performance of an induction machine.

- **Faults of insufficient severity to cause crowbar operation:** In this case, the DFIG provide the fault current controlled and the performance is very similar to a Type IV (full converter) wind turbine.

- **Faults of intermediate severity:** The nonlinearities of converter protection operation are critical, resulting in complex behaviours.

Hence DFIG's behaviour is not easy to predict as there are two variables to take in account

FIGURE 2: Protection scheme for back to back converter [2]

Note: WTG=Wind Turbine Generator, DFG= Double Fed Generator

depending on severity of the voltage dip:

- Converter control strategies.

- Converter protection: Crowbar and/or DC Chopper.

2.2 FULL CONVERTER GENERATOR (TYPE IV WIND TURBINE)

Full Converter wind turbine generators are synchronous machines directly connected to the grid by a Back to Back Converter. They need a bigger converter than type III wind turbines as the full power flows through converter.

FIGURE 3 shows how the generator is connected by a back to back converter provided with thyristors technology at rectifier's side and IGBT technology at inverter's side.

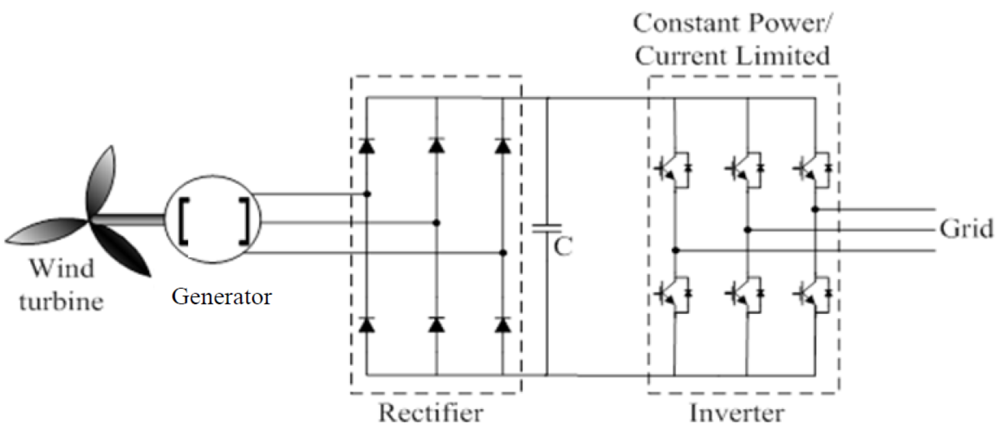


FIGURE 3: Synchronous machine with full converter scheme [2]

This technology presents the following characteristics:

- The flow is independent from the network.
- High power converter.
- Complete speed regulation (100%).
- Torque control independent from the network
- Active and reactive power are fully controlled by the grid side converter of the back to back.
- Converter controllers are really flexible, and they are programmed in order to comply with the requirements of the grid codes
- Under fault conditions, the behaviour of the Type IV wind turbine depends on the converter controls.

2.3 PHOTOVOLTAIC GENERATORS

Photovoltaic panels generate power in DC and therefore, an inverter is needed to connect a photovoltaic power plant to the grid.

In the same way as type IV wind turbines, their performance under short circuit is completely defined by inverter controller, so the same explanations as for the Type IV wind turbines can be assumed in terms of short circuit contribution.

3 PROTECTION FUNCTIONS

As the aim of this document is to analyse the impact of high PEIG on protection functions, this chapter introduce a brief technical description of the main protection function commonly used in transmission networks for detecting short circuits: Line Differential Protection (87L), Distance Protection (21), Directional Earth Fault Protection (67N).

3.1 LINE DIFFERENTIAL PROTECTION (87L)

This function is commonly used as main protection function to detect short circuits in line due to its high reliability.

The principle of Low Impedance Line Differential Protection (87L) is based on 1st Kirchhoff Law, that defines the currents incoming in any electrical node as equal to the currents out coming from the node (see Fig. 4):

$$\sum_{k=1}^{n} \overrightarrow{I_K} = 0$$

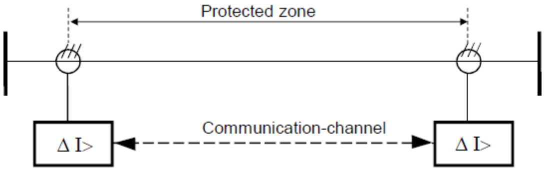


FIGURE 4: Differential protection scheme [3]

As it can be seen in Figure 4, a communication channel is needed in order to exchange current measurements between both ends.

Under normal operation without fault conditions or external fault condition, phasor current measurements in both ends must be equal in magnitude and have 180° angle difference, so there is no differential current measured in the protection devices of the both ends.

In case of fault in the line, short circuit current contribution of both ends will generate a differential current measured from the protection terminals in both ends.

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As shown in FIGURE 5, a typical restraint characteristic is implemented as protection settings'

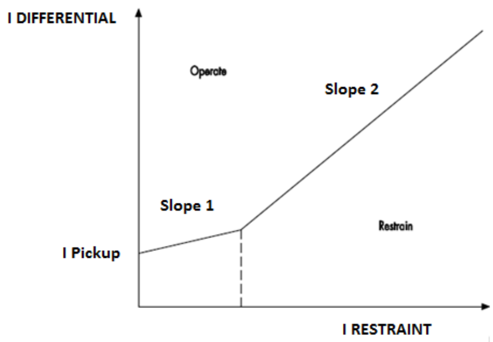

FIGURE 5: Differential restrain slopes [4]

principle in order to ensure stability under external faults and error measurements.

The used setting as restrain magnitude is p.u.t according to the manufacturer instructions and depending on the protected object.

Line differential characteristics follow two slopes:

- **Slope 1:** It is applied for low restrain currents. In this case, errors in magnitude and phase due to the magnetizing current of current transformers are small and slope to restraint use to be small.

- **Slope 2:** It is applied for high restrain currents. Saturation of current transformers in case of external faults could generate high differential currents in protection devices of both ends. In order to avoid unwanted trips 87L trips in case of external faults, a second higher slope is implemented to ensure stability.

3.2 DISTANCE PROTECTION (21)

This function is commonly employed as line protection (either main or back-up) in protection schemes and when no communication system is available, distance protection function is used as main protection function.

The principle of this protection function (see FIGURE 6) is to measure the positive sequence impedance from protection measuring point to the fault. As impedance is proportional to the line length, it can be calculated as the distance to the fault from impedance seen by the protection device.

Fault impendences are compared to certain pre-set limit values ("protection zones' reaches") that are set according to time priority logic. The scheme is based on the principles faults within the primarily protected line that are cleared instantaneously, while faults occurring at remote lines are delayed cleared and only in case the downstream protections failed to instantaneously clear the fault.

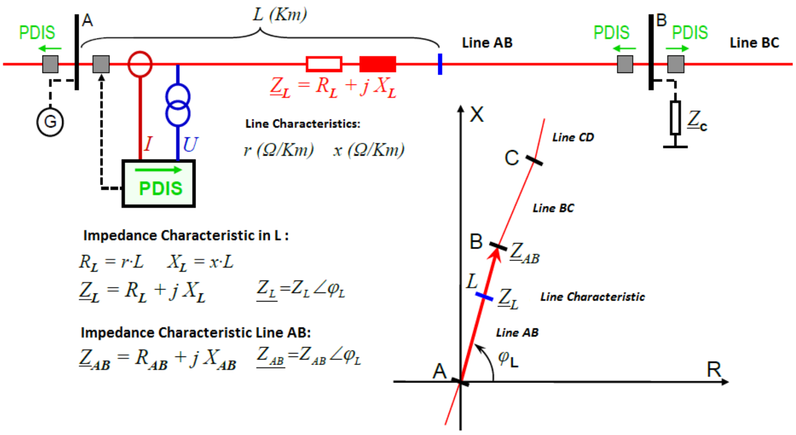

FIGURE 6: Impedance principal measurement of distance protection [3]

Load flow conditions before the fault and fault resistance are the main factors that introduce errors in the impedance measurement [5].

