The Massive InteGRATion of power Electronic devices

Enabling the energy transition by providing solutions for the technological challenges
The MIGRATE project was funded by the Horizon 2020 programme for research and innovation. Coordinated by TenneT, the project gathered 12 Transmission System operators together with 13 other partners bringing research and innovation expertise as well as industrial background.

**Key Figures**

- **4 years** project
- **25 partners**
- **17.8 M€ budget**
- completed in dec. 2019
The MIGRATE project explored these different questions by:

- Investigating the different dimensions of power system stability, how it can be measured, monitored and forecasted;
- From a future perspective: exploring how a power system with 100% power electronics could be operated, and what would be a transitional pathway to that point;
- Developing and testing new tools to ensure power system protection, automated control and power quality in power systems with high PE penetration.

Renewable energies challenge today’s power system

A cleaner energy system is one of the key priorities of the European Union for the next years and even decades. Among other objectives, the European Commission targets at least a 32% share of renewable energy consumption by 2030.

In this energy transition, renewable electricity — mainly generated from wind and solar resources — has a major role to play. But its massive integration into our power system is a real challenge that can be summarized in two questions:

- How much of renewables can today’s electricity network cope with?
- And what should tomorrow’s network look like to integrate more — or even exclusively — renewables?

From its origin, our power system has been designed around large rotating machines — synchronous machines — that generate electricity from conventional energy sources and feed it into our electrical network. Electricity supply is like a balancing game in which all players rely on the conventional system behavior constituted by synchronous generators. The massive employment of renewable energy sources (RES) acts like a game changer and leads to rethinking the way we manage network stability.

The inertia of today’s power system contributes every day to maintain the system’s stability. The massive deployment of renewable electricity sources interfaced to the grid by power converters displaces synchronous generation and therefore reduces the total system inertia and requires innovative solutions in the way power system security of supply is managed.

Indeed, RES like photovoltaics or wind turbines are connected to the network via power electronic (PE) interfaces. Seen from the network, there is no synchronous generator with its conventional behavior anymore but a power electronic converter whose behavior largely depends on the algorithms embedded in its control circuitry. When the RES share increases significantly in a power system, the behavior of the PE converters will dominate the overall power system characteristics. In addition, other PE devices are spreading on the network, such as high-voltage direct current (HVDC) systems, flexible AC transmission systems (FACTS), and PE connected loads from industrial sites.

We, in TenneT, already identified new challenges of a converter dominated power system in the past within our offshore grid connection systems in the German North Sea. Hence, we were aware that further research and investigations are necessary in order to be prepared to operate a power system with increasing share of power electronics and less inertia.

Hannes Munzel
MIGRATE Project Coordinator

This change raises the following questions:

- The inertia in the power system will decrease consequently leading to a ‘faster’ system response. Will the PE converter controls — initially designed for ‘slow’ conventional power systems — be able to cope with this?
- How can the protection schemes — i.e. the detection and isolation of faults — be adapted to the new power system characteristics, e.g. very low fault currents?
- What is the impact of massively integrated PE units on power quality (voltage, frequency, waveform), and how can this impact be mitigated?

Illustration of the main concept of the MIGRATE project. The abscissa represents the PE penetration where L1 and L2 are asymptotes where severe stability problems could be met within the existing framework. The ordinate axis represents a generic stability index.
MIGRATE contributions in brief

There is a technically feasible pathway towards stable 100% PE networks

- Analyses performed on the simplified Irish network show that a conventional power system can cope with up to approx. 65% instant penetration of power electronics based generation units, while maintaining network stability.
- To that end, some adjustments are required on the existing conventional control loops of power electronic based generation units (e.g. wind turbine power converters). These controls are termed “grid following”, controls as they measure the system frequency and provide active/reactive power at that frequency by injecting currents into the energized power grid, i.e. behaving like current sources.
- Introducing in complement a proportion of new grid forming controls in the PE-based generation units, i.e. controls that no longer behave as current sources but rather as voltage sources and synchronize with others, has shown to ensure system stability with up to 90% of PE penetration (defined on MVA base) on the synthetic Great Britain test system.

In the perspective of a full PE-based power network (at least at some points in time), simulations on the test Irish system model showed that a 100% PE network can be operated safely when 30% of PE-interfaced devices are equipped with grid forming controls. Real small-scale tests successfully showed the interoperability of several grid forming controls developed independently.

A first economic assessment of deploying grid forming controls, compared to synchronous condensers (a conventional stability management strategy based on adding physical inertia to the system) points towards the economic competitiveness of the grid forming approach.

