MIGRATE

The Massive InteGRATion of power Electronic devices

Enabling the energy transition by providing solutions for the technological challenges

Project ID

MIGRATE

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.
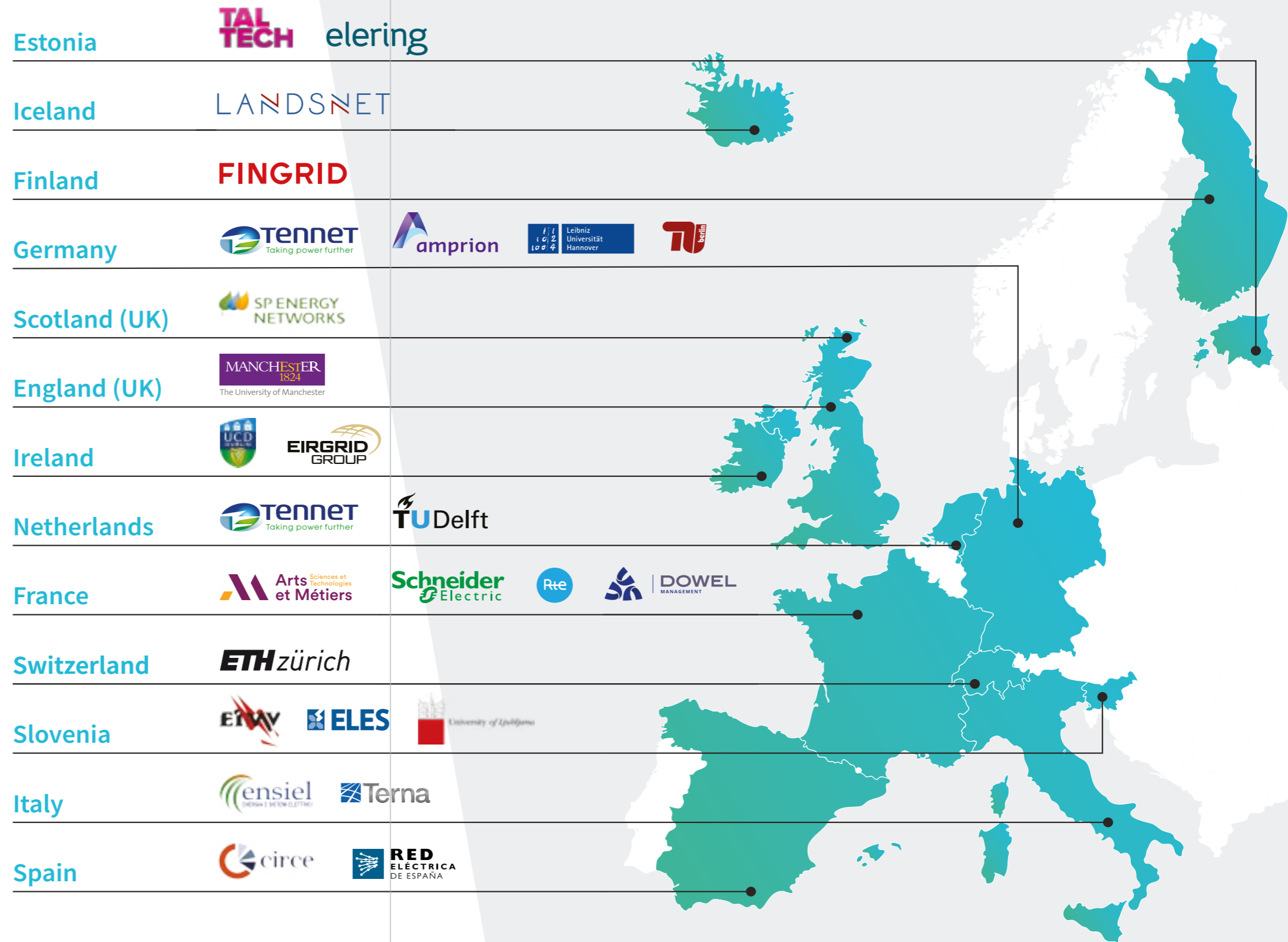
Key Figures