Distance protection function implements complex algorithms in order to detect fault condition, identify faulted phase and calculate impedance, so the way these algorithms are developed in the protection device will have strong impact on the protection behaviour.

Modern distance protection implements two main characteristics for defining zone reach: Mho Characteristic and Quadrilateral Characteristic:

- **Mho Characteristic:** This characteristic is traditionally employed to detect Phase to Phase and Three Phase Faults.

- **Quadrilateral Characteristic:** Due to the better resistive coverage, this characteristic is used for Single Line to Ground Faults and Phase to Phase to Ground Faults. Nowadays, its use is increasing for Phase to Phase Faults and Three Phase Faults in order to get more resistive coverage.

It is important to note that distance protection is not only protecting lines as single elements, but is also backup protection for the power system.

3.3 DIRECTIONAL EARTH FAULT PROTECTION (67N)

Directional Earth Overcurrent provides an additional coverage to phase-ground faults that may not be detected by the main protection functions.

When a fault to ground has a high resistance, it may be out of resistive coverage of the distance protection. In order to detect high resistive faults, Directional Earth Overcurrent (67N) relays have been commonly used in protection schemes.

The operating magnitude of 67N is the Earth Current (3I0). As this 3I0 current can be originated by faults from any phase to ground, in order to obtain directional performance a reference magnitude is needed. This magnitude (in vector plane) is the Polarizing Quantity.

Zero Sequence Voltage (-3V0) is commonly used as Polarizing Quantity, although it is possible to use other magnitudes if the Zero Sequence Voltage is not able to polarize the relay without producing deficiencies or there are magnetic couplings between circuits and then -3V2 amplitude can be used instead. It is possible to use 3I2 as Polarizing Quantity since it may be a more trustable magnitude.

Being provided with mentioned operating and polarizing magnitudes, 67N function defines the fault direction to release the trip decision. Numerical relays have inherited electro mechanic relays' pick-up principles for 67N protection function, so their Forward and Reverse Operating regions are based on the definition of Torque Magnitude.

FIGURE 7 shows 67N characteristic. According to RCA (Relay Characteristic Angle), the Operating regions are defined.

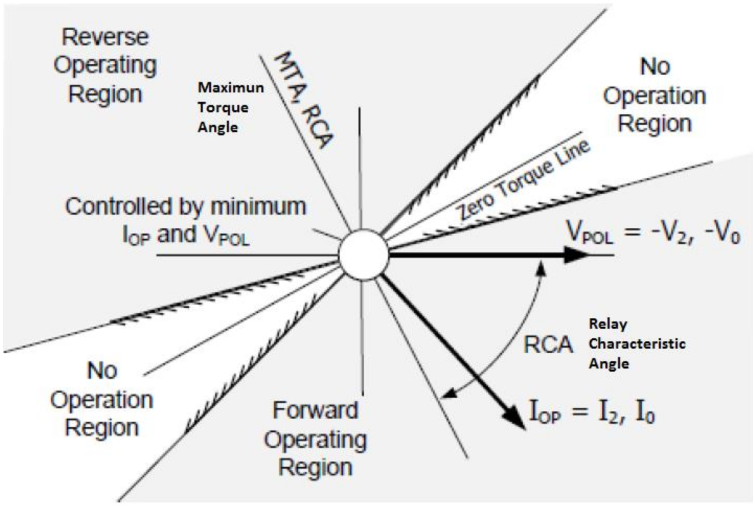

FIGURE 7: Ground directional overcurrent characteristic [4]

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4 PEIG SHORT CIRCUIT CURRENT CONTRIBUTION

As seen in Chapter 2, PEIG has a strong dependence of power electronic control as they are connected to the grid through power electronics converters.

This represents a strong difference against classical synchronous generators, where power electronic converters are mainly used for excitation systems, but never interfaces with the grid.

Another important factor that affects the short circuit current contribution is the speed of the converters, as well as their dynamics. It can be assumed generally for almost every PEIG, that the speed of the control is a critical parameter to take in account in terms of short circuit contribution and therefore it has a strong impact in protection behaviour.

This chapter analyses short circuit current contributions from Type III, Type IV and PV according to the power electronics converters and their connection to the grid.

4.1 DFIG GENERATOR (WIND TURBINE TYPE III)

As mentioned in Chapter 2, the converter protections and their control could have a strong impact in short circuit contribution for DFIG generators.

4.1.1 CONVERTER PROTECTIONS

Crowbar is connected to protect the rotor and the converter from overcurrents produced when severe voltage dips occur [2].

In case of severe voltage dip, the crowbar will act and bypass the current that could damage the rotor and the converter.

When crowbar is connected, the behaviour of the DFIG is similar to induction generator [6].

When the crowbar is not connected the rotor will continue to be powered during fault and the rotor voltage is adjusted by excitation system [7].

As the activation of the crowbar depends on the severity of the voltage dip, there could be cases where crowbar is activated and deactivated several times during the voltage dip.

4.1.2 CONVERTER CONTROL

The control strategies will have strong impact on the currents injected during short circuit and therefore in the behaviour of protection algorithms.

Several strategies are taken not just to fulfil Fault Ride Through requirements but also to provide support to the grid when voltage dips appear.

Under unbalanced grid condition, DFIG control is affected by double frequency oscillating magnitudes. One of the strategies that can be applied to the negative sequence controllers of the converter is to minimize these oscillations in the controls through the decoupling of positive and negative sequence components [8].

FIGURE 8 shows an example of short circuit contribution from DFIG under 3Ph Fault with voltage dip of 20% p.u. on step up transformer MV [2]. As it can be observed, there is a transient period of 50ms, where short circuit peak current is around 3p.u., and crowbar is activated in order to protect converter from this overcurrent. After this transient period of 50ms, DFIG Control acts in order to supply balanced currents up to 1.2 p.u.

As seen in FIGURE 8 the waveform currents in this transient period are difficult to predict as it depends on the crowbar activation and differs from synchronous generator short circuit contribution

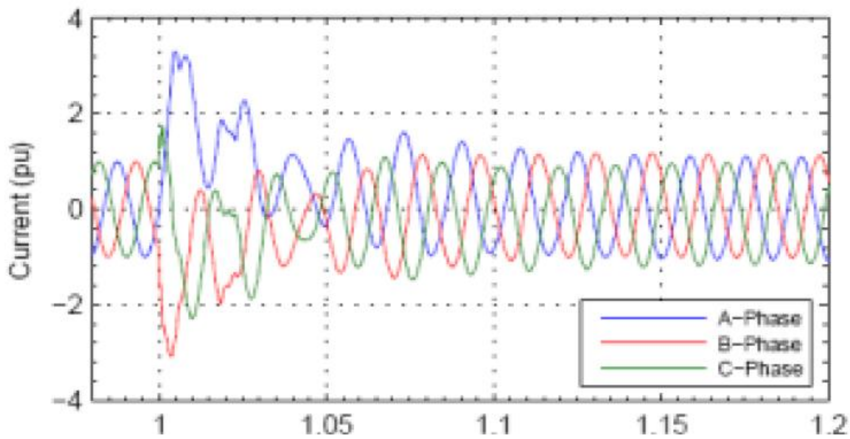

FIGURE 8: 3Ph fault with voltage dip of 0,2 p.u. on step up transformer [2]

for 3Ph faults.

