TECHNOLOGICAL CONTROL CAPABILITIES OF DER TO PROVIDE FUTURE ANCILLARY SERVICES

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ABSTRACT

With the aggregation of distributed generators and loads, a Virtual Power Plant (VPP) can participate on electricity markets and provide ancillary services. This paper describes technological control capabilities of distributed energy resources (DER) to provide future ancillary services for distribution and transmission network operation. The analysed future ancillary services comprise frequency control, voltage control, congestion management, improvement of voltage quality, network restoration, islanded operation and optimisation of grid losses. In addition, the capability to provide fault-ride-through is looked at. Special focus is given to wind turbine generators, photovoltaic systems, hydro power plants and combined cooling, heat and power plants. Also distributed loads and storage units are included into the performed assessment. The results of the study show substantial technological potentials of DER within the framework of VPPs. Especially, inverter-coupled units can provide various ancillary services. Although many of these features would have economic benefits most of them are not used at present. With their application, DER integrated in VPPs are expected to build a supporting role of the future electricity supply and the future network operation.

1 INTRODUCTION

The electricity supply is more and more based on distributed generators (DGs), particularly based on renewable energy sources (RES). Presently, they are only injecting the available power into the interconnected network. Without an integration into network operation DGs based on intermittent energy sources (e.g. Wind Turbine Generators (WTGs) and Photovoltaic (PV) systems) might jeopardise the stability of the network at higher penetration levels. In a more sophisticated approach, they have to participate in network operation to guarantee a sustainable and reliable electricity supply. This network operation is currently performed by large centrally operated conventional power plants. DGs are often not integrated in the network's operation because they are said to be small, not reliable and costly if they are looked at individually. With the concept of Virtual Power Plants (VPPs), the aggregation of the Distributed Energy Resources (DER) units creates large market players out of many small entities and an integrated risk management together with advanced forecasts increases their combined reliability.

Figure 1 illustrates the concept of the VPP and its possible services from a technical perspective and a market perspective. A variety of DER dispersed throughout the distribution network are combined via communication networks by an aggregator within the framework of a virtual power plant. A bunch of services can be provided comprising the participation on electricity markets as well as the provision of ancillary services.

This paper provides fundamental information for the aggregation and optimisation of a composition of different types of DER in the framework of virtual power plants (VPPs) for electricity supply and the provision of ancillary services.

Chapter 2 describes future ancillary services which will probably occur due to the increased penetration of DER in distribution networks. Particularly, ancillary services for distribution networks are expected.

Chapter 3 provides a classification of the different types of DER units whose control capabilities are analysed afterwards. This chapter gives the important assumptions for the following analysis.

Finally, Chapter 4 describes the results of a comprehensive assessment of the technological control capabilities of DER to provide the expected future ancillary services.