4 years project

25 partners

17.8 M€ budget

completed in dec. **2019**

Estonia — TAL TECH · elering

Iceland — LANDSNET

Finland — FINGRID

Germany — TenneT Taking power further · amprion · Leibniz Universität Hannover · TU berlin

Scotland (UK) — SP ENERGY NETWORKS

England (UK) — MANCHESTER 1824 The University of Manchester

Ireland — UCD Dublin · EIRGRID GROUP

Netherlands — TenneT Taking power further · TU Delft

France — Arts et Métiers Sciences et Technologies · Schneider Electric · Rte · DOWEL MANAGEMENT

Switzerland — ETH zürich

Slovenia — ETK · ELES · University of Ljubljana

Italy — ensiel ENERGIA E SISTEMI ELETTRICI · Terna

Spain — circe · RED ELÉCTRICA DE ESPAÑA

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

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

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.

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?

What should tomorrow's power system look like?

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 today's perspective: assessing the maximum share of power electronics in a power system before mitigation measures are required to maintain system stability, and how it should be mitigated;

— 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.
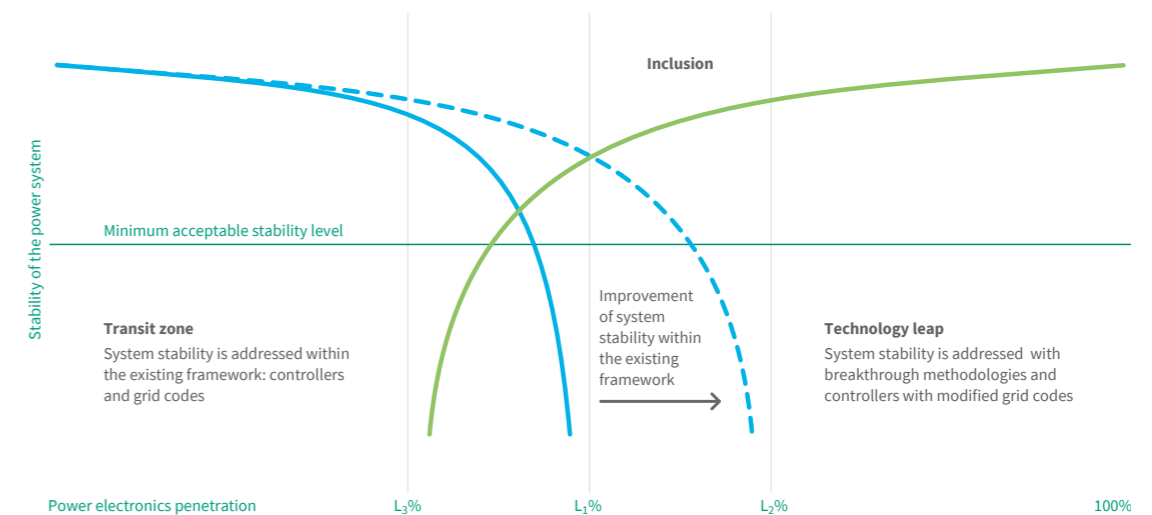

Illustration of the main concept of the MIGRATE project. The abscissa represents the PE penetration where L1 and L2 are asymptotes where severe stability problems could be met within the existing framework. The ordinate axis represents a generic stability index.

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.

MIGRATE contribution towards more renewable energy sources into the grid

Inertia is a local phenomenon, to be dealt with through locational strategies

— Data gathered by synchronized measurement technologies shows that inertia is not a system-wide generic feature, but rather a series of local area characteristics. Power systems behave as dispersed, interconnected centers of inertia.

— Consequently, mitigating low inertia requires locational measures. A WAMPAC system (Wide Area Monitoring, Protection, and Control) was tested in Iceland, combining real time monitoring and fast frequency response services enabled by controls on existing load and generation resources of the energy system (hydro generation and industrial loads). This world-first WAMPAC deployment revealed very successful in improving network stability, with positive perspectives in terms of cost savings and new ancillary services.