4.2 FULL CONVERTER GENERATOR (WIND TURBINE TYPE IV AND PHOTOVOLTAIC GENERATOR)

The stator of the Full Converter generator is connected directly to the grid through back to back converter. It means that converter control will determine completely the short circuit current contribution.

The Grid Codes specify the requirements to PEIG in case of voltage dips, establishing the time that a PEIG has to be connected to the grid and the reactive power supply according to the severity of the voltage dip in order to improve voltage stability.

Nowadays most of the European Grid Codes do not require negative sequence injection in case of unbalanced faults and they usually implement only positive sequence injection for any type of fault, then short circuit current contribution from Full Converter will be balanced in that case.

Converters' controls are flexible and can implement the negative sequence injection in case of unbalanced faults if required.

The sequence networks of the system with Full Converter implementing negative sequence injection can be expressed in terms of positive and negative current sources (FIGURE 9):

The control strategy implemented in the converter, both in the positive and in the negative sequence reference frames, will define the short circuit current contribution for Full Converter generators. FIGURE 9 shows in case of unbalanced faults, negative sequence current will be measured in PCC only for the cases where[1] f Negative Sequence Injection is implemented in the converter control.

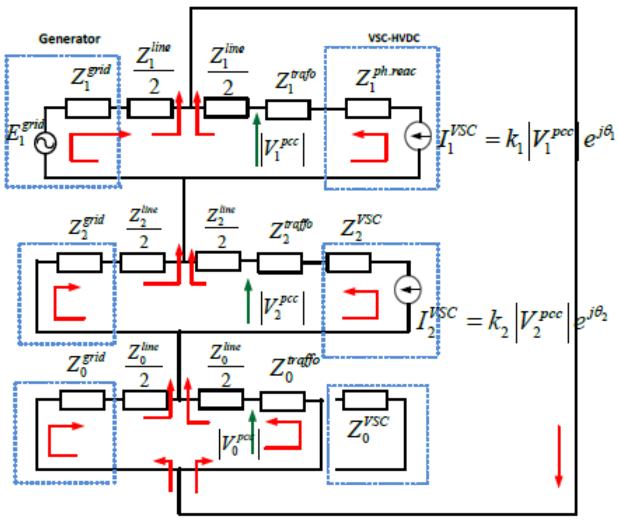

FIGURE 9: Full converter sequence networks for 1PH-G fault with injection of negative sequence [8]

In case of a transmission system with neutral directly earthed, the short circuit contribution in terms of current sequence components of Full Converter wind turbine generator or PV plant in "Point of Common Coupling" (PCC), can be resumed as shown in TABLE 1.

[1] Usually, the injection of negative sequence current is performed or it is potentially requested proportionally to the negative sequence voltage in order to differentiate between balanced and unbalanced grid fault conditions. Moreover, special attention shall be given on the converter overcurrent capacity as the combined injection of positive and negative sequence current component needs to respect the overcurrent capacity of the inverters.

TYPE OF FAULT	I1	I2	I0
1Ph-G	YES	ONLY IF THE INJECTION OF NEGATIVE SEQUENCE CURRENT IS APPLIED (THE K2 VALUE IN FIGURE 9 IS NOT ZERO)[2]	YES (CURRENT CONTRIBUTION FROM NEUTRAL TRANSFORMER STAR EARTHING)
2Ph	YES	ONLY IF IMPLEMENTED IN CONTROL	NO
2Ph-G	YES	ONLY IF IMPLEMENTED IN CONTROL	YES (CURRENT CONTRIBUTION FROM NEUTRAL TRANSFORMER STAR EARTHING)
3Ph	YES	NO	NO

TABLE 1: Full converter short circuit current sequence components

As it was mentioned, the speed of the control is a factor that affects directly to the short circuit contribution. Sometimes the speed of the control depends on the stiffness of the grid connection points, or in other words, the short circuit ratio. When PEiG are connected to weak grids (SCR below 4), vendors tend to make the control slow, or reduce the control bandwidth in order to avoid control interactions. This would mean slow injection of reactive currents during the faults.

It can be assumed that Full Converter control needs about 20-60ms in order to supply balanced currents up to 1.1/1.2 p.u. (thermal limit of power electronic devices) under any type of fault.

In this transient period of 40-60ms, currents waveforms are very difficult to predict, resulting current waveforms not purely sine. This represents a great different from classical synchronous generation short circuit contribution.

5 POTENTIAL IMPACT ON MAIN PROTECTION FUNCTIONS OF TRANSMISSION LINES

As described in Chapter 4, short circuit contribution from Type III, Type IV, and PV generators has a great dependence of control implemented in the power electronics converters.

[2] For all full converter interfaced PEBG and MMC-HVDC stations, there is default implementation of negative sequence current from vendors. The vendors implement negative sequence suppression control and control the negative sequence current flow to zero during unbalanced faults in order to protect the IGBTs for high uncontrolled unbalanced currents.

It is the injection of the negative sequence current proportionally to the negative sequence voltage at the PCC that would enable negative sequence current flow. On the other hand, negative sequence current suppression control (K2=0) results in zero negative sequence current.

Nowadays the algorithms implemented in protection relays devices are based on short circuit current contribution from synchronous generator, and the question that arises is if these algorithms are still valid for networks with high penetration or PEIG.

In addition, as already was discussed in the Figure 9, the suppression of the negative sequence current from PEIG during 2Ph faults, results in only positive sequence currents which are much lower to Synchronous Generators.

This chapter analyses the potential impact on the principal protection functions used on transmission systems.

5.1 Distance Protection (21)

As mentioned in Chapter 3, distance protections are based in complex algorithms which describe the relay performance under short circuit conditions.

Each manufacturer implements its own algorithms, and therefore, based on the principles of these algorithms the performance of the protections will be defined.

5.1.1 Impedance Measurement

5.1.1.1 DFIG Generator:

As the short circuit contribution is strongly determined by protection of the back to back converter (mainly determined by crowbar action) and control strategy, it can be deduced that impedance measurement could appear in the following situations:

- In cases where crowbar is activated and not removed during the voltage dip, short circuit contribution is similar to induction generator and impedance measurement will not be affected.
- When voltage dip is not so severe, crowbar is not activated and short circuit current contribution is driven by the converter. During the transient state in which converter control is acting to supply the limit current, impedance measurement can be affected due to the current waveforms of these transient state. After this transient state, DFIG generator is supplying currents according to the control implemented in the converter control, and impedance measurement will be probably accurate.
- Multiple switching of the crowbar has a great impact in short circuit contribution, obtaining current waveforms not predictable and not purely sine. Under these conditions, calculating the current and voltage phasors will be difficult for protection devices due to current and voltage waveforms.

Therefore, the conventional impedance measurement can be strongly affected during multiple crowbar switching.

5.1.1.2 FULL CONVERTER:

As mentioned in Chapter 4, short circuit current contribution of Full Converter generators is fully driven by the converters.

After fault inception, there is a transient state (40-60 ms duration) where currents are not predictable.

During the action of the control of the converters in this transient state, current waveforms are not purely sinusoidal, and can lead to errors in impedance measurement.