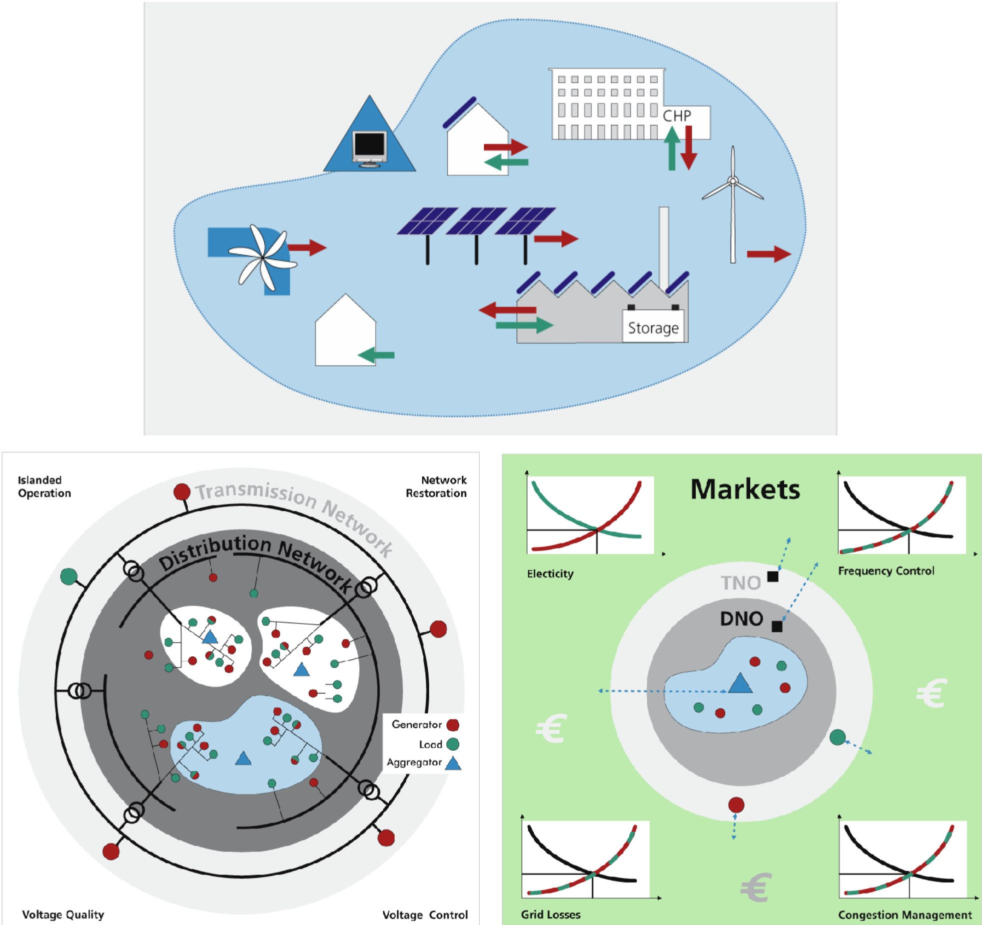

Figure 1: *The Concept of a Virtual Power Plant from a Technical Perspective and a Market Perspective*

2 FUTURE ANCILLARY SERVICES

With an increased penetration of DER at the distribution network combined with the objective of a more reliable and cost-efficient network operation, it becomes supportive to apply new ancillary services in the future operation of the distribution and transmission network by Distribution Network Operators (DNOs) and Transmission Network Operators (TNOs).

Consequently the definition of present ancillary services according to Eurelectric has to be modified:

"Ancillary Services are those services provided by generation, transmission and control equipment which are necessary to support the transmission of electric power from producer to purchaser. These services are required to ensure that the System Operator meets its responsibilities in relation to the safe, secure and reli-

able operation of the interconnected power system. The services include both mandatory services and services subject to competition." [1]

A definition of future ancillary services should include the DNO and his infrastructure in addition to the TNO. Moreover, beside of generation, also consumption and storage equipment can provide ancillary services.

The expected future network operation uses the following ancillary services (provided to the DNO and/or the TNO as noted in brackets):

- Frequency Control (TNO)
  - Primary Frequency Control
  - Secondary Frequency Control
  - Tertiary Frequency Control
- Voltage Control (DNO, TNO)
  - Primary Voltage Control
  - Secondary Voltage Control
  - Tertiary Voltage Control
- Congestion Management (DNO, TNO)
- Optimisation of Grid Losses (DNO, TNO)
- Improvement of Voltage Quality (DNO, TNO)
- Network Restoration / Black Start (DNO,TNO)
- Islanded Operation (DNO, TNO)

One additional service is considered which increases the power quality by providing voltage control support in case of voltage disturbances in order to increase the reliability of supply (this excludes the consideration of protection issues):

- Fault-Ride-Through Capability (DNO, TNO)

One important distinction is based on the way of the provision of the service:

- fast, local and generally automatic control within seconds (e.g. primary voltage or primary frequency control), or
- remote, centralised and coordinated control within minutes (e.g. secondary/tertiary voltage control or secondary/tertiary frequency control).

These two ways include different time horizons (speed of service provision) and different spatial perspectives (local or remote).

The *basic* control capabilities which are necessary for the provision of these ancillary services (exclusively the improvement of voltage quality) are active power, reactive power, direct voltage and direct frequency control. Table 1 shows their allocation to the ancillary services they can be or have to be applied for.