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.
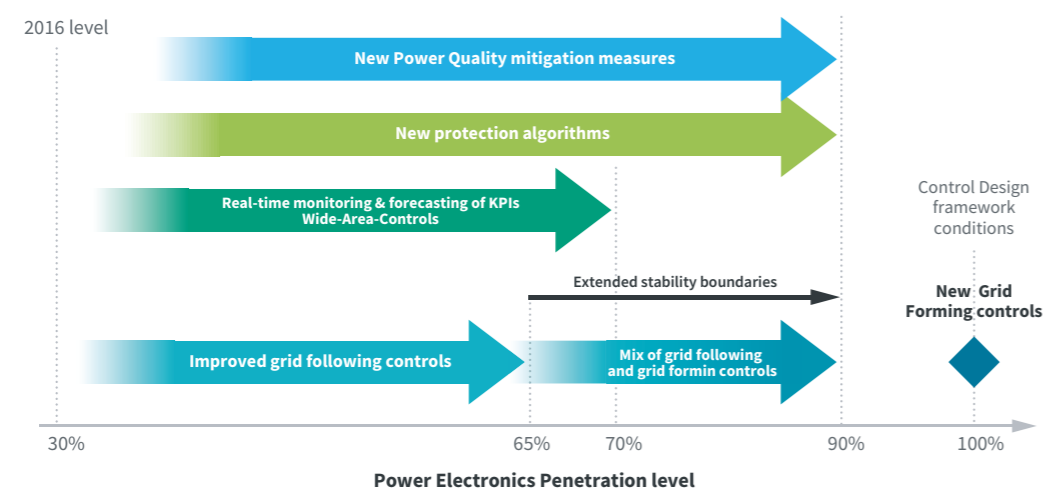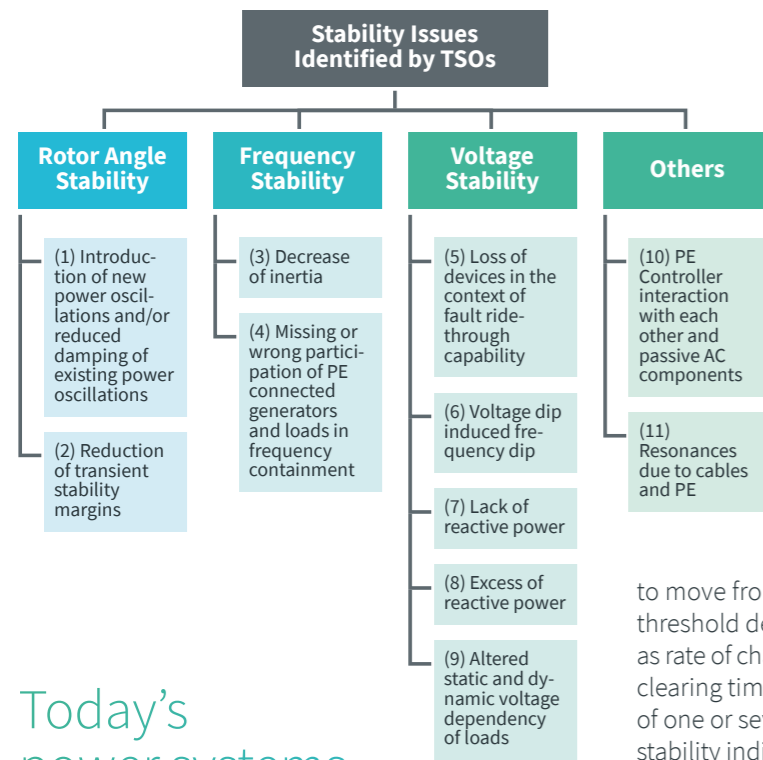
Power quality

— 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).