After this transient state, converter control is supplying the current according to the strategy implemented in the control, reaching the current limits imposed by the control strategy. Impedance measurement in this steady state will probably be accurate and impedance measurement errors are not expected.

5.1.2 FAULTY PHASE SELECTION:

5.1.2.1 DFIG GENERATOR:

As explained in previous Chapters, the crowbar action is affecting the short circuit current contribution from DFIG generators.

Algorithms based on superimposed quantities (and therefore, not based on phasor measurement) can be affected due to the current waveforms in case of multiple switching of the crowbar. Then, errors in Faulty Phase Selection could be expected in case of implement superimposed quantities algorithms.

As DFIG generators under unbalanced faults injects Negative Sequence currents, algorithms based on phasor angle difference between Negative Sequence Current (I2) and Zero Sequence Current (3I0) are expected to present good behaviour even in case of multiple switching of the crowbar.

5.1.2.2 FULL CONVERTER:

The transient state after fault inception could affect algorithms based on superimposed quantities due to the current waveforms in this period. Then, errors in Faulty Phase Selection could be expected in case of implement superimposed quantities algorithms.

As Full Converter generators under unbalanced faults injects Negative Sequence currents if it’s implemented in the control strategy, it can be deduced that performance of algorithms based on phasor angle difference between Negative Sequence Current (I2) and Zero Sequence Current (3I0) will depend on the control strategy:

- **Suppression of Negative Sequence Strategy:** In this case, performance of algorithms based on phasor angle difference between Negative Sequence Current (I2) and Zero Sequence Current (I0) are expected to be affected under unbalanced faults.

- **Injection of Negative Sequence Strategy:** In this case, performance of algorithms based on phasor angle difference between Negative Sequence Current (I2) and Zero Sequence Current (I0) are expected to work properly under unbalanced faults.

5.2 LINE DIFFERENTIAL PROTECTION (87L)

5.2.1.1 DFIG GENERATOR:

As this function is two ended protection or "single object-oriented protection", short circuit currents under fault condition could be enough to pick-up the function, regardless of the kind of generation connected to the end buses.

It could be guessed that as long as you have a strong end with synchronous generation, pick-up level will be asserted for the weak end too (inter-trip feature).

This function is expected to work properly in cases of high penetration of PEIG for DFIG Generator.

5.2.1.2 FULL CONVERTER:

In the same way as DFIG generators, Line Differential Protection (87L) in case of Full Converter generation is expected to work properly.

5.3 DIRECTIONAL EARTH OVERCURRENT (67N)

5.3.1 PICK-UP CURRENT LEVEL

5.3.1.1 DFIG GENERATOR:

In cases where polarization magnitude is Zero Sequence Voltage (-3V0) and operation quantity is the level of fault current (3I0) flowing from neutral star of transformer connected to the ground could be sufficient to pick up the Directional Earth Fault (67N) and no issues are expected to pick up 67N.

In cases where polarization magnitude is Negative Sequence Voltage (-3V2) and operation quantity is Negative Sequence Current (3I2), as DFIG generator injects Negative Sequence current in case of unbalanced faults, no issues are expected to pick up 67N.

5.3.1.2 FULL CONVERTER:

In cases where polarization magnitude is Zero Sequence Voltage (-3V0) and operation quantity is the level of fault current (3I0) flowing from neutral star of transformer connected to the ground could be sufficient to pick up the Directional Earth Fault (67N), and no issues are expected to pick up 67N.

If polarization magnitude is Negative Sequence Voltage (-3V2) and operation magnitude is the Negative Sequence current (3I2), as the Negative Sequence current injection depends on the control strategy implemented in the Full Converter control, it can be deduced:

- **Suppression of Negative Sequence Strategy:** In this case, the lack of Negative Sequence current will not provide operation magnitude and issues with pick up level of 67N are expected.
- **Injection of Negative Sequence Strategy:** In this case, there is injection of Negative Sequence current, and depending on the current injected and the protection settings, no issues are expected to pick up 67N.

5.3.2 DIRECTIONALITY

5.3.2.1 DFIG GENERATOR:

In cases where polarization magnitude is Zero Sequence Voltage (-3V0) and operation magnitude is the fault current (3I0), directionality issues are not expected.

If polarization magnitude is Negative Sequence Voltage (-3V2) and operation magnitude is the Negative Sequence current (3I2), as DFIG generator injects Negative Sequence Current, directionality issues are not expected.

5.3.2.2 FULL CONVERTER:

In cases where polarization magnitude is Zero Sequence Voltage (-3V0) and operation magnitude is the fault current (3I0), directionality issues are not expected.

If polarization magnitude is Negative Sequence Voltage (-3V2) and operation magnitude is the Negative Sequence current (3I2), as Negative Sequence current injection depends on the control strategy implemented in the Full Converter control, it can be deduced:

- **Suppression of Negative Sequence Strategy:** In this case, the lack of Negative Sequence current will not provide operation magnitude for the Directionality of Directional Earth Fault (67N), and it could lead to wrong polarization of 67N.
- **Injection of Negative Sequence Strategy:** In this case, there is injection of Negative Sequence current, and depending on the current injected and the protection settings, polarization issues are not expected for 67N.

5.4 MEASURES SUITABLE FOR LARGE PEIG- ENERGY STORAGE PARKS

For cases with extremely low available current infeed from the side of the generating park during short circuits the appropriate protection functions that are proposed are the Voltage and the Frequency based ones.

Using these functions, it's possible to the correctly detect the symmetrical faults (e.g. using Minimum Direct Voltage [code 27]) or asymmetrical faults (e.g. using Maximum Negative Sequence Voltage [59V2] and/or Neutral Voltage Displacement [59N]).

These functions are normally integrated within protections frequency based that are usually used to separate PEIG area in case of unwanted asynchronous condition ("Unintentional Islanding' case).

The most commonly used frequency-based functions are:

- Under/over voltage and under/over frequency
- Voltage Shift (Phase Jump) Detection
- Switching Frequency

The problem using these functions is the restricted capabilities of time selectivity/ stepped coordination

In the following figure, it is presented an example of an application of grid connection (HV) for 12 MVA storage plant (Energy Storage System) with the proposed settings using Voltage/Frequency based protection scheme.