- Active power control is necessary for frequency control. This not only the case for the interconnected grid but also for frequency control in islanded operation of distribution grids as shown in [2].
- Voltage control (as well as fault-ride-through capability), congestion management and the optimisation of grid losses mostly depend on the reactive power control. However, also active power control has an impact and can be used (especially on the distribution grid level) but generally as the second-best option because of its mostly higher economic value compared to reactive power. In islanded operation of distribution grids it is also recommended to use reactive power control for these services [2].
- Active and reactive power control capabilities are necessary for network restoration and islanded operation. Moreover the direct control of voltage and frequency is required to set the values.

Table 1: Basic Control Capabilities (P,Q,V,f) for Ancillary Services
(X: required; x: also possible)

Ancillary Services	*Active Power* *P*	*Reactive Power* *Q*	*Direct Voltage* *V*	*Direct Frequency* *f*
Frequency Control	X			
Voltage Control, Congestion Management, Optimisation of Grid Losses	x	X		
Black Start	X	X	X	X
Islanded Operation	X	X	X	X
Fault-Ride-Through	x	X		

These fundamental control necessities for most of the ancillary services demand for an optimisation process by the network's operation which takes into account interdependencies[1] and treats the trade-offs according to the objective followed.

Presently, many of these foreseen services are not used by DNOs. Mostly, they rely on their planned network which is designed according to the predicted load development with appropriate capacity reserves. In the future, the connection of an increasing amount of DG, esp. intermittent DG, requires the adjustment of network operation to the new generation characteristics. Two approaches can be applied for secure network operation: ancillary services and network reinforcement. The optimal cost-efficient network operation is achieved when the costs for network reinforcement together with the costs for the provision of ancillary services are minimal for the generation of a certain utility.

These ancillary services for DNOs but also for TNOs could be provided by DER as described in the introduction of this paper. The chapter after the next one provides the results from a comprehensive analysis of the capabilities of DER to provide these future ancillary services. But beforehand, the next chapter provides the assumptions and terms subsumed under DER units.

3 DER UNITS

DER units comprise Distributed Generators (DGs), distributed loads and distributed storage. These are described in more detail in the following.

3.1 Distributed Generators

The focus of the study is on DG units based on a definition of DG by Working Group 37-23 of CIGRE which defines DG as all generation units with the following four aspects [3]:

- not centrally planned,
- today not centrally despatched,
- usually connected to the distribution network, and
- smaller than 50-100 MW.

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[1] Two examples of the mentioned interdependencies are:

1) A change of reactive power has an impact on the voltage profile, congestions and grid losses.
2) A change of active power has an impact on the frequency, voltage profile, congestions and grid losses.

This paper considers the following four relevant DG units:

- Wind Turbine Generators (WTGs),
- Photovoltaic (PV) Systems,
- Hydro Power Plants, and
- Combined Cooling, Heat and Power (CCHP) Plants.

All these DG units (as well as storage units) have a grid coupling device which feeds electrical energy into the grid as the last element of a chain of energy converters of the unit. These grid coupling technologies comprise:

- directly-coupled induction generators (IGs),
- directly-coupled synchronous generators (SGs) [2],
- doubly-fed induction generators (DFIGs), and
- inverters (Inv.s).

CCHP plants comprise a large variety of systems (e.g. with steam turbine, gas turbine, microturbine, piston internal combustion machine, Stirling engine and fuel cells). They are distinguished from the other three types of DG units because of their heat conversion process. The heat conversion process demands for considering an additional energy flow next to electricity. CCHP plants can be differentiated by units which do not use the thermal energy flow (condensing plants) and units which use the heat. The latter can have different priorities for the exploitation of heat and electricity:

- thermal-driven without storage,
- thermal-driven with storage, or
- electricity-driven.

In case of a thermal-driven CCHP plant without storage, the heat production is optimised, while electricity is only a sub-product. It is not possible to change the active power output because this would influence the heat production which has to follow a given heat profile.

An electricity-driven CCHP plant can vary the active power output according to the electricity needs. The heat is only a sub-product which creates no restrictions to the whole unit.

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[2] Permanently-excited synchronous generators are out of scope of this analysis because they are mostly inverter-coupled and if directly-coupled they behave similar to induction generators.

If a thermal-driven CCHP plant can be equipped with storage for the thermal processes it becomes possible to vary the active power output within the limitations given by the storage capacity. The storage could be installed with a large capacity which enlarges the limitations to the requirements for the active power control services of interest. In this situation, the thermal-driven process can be considered as an electricity-driven one.