MIGRATE contributions in detail

Stability Issues Identified by TSOs			
Rotor Angle Stability	**Frequency Stability**	**Voltage Stability**	**Others**
(1) Introduction of new power oscillations and/or reduced damping of existing power oscillations	(3) Decrease of inertia	(5) Loss of devices in the context of fault ride-through capability	(10) PE Controller interaction with each other and passive AC components
(2) Reduction of transient stability margins	(4) Missing or wrong participation of PE connected generators and loads in frequency containment	(6) Voltage dip induced frequency dip	(11) Resonances due to cables and PE
		(7) Lack of reactive power	
		(8) Excess of reactive power	
		(9) Altered static and dynamic voltage dependency of loads	

Today's power systems can cope with approximately 65% of power electronics

Rethinking power stability assessment under high PE penetration

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.

Adjusting existing controls allows to reach approx. 65% PE penetration

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 (FAPI) 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.

The transition pathway towards a 100% PE system is technically feasible

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

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.

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.

Grid forming controls can bring additional economic value

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.

Resulting controls' interactions can be managed

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:

— Recommendations for the tuning of PE controls via parametric sensitivity analysis or optimization,

— 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 SCCI in the operational time frame is promising, and further research is required to complement and test the robustness of this approach.

Grid forming controls can allow operation of a grid with 100% PE

The algorithmic developments, simulations and laboratory tests performed in MIGRATE showed that operating a system with 100% PE is indeed possible. A necessary condition is that some converters are equipped with grid forming controls, as defined below.

The simulations performed on the Irish system showed that operating a stable 100% PE network requires that *approximately 30% of converters are equipped with grid forming controls*.

A definition of grid forming

Grid forming controls shall

— behave as a voltage source.

— be synchronized with other voltage source, if any.

— behave properly in islanded mode (do not rely on direct frequency measurement).

— take care of overcurrent limitation (be a voltage source as much as possible).

— be compatible with all presently connected devices, including synchronous machines and other grid following controlled units in the system.

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
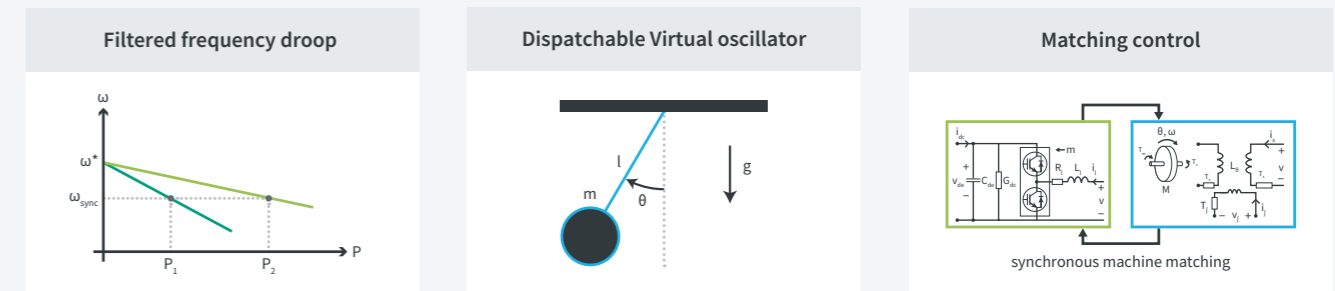
Unlike synchronous generators, power converters can only cope with small overcurrent (of a few percent of their own rated current). In order to protect their semiconductors from the damage caused by over-currents, a *current limitation strategy* was developed and integrated in the converter control algorithm. 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.

Filtered frequency droop	Dispatchable Virtual oscillator	Matching control

synchronous machine matching

Grid forming could compete with synchronous condensers

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).