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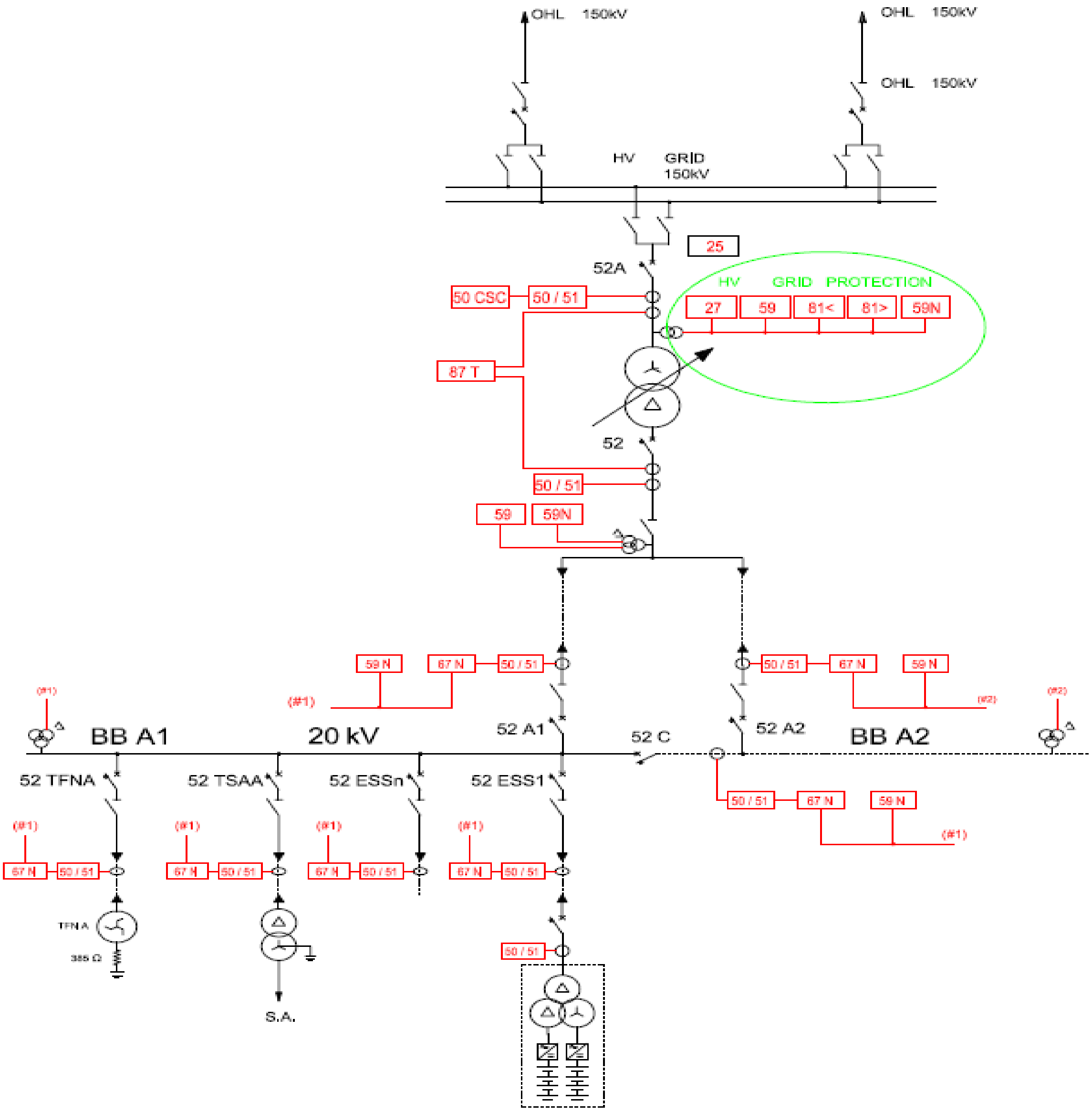

Settings Table					
Area	Protection Function	Aim	Setting		Command
			Pickup	delay	
HV Grid	27	Multi-phase fault HV Grid	80 %Vn	2,00 s	Trip Breaker 52A
	59 I° step	Over-Voltage HV Grid	115 %Vn	1,00 s	Trip Breaker 52A
	59 II° Step	Over-Voltage HV Grid	130 %Vn	0,10 s	Trip Breaker 52A
	59N	Phase-Ground fault HV Grid	20 %Vres Max	2,00 s	Trip Breaker 52A
	<81 I° Step	Low- Frequency HV Grid	0,95 Fn	4,00 s	Trip Breaker 52A
	<81 II° Step	Low- Frequency HV Grid	0,93 Fn	0,10 s	Trip Breaker 52A
	>81 I° Step	Over- Frequency HV Grid	1,03 Fn	1,00 s	Trip Breaker 52A
	>81 II° Step	Over- Frequency HV Grid	1,05 Fn	0,10 s	Trip Breaker 52A

FIGURE 10: Single line protection diagram of voltage / frequency protection principles with settings proposal (Source: Terna)

6 POTENTIAL IMPACT IN OTHER PROTECTION FUNCTIONS

As the scope of this document is related to the short circuit contribution of PEIG and the impact on short circuit protection functions, other operational protection functions like Under Voltage Load Shedding (UVLS) and Under Frequency Load Shedding (UFLS) have not been included. Nevertheless, for integrity purposes the relation of these applications with high penetration of PEIG are briefly outlined below.

UVLS and UFLS are considered as System Integrity Protection Schemes as they protect the integrity of the system, and they prevent from unstable conditions of the network.

These protection functions may be also affected by high penetration of PEIG.

Voltage support by PEIG during voltage dips are defined in Grid Codes (Fault Ride Through Capabilities), and the contribution to Voltage Stability is under study for different penetration of PEIG. Therefore, the control strategy of the PEIG has strong impact on network Voltage Stability, and then, in UVLS performance.

Inertia is a concept related to rotating mass of the rotor of synchronous generators. Type IV and PV plants are connected directly to the network through power electronic converters, so physical inertia does not exist for these PEIG, and then, an emulation of inertia might be implemented in order to have similar behaviour as synchronous generation.

Synthetic inertia on PEBG is under study for different penetration of PEIG, and as well as the capability of converter control to fix the system Inertia. In the same way as UVLS, it may have strong impact on performance and managing of UFLS.

7 TSO’s QUESTIONNAIRE

A questionnaire was completed by TSO’s within ENTSO-E Protection Equipment subgroup during March – April 2017, in order to gather information about PEIG penetration in the network, software and models used in case of PEIG, problems faced and special protection schemes implemented when high penetration of PEIG.

The TABLE 2 shows the members of ENTSO-E SG Protection Equipment that filled in the questionnaire.

No	TSO	COUNTRY
1	CEPS	CZECH REPUBLIC
2	ELES	REPUBLIC OF SLOVENIA
3	ELIA	BELGIUM
4	EMS	SERBIA
5	ENERGINET	DENMARK
6	ESO	BULGARIA
7	IPTO	GREECE
8	LITGRID	LITHUANIA
9	MAVIR	HUNGARY
10	NG	UNITED KINGDOM
11	PSE	POLAND
12	REE	SPAIN
13	REN	PORTUGAL
14	RTE	FRANCE
15	SEPS	SLOVAKIA
16	TERNA	ITALY
17	TRANSELECTRICA	ROMANIA

TABLE 2: TSOs responded to questionnaire

7.1 TECHNOLOGIES INSTALLED

- **[Question] Q 1.1. Which Types of PEIG do you have in your network?**

As most of TSOs declare, Wind Turbines are the main installed in their networks, but also Solar PVs are installed to a lesser degree. As it is possible to see from Q1.1, all the participants who answered this question placed more importance on wind generation than other technologies.

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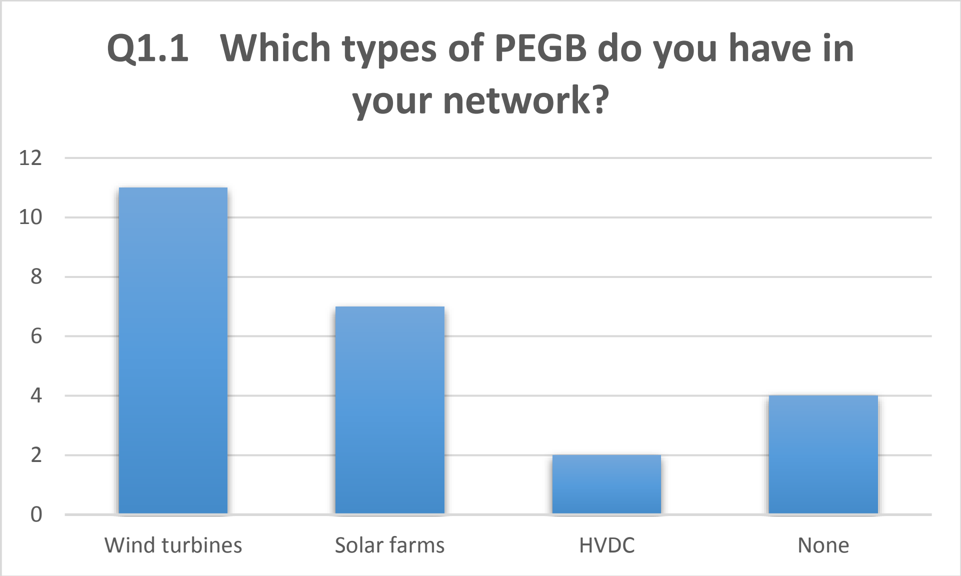


FIGURE 10: Q1.1 Which types of PEIG do you have in your network?