The same CCHP plant might change its operation mode. In winter's peak heating period a heat-driven mode could be the choice while in seasons without heat demand an electricity-driven mode could be applied.

3.2 Distributed Loads

Distributed loads are not differentiated in more detail because of the large variety of types and the focus on DG units in this study. A possible activation and deactivation of loads with flexible consumption processes is considered (see potentials in [4]), e.g. of washing machines or refrigerators. Less flexible loads (according to the consumer's requirements), e.g. TV sets or microwave ovens, are out of scope.

3.3 Distributed Storage

Similarly to loads, also storage units are not considered in the very detail. They can be operated similar to generators as well as similar to loads. Hence, they have characteristics which are formed of the other two. One important limitation is the storage capacity which only allows an oscillating operation between generation and consumption. The objective of the majority of presently installed storage units is islanded operation in various applications such as small stand-alone applications, hybrid systems or uninterruptible power supplies. A large variety of storage technologies are available. Lead acid batteries, lithium batteries, supercapacitors, nickel batteries, redox flow batteries and all other types of electrochemical batteries are DC sources and need an inverter for grid coupling. Flywheels with their large speed variations can be connected via an inverter or via a variable speed gearbox by SGs. Only pneumatic and hydraulic storage, which are based on a mechanical energy conversion process, allow a direct coupling via a rotating generator which can be an IG, a SG or an inverter-coupled generator.

Based on this view of DER and the future ancillary services (described in the previous chapter), the next chapter presents the assessment of the control capabilities of DER to provide ancillary services.

4 ASSESSMENT OF TECHNOLOGICAL CONTROL CAPABILITIES OF DER TO PROVIDE FUTURE ANCILLARY SERVICES

4.1 Previous Studies

Previous studies ([5] -[11]) show different results because of different assessment approaches. The analysis of these previous studies identifies three main short-comings.

1) On the one hand, economic and technological capabilities need to be analysed separately. This separation is necessary because the economic framework is different in many countries and is expected to change in the future considerably while the technological capabilities are expected to change only due to the long-term technological progress. In other words, the technological capabilities are based on physical laws, while the economic attractiveness is based on the applied economic framework which uses assumptions, e.g. for the discount rate or future market prices, with a high degree of flexibility.

2) On the other hand, the technological capabilities need to be analysed separately for the grid coupling technology and the rest of the DG unit. This separation is necessary because the grid coupling technology is the entity which connects the DG unit to the grid and defines many of the technological capabilities of the DG unit. This coupling device can be different for the same DG unit. For instance, a biomass plant might be preferred to be equipped with an inverter as a substitute of a SG because of its additional capabilities for the improvement of voltage quality. This high flexibility for component combinations needs to be taken into account.

3) A third short-coming arises from the number of ancillary services and DER units which is looked at. Many studies only analyse a couple of ancillary services or a couple of DER units without giving the whole picture.

As a result from these identified shortcomings a need was seen to analyse the technological capabilities systematically and comprehensively for a large range of DER units and a large range of ancillary services.

4.2 Systematic Assessment Approach

The analysis provides a comprehensive survey and assessment of the capabilities of individual DER to provide ancillary services. An approach is applied which separates technological capabilities based on physical laws from the economic attractiveness which depends on different framework conditions. Figure 2 shows this approach schematically.

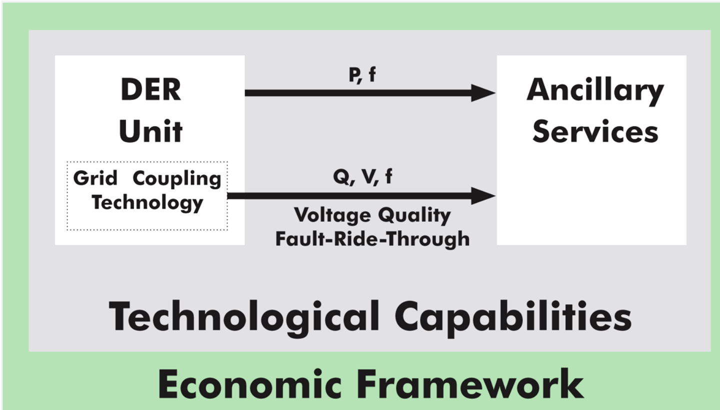

Figure 2: *Applied Assessment Approach*

Moreover, the technological capabilities are analysed with an approach of looking firstly at the grid coupling technology of the DER unit, and secondly looking at the whole DER unit. This distinction is necessary because different types of grid coupling technologies can be applied within the same DER unit and the grid coupling technology determines many capabilities of the whole DER unit.