Considering adjustments in present protection philosophies and the introduction of new protection technologies adapted to this new scenario together with the definition of rules for the behavior of PE based generators during short-circuits would allow a safe integration of renewable energies maintaining present levels of security of supply.

New protection schemes are required… and available

- Some protection schemes are seriously impacted by a high penetration of power electronics in the system, and particularly the distance protection function. New tools, a clear definition of the required response of power electronics during short-circuits and a more cross-disciplinary approach with the power electronics field are required to prepare the future.
- New protection algorithms were developed and successfully tested to operate under massive PE penetration: they include fault detection, faulted phase selection and underfrequency load shedding scheme. Three patents were submitted, one being under further feasibility analysis for integration into the commercial offer of the equipment manufacturer partner.

Power quality

- Simulation performed according to a probabilistic approach to harmonic propagation, showed that an increased PE penetration (from 60 to 90%) leads to a tripling of frequency variations and an increase of the total harmonics distortion (THD) above the 3% in 5% of substations.
- Mitigating frequency variations could be performed by wind turbines providing a new type of balancing services, through adjusted controls allowing to store and then release some of their kinetic energy.
- While PE devices introduce harmonic distortion into the grid, they can also be part of the solution. New controls can be implemented to minimise the device emissions and even to introduce additional damping to the system, contributing to an overall reduction in harmonic levels. Mitigating harmonic distortions requires an economic trade-off between a decentralised approach (controls and filters at PE device level) and a centralised approach (filters on the network).
The first step in MIGRATE was to investigate the main instability phenomena triggered by high PE penetration in order to propose updated stability measurement methods and tools. Eleven critical stability issues were identified and prioritized with the help of European TSOs, the four major ones being frequency stability, rotor angle stability, short-term voltage stability and sub-synchronous controller interactions.

Based on this knowledge, a methodology was proposed to evaluate the distance to stability, i.e. the tendency of the system to move from a stable condition to the stability limit (i.e. the threshold defined by the operator for a stability indicator such as rate of change of frequency (RoCoF), frequency nadir or critical clearing time). KPIs were therefore defined, allowing a mapping of one or several system-variables onto the actual value of a stability indicator.

In complement, a PE penetration forecast tool was developed for accurate forecasts up to 3 hours ahead, based on optimized artificial intelligence models (Artificial Neural Network), as well as a related prototype visualization tool for the control room as guidance.

Combining grid following and grid forming controls allows to push further the stability limit — up to a theoretical 100%

In order to address this 100% PE system perspective, MIGRATE developed a new type of controls, called grid forming (in opposition to grid following), as they no longer behave as a current source — but rather as voltage sources and synchronize with others. The grid forming concept and developments are detailed in the next pages.

The approach presented in the previous page focused on increasing the PE penetration in today’s power systems by modifying the existing controls in the grid. In complement, MIGRATE also considered the perspective of a 100% PE system in order to investigate whether and how such a system could be operated safely. And possibly, whether those two complementary approaches were compatible at some point.

The analysis performed on a synthetic Great Britain power system model showed that a combination of modified grid following controls and new grid forming controls on power electronic interfaced RES allow the stable operation under up to 90% share of PE.

Grid forming controls can bring additional economic value

Having a number of PE converters located in the close vicinity of each other can lead to adverse interactions between these PE devices (in particular series compensated systems), referred to as sub-synchronous controller interactions (SSCI). A methodology was therefore proposed to investigate such interactions. It includes:

- A method to design, evaluate and validate different mitigation solutions to tackle SSCI,
- A new approach based on artificial intelligence to manage SSCI risk during real-time operation.

This first step to manage SSCI in the operational time frame is promising, and further research is required to complement and test the robustness of this approach.

The next objective was to test whether and how existing controls of PE connected generators, storage devices or demand responsive loads could be adjusted in order to allow for an increased penetration of power electronics. By existing controls are meant grid following controls, i.e. controls that provide active and reactive power by injecting currents into the energized power grid (current source behavior). A set of adjusted grid following controls were therefore built upon and evaluated based on IEC standard models and hardware in the loop testing. Results show that those modified controls allowed to reach approx. 65% of PE penetration in the studied system while maintaining stability in particular:

- Fast active power injection (FAPPI) controllers implemented on type-4 wind generators allow to keep the maximum frequency deviation (Nadir) within the threshold defined in current grid code requirement.
- Supplementary damping control (SDC) on wind generators help to reduce the first swing’s maximum rotor angle deviations and to successfully damp out electromechanical oscillations.
- Some forms of sub-synchronous controller interactions were successfully mitigated by tuning of wind generators’ converter controllers as well as by introducing auxiliary controllers in the converters.