- **Q1.2. Which Types of Wind Turbines generators are installed in your network wind farm power plants?**

This question shows the types of Wind Turbines installed in TSOs' network. Type III (DFIG) and Type IV (FC) are mainly wind turbine generators installed.

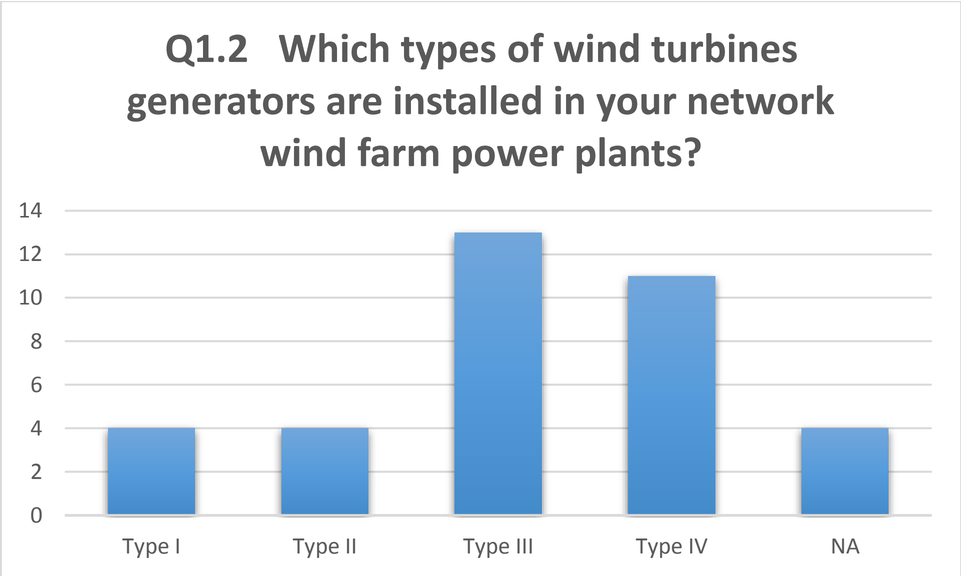


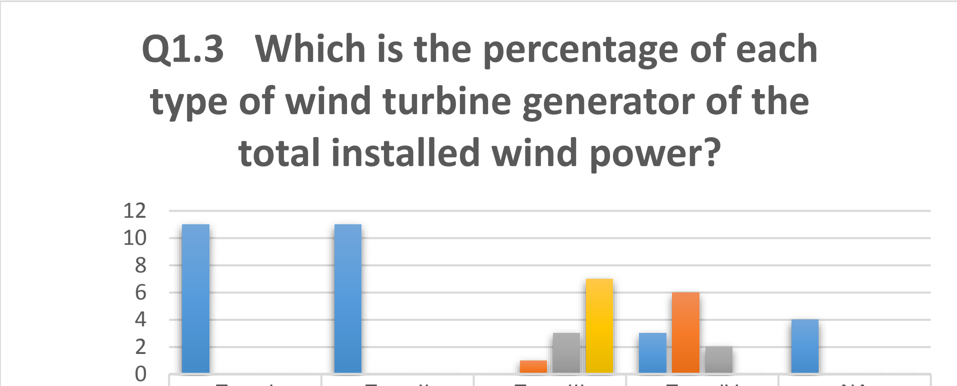
FIGURE 11: Q1.2 Which types of wind turbines generators are installed in your network wind farm power plants?

- **Q1.3 Which is the percentage of each type of wind turbine generator of the total installed wind power?**

It is remarkable that 7 TSOs declare that at least 70 % of their wind generation installed is type III turbines and other 3 estimate that this technology represents 40-70 % of their wind generation.

The second technology by percentage declared by each participant is type IV turbines as 6 TSOs estimate that between 40-70 % of their installed power correspond to this technology.

Type I and type II turbines do not represent a significant weight in wind generation.



	Type I	Type II	Type III	Type IV	NA
<15 %	11	11	0	3	4
15 - 40 %	0	0	1	6	0
40 -70 %	0	0	3	2	0
>70 %	0	0	7	0	0

FIGURE 12: Q1.3 which is the percentage of each type of wind turbine generator of the total installed wind power?

- **Q1.4 How many HVDC Links do you have in your network?**

50% of participants declare that not having any HVDC Links but 4 HVDC links are planned.

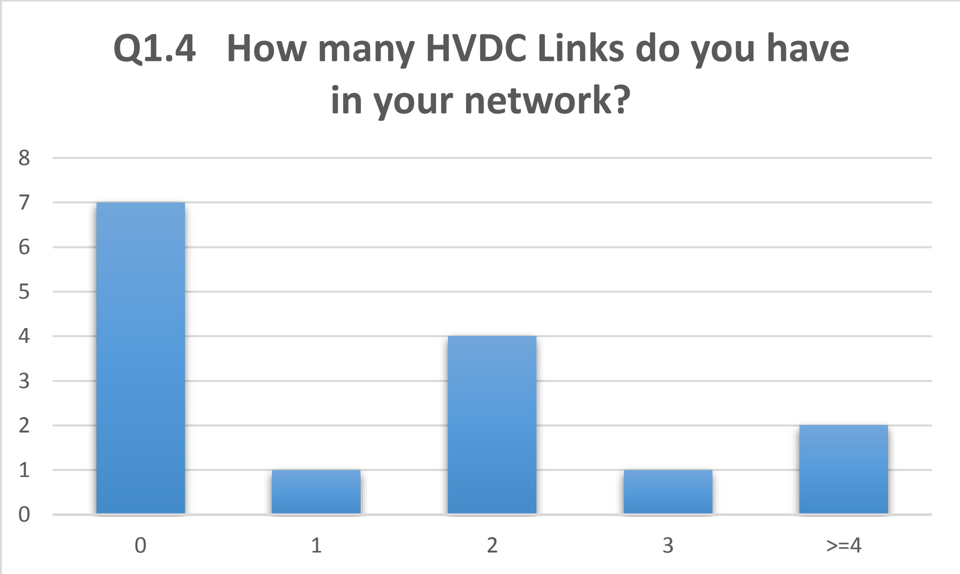


FIGURE 13: Q1.4 How many HVDC Links do you have in your network?

7.2 Tools Employed to PEIG Studies

- **Q1.5 Which magnitude/criteria do you use for considering a network area has a high penetration of PEIG?**

Just one TSO has defined a ratio in order to know if PEIG penetration in a node is high or low.

This TSO consider the PEIG power installed relative to consumed power in that area. A high rate of PEIG power over power consumption indicates a high PEIG penetration. They also use as additional criteria the power flow through transformers installed in the network area considered.