Firstly, the technological capabilities of the considered grid coupling technologies are analysed. Secondly, the technological capabilities of the whole DER unit are presented.

4.3 TECHNOLOGICAL CONTROL CAPABILITIES OF GRID COUPLING TECHNOLOGIES

As the grid coupling technologies only transform the available power input into a power output of a different characteristic, active power control is provided by the unit components of the prime mover side. Similarly, the direct frequency control depends on the speed control of the prime mover for directly-coupled SGs and IGs. The DFIG allows an additional influence by the rotor-side inverter compared to the IG. Only the inverter can define the frequency independently from the DG unit. Consequently, only reactive power control, direct voltage control, the improvement of voltage quality, and the fault-ride-through capability are analysed for the grid coupling technologies. The qualitative results are summarised in Table 2.

Directly-coupled IGs can provide ancillary services by active power control. Reactive power control is only possible by external equipment, e.g. capacitor banks, which is assumed to be not part of the grid-coupling technology itself. All the other grid-coupling technologies (DFIGs, directly-coupled SGs and inverters) have advanced capabilities due to their reactive power control capabilities as well as their direct voltage control capability. DFIGs show smaller capabilities because they basically need to compensate the reactive power demand of the comprised IG.

The **Improvement of Voltage Quality** depends on the grid-coupling technology. There are differences between inverter- (DFIG and inverter) and non-inverter-coupled (IG and SG) DG/storage units. Only inverters can be controlled to improve actively voltage quality [12]. In comparison, inverter-coupled DG units show a better performance than DFIG-coupled DG because they are full-size converters. In contrast, rotating generators without inverters cannot participate actively in the improvement of voltage quality.

The **Fault-Ride-Through Capability** depends on the grid-coupling technology which has to balance the power flow on the grid-side and the DC-side in case of voltage disturbances. While inverters show the highest quality because of a fully decoupled energy generation process from the grid, DFIGs have a reduced quality because of their inverters of smaller size. Both can support the voltage stability by supplying reactive power. On the other hand, SGs and IGs show only little capabilities because they have the risk of loosing synchronism with the grid which depends on their inertia (which is assumed to be too small for most of the considered DG units). Of these two coupling devices the SG has the better performance because a reactive power generation for voltage support is possible. In addition, fast excitation control can partly compensate the risk of loosing synchronism.

Inverter-coupled units can be distinguished in inverters which couple a DC source to the grid and inverters which couple a rotating generator to the grid. The former ones show extremely good fault-ride-through capabilities because the DC voltage can be changed promptly, the latter ones need variable resistances which decouple the power reduction delay due to their inertia (cf. active crowbar solution for WTGs with DFIGs).

Table 2: Technological Control Capabilities of Grid Coupling Technologies

Control Capabilities	*IG*	*DFIG*	*SG*	*Inverter*
Reactive Power Control	No	+	++	++
Direct Voltage Control	No	+	++	++
Improvement of Voltage Quality	No	+	No	++
Fault-Ride-Through Capability	--	+	-	++

Legend:

++	indicates very good capabilities
+	indicates good capabilities
-	indicates little capabilities
--	indicates very little capabilities
No	indicates that this is not possible without additional external equipment

4.4 TECHNOLOGICAL CONTROL CAPABILITIES OF DER

An overview of the technological control capabilities of DER is given in Table 3. These capabilities are summarised in the following paragraphs.

Frequency Control based on active power control can be provided by all DER units but not by thermal-driven combined cooling, heat and power (CCHP) systems because they have to follow the required thermal profile. In contrast, the capability of electricity-driven CCHP (see an example in [13]) as well as storage units is very good because they have a high availability and flexibility. Intermittent energy systems, i.e. WTGs, PV systems and hydro power plants, as well as loads can control their active power but their availability is limited. This disadvantage can be covered by integrating them in a VPP. Frequency control comprises services of different reaction times (from seconds to minutes). All the reaction times can be covered by DER. Also the provision of non-spinning reserve would be possible. This excludes high temperature fuel cells whose reaction times can be too slow.