Resulting controls’ interactions can be managed

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Today, several TSOs chose to invest in synchronous condensers to provide electrical inertia and voltage strength to their system and support network stability. The large-scale deployment of grid forming controls could constitute a viable alternative to that strategy.

MIGRATE developed use cases for France and Germany to compare the costs of those two alternative strategies under scenarios of high PE penetration. Results show that the overall costs (CAPEX and OPEX) are of the same order of magnitude, even leaving aside the potential value of additional ancillary services that grid forming controls could provide (see above).

Grid forming controls could be interoperable

Different grid forming controls can be interoperable

During the project, three types of grid-forming controls were developed:

- Droop control, which adjusts voltage frequency with active power. It synchronizes the sources on transmission grid and provides in addition some inherent frequency control.
- Dispatchable virtual oscillator, which uses the oscillator self-synchronization property to synchronize on the grid.
- Matching control that matches the equations of the synchronous machine to the equations of an inverter with a DC source.

All three algorithms developed were tested with real hardware at small scale and turned out to be interoperable. The algorithms are released open source.

Converters’ vulnerability to overcurrent can be dealt with

Unlike synchronous generators, power converters can only cope with small overcurrent (of a few percent of their own rated current). In order to protect their semiconductors from the damage caused by over-currents, a current limitation strategy was developed and integrated in the converter control algorithm. This allows to prevent the current from going over a defined limit, while maintaining the voltage source behavior (required in grid forming controls – see definition above) during the fault. It is based on the tuned combination of two conventional current limitation techniques that are virtual impedance and current saturation.

A paradigm shift for ancillary services

Grid forming controls could then be used to provide both existing system services like frequency control, and new services that exploit the flexibility and fast actuation of power converters, such as electrical inertia or fast frequency response with limited storage.

MIGRATE provided a proof of concept on the provision of such ancillary services, complemented by a method to optimize the location and parameters of power converters providing grid support. Indeed, location matters: results show that the efficiency of the virtual and electrical inertia services provided depends not only on their amount but also on their location in the grid. A real shift in paradigm for the ancillary service markets, which do not capture this locational dimension so far.
"Location matters":
Inertia has a local dimension that can be monitored using synchronized measurement technologies

MIGRATE investigated how the commercially available synchronized measurement technologies could be better integrated to improve the knowledge, monitoring and forecast of stability indicators in low-inertia and PE-intensive systems.

Measurements using synchrophasor technologies such as phasor measurement units (PMUs) show that a power system does not behave like a single center of inertia but rather like dispersed, interconnected centers of inertia.

MIGRATE developed the concept of **Effective Area Inertia** as a key performance indicator that reflects the regional dimension of inertia, by capturing the relationship between the power imbalance and the rate of change of frequency (RoCoF) of a given area. Such KPI can be processed thanks to PMU data and directly used to determine area-based frequency response requirements or to design fast frequency control schemes (see next page).

A set of tools to monitor this area inertia KPI were developed and tested using network data from the wider consortium of TSOs. The TSOs data represented vastly different networks with different behaviors and characteristics, allowing to extensively test and validate the tools.

Complementary tools were also developed to monitor System Strength and Short Circuit Capacity. System Strength refers to non-fault, near-nominal voltage characteristics. As the system behavior changes due to the increase of PE, these two characteristics are becoming increasingly distinct and different. The tools were validated following the same approach.

**Forecasting tools** for these indicators were also developed using machine learning (neural networks) and tested on both model-based simulations and measurement-based results.

The Icelandic network (see illustration on the right) features distant centers of inertia that are separated by long transmission corridors, leading to serious angle stability issues. A pilot WAMPAC system (Wide Area Monitoring, Protection, and Control) was deployed on the Icelandic grid in order to mitigate instability events through services provided by existing equipment connected at generation and demand side. Those services, called fast-acting grid control, are enabled by PMU data combined with control measures that can ramp-up and down some generation resources (hydro) or step-up and down some loads (smelter and factory loads).

The control methodology developed can identify the area where disturbance occurs, and its severity based on the inertia estimates and the rate of change of frequency (RoCoF). Once the disturbance location is quickly and reliably detected, the available response within each area can be triggered in order to improve frequency and angle stability. Pilot tests showed that response triggers could be delivered in less than 0.5 seconds, and discrete response fully activated in less than 1 second. Shorter response time could be achieved if needed with further work.