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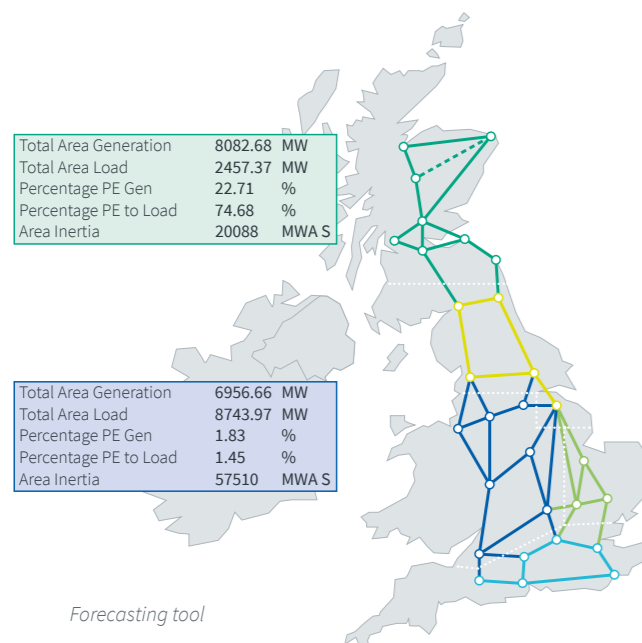
Measurements using synchrophasor technologies such as phasor measurement units (PMUs) show that a power system does not behave like a single center of inertia but rather like **dispersed, interconnected centers of inertia**.

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: Short Circuit Capacity relates to the system performance during a fault, while 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.

Total Area Generation	8082.68	MW
Total Area Load	2457.37	MW
Percentage PE Gen	22.71	%
Percentage PE to Load	74.68	%
Area Inertia	20088	MWA S

Total Area Generation	6394.48	MW
Total Area Load	8873.86	MW
Percentage PE Gen	32.57	%
Percentage PE to Load	23.47	%
Area Inertia	47628	MWA S

Total Area Generation	6956.66	MW
Total Area Load	8743.97	MW
Percentage PE Gen	1.83	%
Percentage PE to Load	1.45	%
Area Inertia	57510	MWA S

Total Area Generation	3334.47	MW
Total Area Load	3396.79	MW
Percentage PE Gen	22.22	%
Percentage PE to Load	21.81	%
Area Inertia	9090	MWA S

| Total Area Generation	6224.22	MW
Total Area Load	7216.24	MW
Percentage PE Gen	10.58	%
Percentage PE to Load	9.13	%
Area Inertia	19440	MWA S

Forecasting tool

Fast locational wide area control is a viable low-inertia mitigation

Regional inertia issues can be addressed by fast control that is sensitive to disturbance location.

A world-first live wide area control demonstration in Iceland proves the capability to use existing demand and generation for fast, locational, proportionate response to mitigate low inertia problems.

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).

220kV
132kV
66kV
30kV
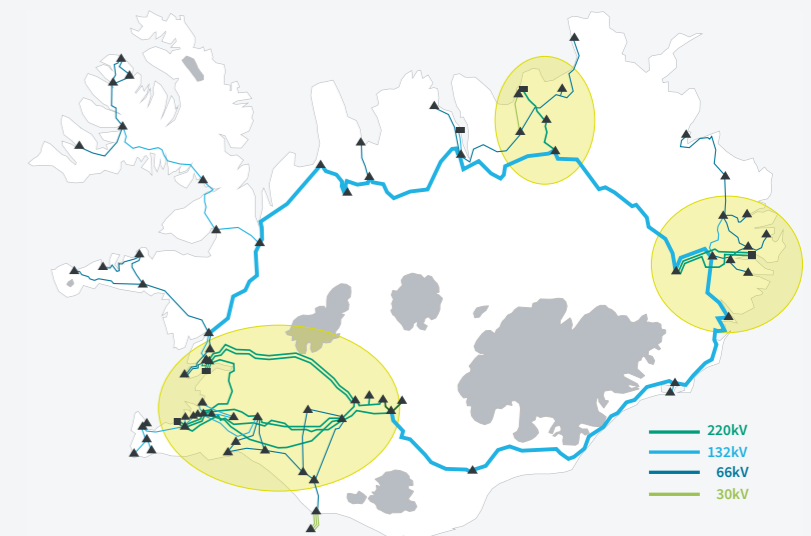
The control methodology developed can identify the area where disturbance occurs, and its severity based on the inertia estimates and the rate of change of frequency (RoCoF). Once the disturbance location is quickly and reliably detected, the available response within each area can be triggered in order 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 inter-

connections where parts of the system undergo low inertia and transmission boundary constraints.