- **Q1.6 Do you have network areas with high penetration of power electronics-based generation/HVDC links?**

At this moment, only four TSOs have areas with a high penetration of PEIG and/or HVDC links.

Some of the participants answer that most of their PEIG is connected to distribution network so it is difficult to consider zones with high penetration of PEIGs.

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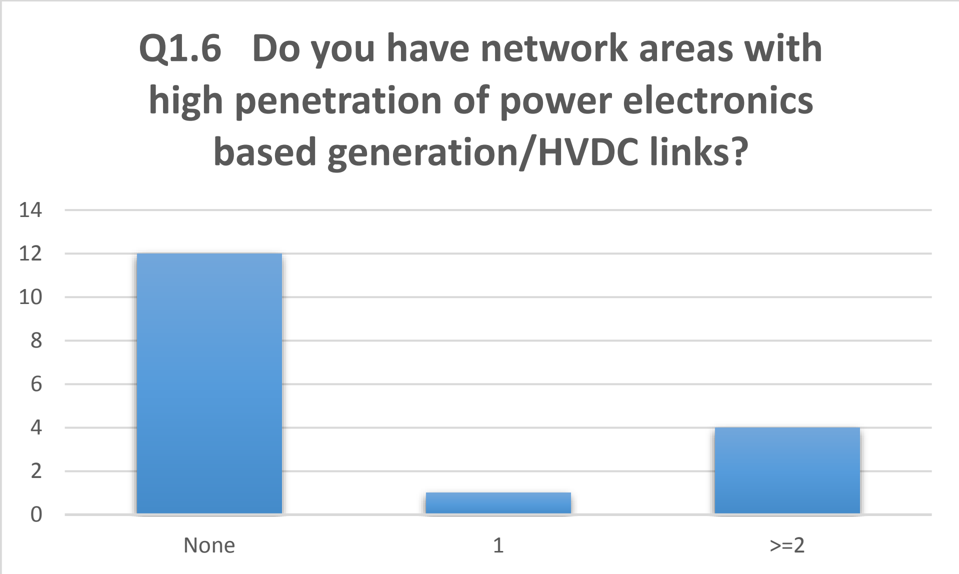

FIGURE 14: Q1.6 Do you have network areas with high penetration of power electronics-based generation/HVDC links?

- **Q.1.7. Which software do you use for short circuit calculation?**

According to the responses received the statistical set-up of the used S/W is shown at Figure 15.

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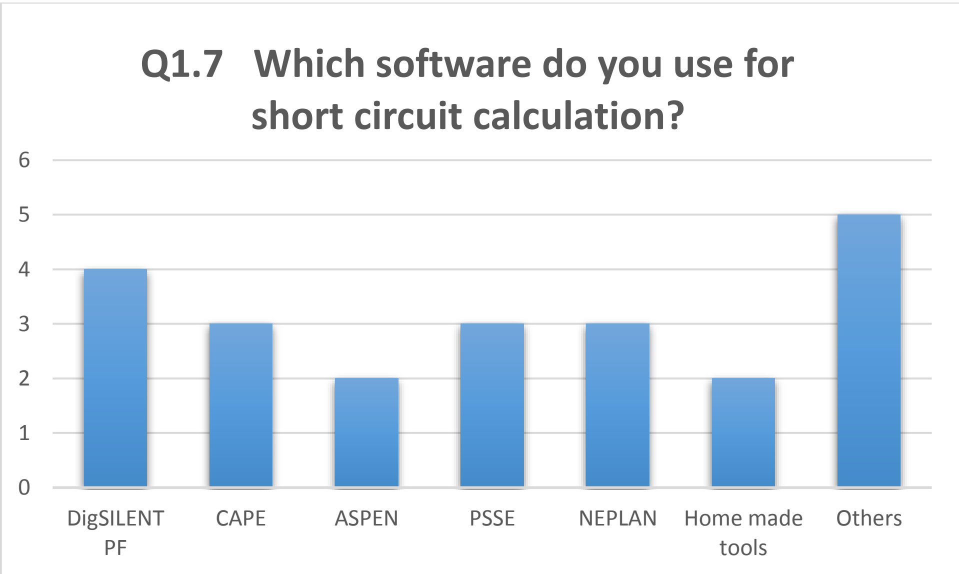


FIGURE 15: Q1.7 which software do you use for short circuit calculation?

- **Q1.8 Does this software implement reliable model for power electronic based generation?**

The statistical set-up of the responses received concerning the satisfaction of the used S/W is shown at Figure 16.

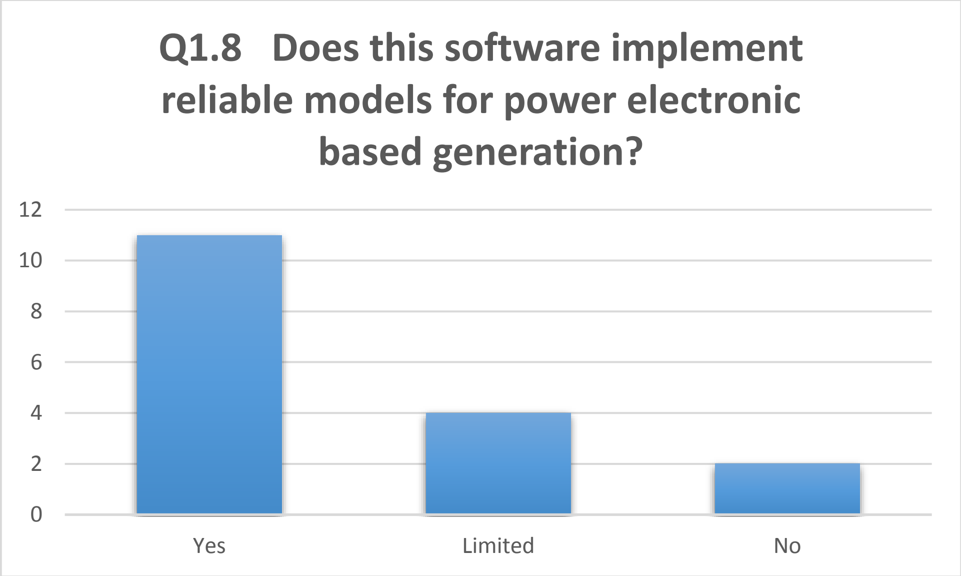


FIGURE 16: Q1.8 Does this software implement reliable models for power electronic based generation?

7.3 Problems Found and Solutions Applied

- **Q3.1 Do you use special protection schemes use in transmission lines with high penetration level of PEIG/HVDC Links different from the usual protection schemes? Describe these protection schemes.**

Five TSOs apply special protection schemes in case of high penetration of PEIG. Basically, they implement double Line Differential Protection 87L or Line Differential protection 87L and Distance protection 21 with communication scheme.