Wide-Area-Control schemes clearly proved to be successful in the Icelandic grid to improve system stability. This experience is valuable for other low-inertia systems and for larger interconnected centers of inertia (see next page).

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Protection schemes are crucial to detect and isolate disturbances on the network, whose propagation would otherwise trigger blackouts of considerable areas of the power system.

Present protection schemes have been developed considering that synchronous generators were the main source of short-circuit current. Whereas synchronous generators’ behavior is well-known and predictable, PE-based generators respond differently during short circuits, and their behavior can differ from one manufacturer to another.

In MIGRATE, experts in power system protection and in power electronics worked jointly to assess the impact of a massive PE penetration on protection schemes and explored how the related equipment and algorithms should be modified in order to cope with higher shares of power electronics in the grid.

MIGRATE developed and patented innovative short circuit protection and system integrity protection schemes to cope with high PE levels — one of them is under industrialization process.

The first three algorithms were tested into real commercial or pre-commercial protection relay platforms, with conventional generators and with three types of PE-connected generators (photovoltaic, full converter wind turbine and doubly fed induction generation) on three different lines of different lengths. Test results were conclusive with promising perspectives.

Based on the previous findings, MIGRATE developed and tested several protection algorithms to overcome the barriers identified with regards to protection scheme performances under high PE penetration scenarios. Developments include:

- A faulted phase selector that improves the overall behavior of present distance protections. It uses an adaptive time window that avoids the issues of present algorithms concerning the different response times and transition periods of PE-based generator controls. A European patent has been submitted for this algorithm.
- A fault identification algorithm that overcomes the problems of nuisance tripping of distance protections. The phase selection is determined by assessing fault detection, impedance computation and directionality (zone determination). It is under patenting process.
- An undervoltage algorithm, i.e. a fault detection algorithm that uses an adaptive undervoltage criteria to detect faulty phases.
- An algorithm for underfrequency load shedding schemes (UFLS), combining a one-stage scheme for systems with known constant of inertia, and a two-stage scheme for systems with unknown inertia constant.

Results show that:

- For short circuit protection, distance protection is the most affected function, with mal-operation at fault detector, fault phase detector and directionality levels. Also, the strong influence of PE converters control behaviors on these functions requires to fully incorporate expertise on power electronics in protection studies (models and tools, academic curricula).
- The tested System Integrity Protection Schemes (SIPS) are not fully reliable under high PE penetration, and require adaptations to cope with higher shares of PE.
- It is important to clearly define requirements for the behavior of power electronics based generators during short-circuits.

The studies conducted allowed to identify the main control parameters of PE converters that impact protection systems, and which protection schemes and functions were affected during short circuits fed by PE-based generators.

Two types of protections were tested:

1. Short circuit protection relays, which measure and act locally in a single element (a line, transformer, generator) within tens of milliseconds. Three key protection functions were tested: differential protection, distance protection and ground directional overcurrent protection. Hardware in the loop testing was performed on real devices from four different manufacturers.

2. System Integrity Protection Schemes (SIPS) which monitors stability at system level via measurements in different points of the network, in hundreds of milliseconds. Three SIPS applications were modeled and tested under different scenarios of PE penetration, namely undervoltage load shedding, underfrequency load shedding and power swing tripping.

The results show that, with the adaptations proposed by MIGRATE, the impact of the penetration of PE-based generators in present distance protection functions can be mitigated.

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- The tested System Integrity Protection Schemes are not fully reliable under high PE penetration, and require adaptations to cope with higher shares of PE.
- It is important to clearly define requirements for the behavior of power electronics based generators during short-circuits.
The proliferation of power electronics devices in the power system triggers an increase in harmonics, i.e. voltages or currents whose frequencies are multiples of the network’s fundamental frequency, which constitute a deterioration of the power quality. This can be an issue for some sensitive industrial consumers, but also for the overall power system: higher harmonic distortion combined with higher frequency deviations leads to increased power losses on the network, can induce errors in the measurement devices of the grid, or even negatively contribute to certain network events (short circuits, loss of the supply or load, etc.).

The methodology was implemented on a test network to assess the impact of an increasing penetration of power electronics on power quality. Results show that increasing the PE share from 60% to 90% leads to:
- A tripling in frequency variations,
- An increase in total harmonic distortion above the widely accepted 3% limit in 5% of the substations.

A probabilistic approach was therefore developed to assess harmonics propagation considering the uncertainties in harmonic sources’ location and rate of harmonic generation. This methodology allows to detect the most vulnerable areas in the network, identify harmonic propagation patterns, and assess the impact of an increasing presence of PE devices on these areas. Then, an optimization-based approach allows to design the most cost-effective mitigation strategy.