The approach is also economically viable as significant cost savings can be reached by harnessing the capabilities of existing connected load and generation when compared to deploying dedicated devices such as battery storage to provide fast response services.

In addition, it creates new opportunities for any grid user with significant response capability to participate to ancillary service markets, with services that combine angle stability, frequency stability, balancing and islanding.

Power system protection shall fully incorporate power electronics expertise

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.

Distance protection is the most severely impacted by massive power electronics

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 tenths 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.

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 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.

New protection schemes can cope with massive PE shares in the system

> 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.

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.

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.

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.

The algorithms were then tested against their industrial feasibility (CPU loads and memory needs), and the undervoltage algorithm and the improved faulted phase selector algorithm revealed strong potential for industrialization. The undervoltage algorithm and faulted phase selector will be potentially included in a new generation of relays that will be released during the next years.

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.).

Harmonics caused by power electronics can be assessed and mitigated to preserve power quality

A probabilistic approach to assess and mitigate harmonics propagation

Tackling harmonics implies to assess how they propagate over the network in order to apply mitigation measures accordingly: a real challenge, as there are numerous potential sources of harmonics, which generate them in a random manner with variable propagation patterns.

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 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.

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

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.
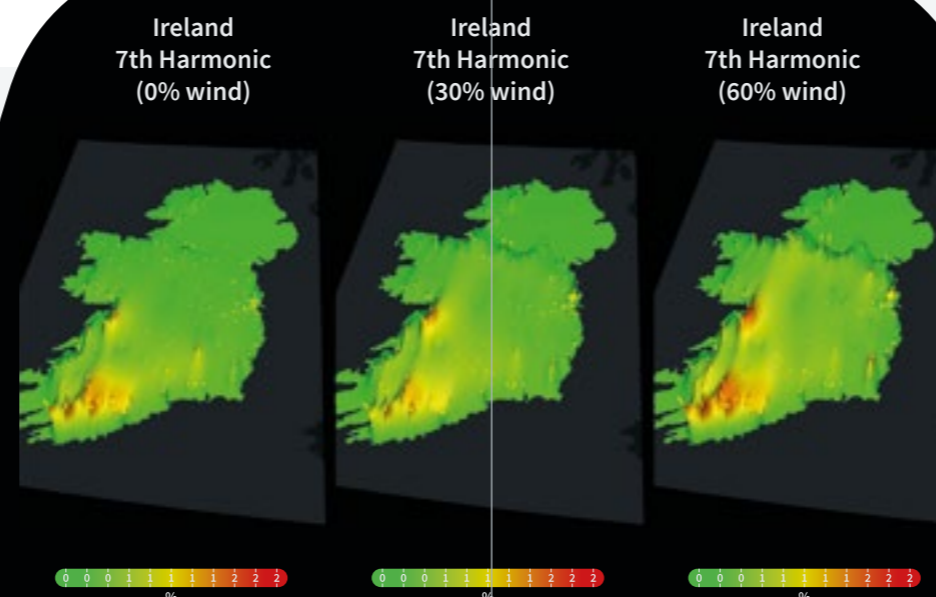
The future challenge of power quality

— The importance of power quality among European TSOs is increasing and more resources are allocated to its management.

— The most relevant power quality characteristic considered in Europe is harmonics.

— Most of the TSOs who deal with power quality have respective procedures available for defining/setting limits for new customer connections and for compliance verification.

— However, different methodologies are implemented by European TSOs in order to determine respective planning and compatibility levels in the system and for customers.

Maintaining power quality in future high PE penetration scenarios implies new economic and market considerations

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

Ireland
7th Harmonic
(0% wind)

Ireland
7th Harmonic
(30% wind)

Ireland
7th Harmonic
(60% wind)

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 historic 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

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