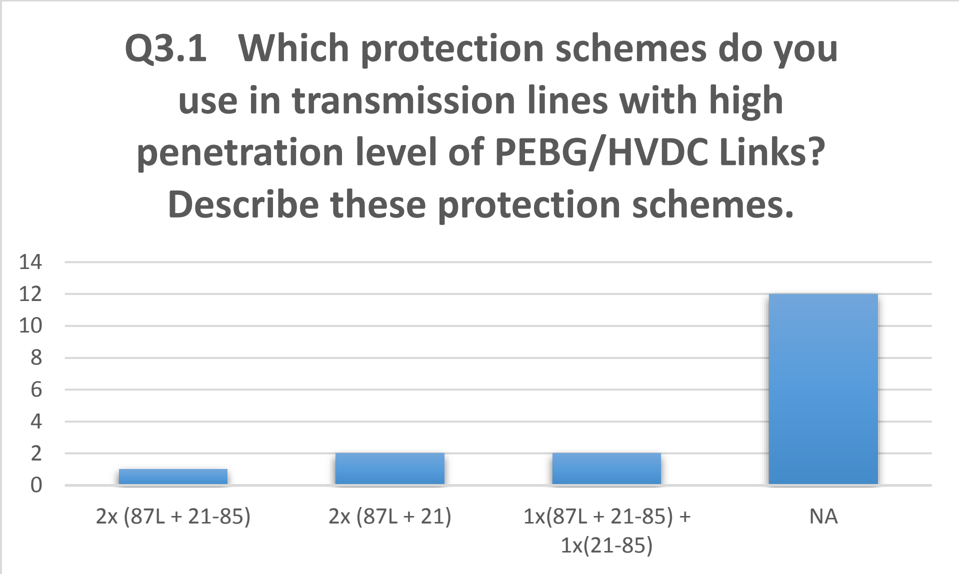


FIGURE 17: Q3.1 Which protection schemes do you use in transmission lines with high penetration level of PEIG/HVDC Links? Describe these protection schemes.

- **Q3.2 Are you facing problems with bad operation of protection devices when you have high penetration level of PEIG or HVDC links?**

  Q3.3 Can you describe the causes of the bad operation of protection devices (E.g: Under/Over reach due to wrong reactance/resistance calculation, wrong phase selection, wrong directionality declaration, tripping delays…)

  Q3.4 Can you provide analysis reports from these incidents? In affirmative case, please attach the report.

Q3.2 and Q3.3 show that up to now there has not been any bad operation of protection devices. At the moment the penetration of PEIG is low so problems related to these technologies have not been raised as any of Q3.2 answers show any problems. Q3.3 and Q3.4 about causes and investigation reports of the incidents have been filled in.

- **Q3.5 Do you have special criteria for grading Distance Protection (21) and set up Line Differential Protection (87L) and Directional Earth Overcurrent (67N) when you have high penetration level of PEIG or HVDC links? In affirmative case, please describe these criteria.**

  Q3.6 Do you have special criteria for any other protections function when you have high penetration level of PEIG or HVDC links? In affirmative case, please describe this criterion.

The responses to these questions were uniform, any of the questioned TSOs have no special criteria for the mentioned functions and they are implementing their usual criteria for line protection. The only remarkable answer is one TSO that is implementing an overvoltage function (ANSI code 59) in substations where a HVDC is connected.

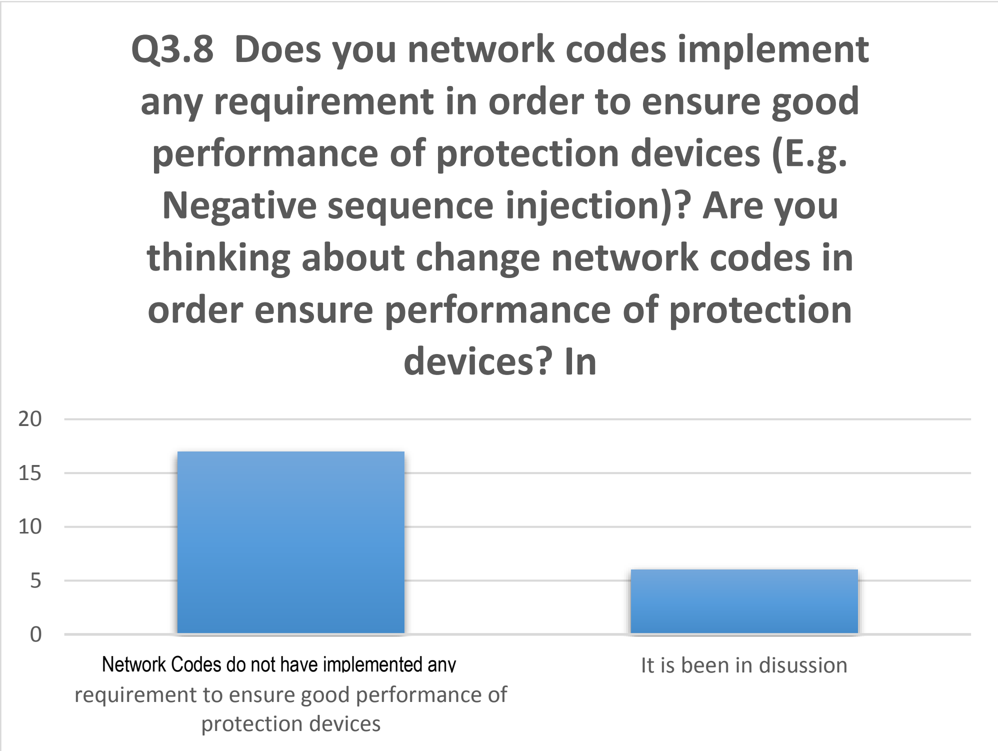
- **Q3.7 Are you implementing solutions based on new technologies as Travelling Waves? In affirmative case, please describe it.**

Just one TSO has answered affirmatively to Q3.7, having a fault locator on one of their 400 kV OHL.

- **Q3.8 Does you network codes implement any requirement in order to ensure good performance of protection devices (E.g. Negative sequence injection)? Are you thinking about change network codes in order ensure performance of protection devices? In affirmative case, please, describe it.**

All the TSO's answered that nowadays there is no requirement about Negative Sequence Current Injection implemented in Wind Turbine Generation and PV generators.

Six TSO's answered that it's under discussion the implementation in the Grid Codes the requirement of Negative Sequence Current Injection implemented in Wind Turbines Generators.



8 CONCLUSIONS

As seen in this document, a high penetration of PEIG could have important impact in transmission protection function behaviour.

As PEIG short circuit contribution is different from classical synchronous generation, protection algorithms implemented in protection devices could present bad performance under high penetration of PEIG as they are designed for detecting short circuit in networks with synchronous generators.

Although nowadays the penetration level of PEIG is not leading to bad performance of protection devices, it's possible that with higher penetration this bad performance arises.

Distance protection (21) performance could be the most affected function in case of high penetration of PEIG. The level of affection depends on the type of PEIG, their control and the algorithms implemented in Distance protection (21).

As this function is not only used to protect lines as single elements but it is also used as the main backup protection for the transmission system, this could represent an important risk since bad operation of this function could be expected in cases of high penetration of PEIG.

Due to its differential principle, Line Differential Protection (87L) is considered to work properly under high penetration of PEIG since current contribution from two ends of the line could be sufficient to pick up 87L, even in scenarios with PEIG short circuit contribution from both ends of the line.

Directional Earth Fault Protection (67N) performance could be affected as well in case of high penetration of PEIG. However, as this function is a backup protection to detect resistive ground faults and it's not used for instantaneous tripping, in cases with sufficient ground fault current (3I0) to pick up and polarize 67N, good performance of this function is expected.

Since Line Differential 87L protection seems to be the more reliable protection function for detecting short circuits (Phase and Ground Faults) in cases with high penetration of PEIG, protection schemes with double Line Differential protection 87L with independent and redundant communication systems could be necessary in cases of high penetration of PEIG.

Directional Earth Fault (67N) could be implemented in the protection scheme as backup protection for ground fault detection.

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