The ODIN-PQ tool was developed to provide a 4D graphical representation of harmonics propagation, enabling a rapid visual check of the power quality situation on the grid. The tool uses either measurement results or simulations as inputs and provides video-style (time-lapse) animations on historic data for control and analysis purposes, or on simulated data for the study of future scenarios.

The tool can be freely downloaded at TU Delft Repository.

4D visualization of harmonics propagation to support network monitoring and control

Wind farms should enter the ancillary services markets

MIGRATE also studied how to better maintain acceptable power quality levels by reducing frequency variations caused by a high penetration of intermittent renewable energy sources.

Frequency variations increase as the RES penetration increases and trigger a growing demand in energy balancing services in order to maintain frequency stability. Such a demand cannot be met by the remaining synchronous generators that become fewer and fewer in a high-RES scenario.

A mitigation method was therefore developed, enabling wind turbines to provide such balancing services. The method uses wind speed forecast and system frequency forecast as inputs, and it adjusts controls to allow wind turbines to use the kinetic energy stored in their rotating masses. The related algorithm is currently investigated for patent eligibility.

This paved the way to a real participation of wind generation to ancillary service markets, but also opens regulatory perspectives on new requirements in network codes.

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MIGRATE recommends

+ to encourage TSOs to make use of their synchro-phasor data. There is a critical need to observe the dynamic characteristics as inertia and system strength issues impact stability among other stability KPIs.

+ to consider inertia as clusters connected by network corridors, and not as a single system-wide inertia. Angle stability is also related to regional inertia, and islanding can occur in low-inertia regions even in larger high-inertia systems or interconnections.

+ to encourage TSOs to explore possibilities of Wide-Area-Controls within their grids. They are a very valuable and economical approach for locational fast frequency control, enabling network stability improvements together with frequency management.

+ to differentiate system strength (or “stiffness”) from short circuit level. The historical assumption that they were approximately the same is no longer valid.

+ to be aware of system strength issues which can lead to higher frequency oscillation phenomena, typical 4-12Hz voltage control oscillations. Fast oscillatory instability detection is available that can be used to detect, alarm and potentially mitigate the rapid onset of these oscillations.

+ to use probabilistic approach to harmonics mitigation since taking into account future scenarios enables more future-proof solutions.

+ to use optimization-based approaches to design the most cost-effective mitigation strategies for harmonics.

+ to use new wind turbines control algorithm, which significantly reduces the frequency variations, is easy to implement in (existing) wind turbines and only minimally reduces total energy output.

+ to create new or modify the existing balancing service, focusing on frequency variations mitigation using wind turbines in order to significantly reduce the primary and secondary regulation needs.

+ to consider requiring grid forming control functionality in the specification of future PE projects.

+ to prepare for more detailed modeling of power systems and PE units in order to maintain TSO ability to analyze future power system stability under high PE penetration, in particular in terms of SSCI and PQ.

+ to continue the in-depth analysis how the application of AI techniques in grid planning and operation can facilitate the massive PE integration.

+ to further explore the possibilities how PE penetration can be monitored using real-time online measurements of typically available power system signals.

+ to open the grid code for grid forming requirement from inverters. Main guidelines are presently within MIGRATE. Grid forming technology is the only enabler for a 100% PE grid, and it already showed positive impact on grid with synchronous machines.

+ to review protection philosophy and criteria in order to ensure a secure transition towards a power system with high penetration of power electronics.

+ to define clear requirements for the behavior of power electronics during balanced and unbalanced faults and, ideally, these requirements should be harmonized at European level.

+ to implement new protection technologies such as adapted distance protection algorithms, time-domain protection functions and WAMPAC systems can facilitate the transition, however careful assessment of these technologies and their applicability to specific power systems must be made, as their behavior will be greatly affected by the controls of power electronics.

+ to review the tools commonly employed by protection engineers in their studies, in order to adapt them to this new scenario in which power electronics expertise must be included.
MIGRATE is the largest TSO project funded by the European Commission under the framework of Horizon2020.

Thanks to all who worked on the project tasks during the past four years. It was a real pleasure to collaborate with such dedicated people from different countries, with different backgrounds and different cultures. However, all of the involved colleagues had and have the same aim. Hopefully, the efforts and results of MIGRATE will make the energy system of the future more reliable and sustainable.

On behalf of TenneT
Hannes Munzel (Coordinator)

More information and public deliverables can be found here:

www.h2020-migrate.eu