The majority of the presently installed WTGs are actively pitch-controlled. This allows a control of the mechanical power by changes of the blade angles as described in [14] - [17]. An active power control is possible with all WTGs with pitch-control independent of their grid-coupling technology. The active power control changes are fast enough to fulfil the requirements of primary frequency control (cf. measurements in [18] and [19]).

PV inverters use maximum power point (MPP) tracking to operate at the MPP. Active power control in both directions becomes possible if this MPP algorithm operates below the MPP by applying suboptimal DC voltages. A control of the DC voltage allows very fast active power control.

Hydro power plant can operate part-loaded. This is achieved by reducing the water flow through the water turbine (spilling water) or operating the turbines suboptimal. A change of the turbines mechanical output allows the control of the active power.

Voltage Control, **Congestion Management** and **Optimisation of Grid Losses** is mainly dependent on the reactive power control capability of the grid-coupling technology but also on the active power control capability of the DER unit. Inverter- and SG-coupled DG/storage units show a very good reactive power control capability. This capability is lower for DFIG-coupled units because they have a lower range of reactive power control. Finally, IG-coupled units have no reactive power control capability but partly an active power control capability which gives them a capability of lower quality, but not for thermal-driven CCHP units. Also loads can be activated and deactivated to provide these services. Voltage control comprises services of different reaction times (from seconds to minutes). All the reaction times can be covered by DER.

The **Improvement of Voltage Quality** as well as the **Fault-Ride-Through Capability** is dependent on the grid-coupling technology of the DG/storage unit according to Chapter 4.3. In addition, loads can improve voltage quality by being deactivated if they produce negative impacts.

Islanded Operation requires the capability to control active power, reactive power, voltage and frequency. Active power control is not possible with thermal-driven CCHP plants. In contrast, electricity-driven CCHP plants show very good active power control capabilities. These are less good in case of intermittent DG, i.e. PV systems, WTGs and hydro power plants, because they show a lower availability and primary source fluctuations. Anyhow, active power control is possible, particularly if integrated in VPPs. IG-coupled DG units do not have islanded operation capability because they cannot control reactive power and voltage. The other grid coupling technologies are capable to control reactive power and voltage, whereas the capability is lower in case of DFIG-coupled WTGs. While DFIG-coupled and inverter-coupled DG units can define the frequency directly, SG-coupled units need a speed control. Distributed storage is mostly designed for islanded operation for uninterruptible power supplies. In contrast to DG/storage units, loads can only support islanded operation by their active and reactive power control capabilities. DER are particularly suitable for islanded operation due to their load-near location.

Black Start needs the same control capabilities as islanded operation. In addition, it demands for a grid-independent system start. This is possible for the same DER units if the necessary storage support is assumed to be implemented and the inverters are assumed to be self-converting and not grid-converting.

4.5 RESULTING NEEDS FOR TECHNOLOGICAL ENHANCEMENTS OF DER

The basic technical enhancements, which are necessary in order to provide these services, comprise enhanced generator control, advanced measurement devices for local functions and information exchange as well as the communication technology equipment for centralised functions. This whole Information and Communication Technology (ICT) infrastructure, which is able to integrate a large quantity of DER, forms the VPP infrastructure. The individual DER units need an enhancement of their implemented control features. In addition, inverter-coupled rotating generators require for fault-ride-through capabilities variable resistances or an overdimensioning which could also be of interest for IG- and SG-coupled units. Finally, network restoration might require enhanced storage support in order to start the system without the grid's voltage. This is particularly necessary for CCHP systems. In addition, synchronisation equipment is necessary to enable an interconnection after islanded operation.

Table 3: Technological Capabilities of DER units to Provide Ancillary Services

Ancillary Services \ DER Unit	WTG		PV	Hydro		CCHP thermal-driven		CCHP electricity-driven		Storage		Loads
Frequency Control		+	+		+		no		++		++	+
Voltage Control, Congestion Management, Optimisation of Grid Losses	Inv	++	++	Inv	++	Inv	+	Inv	++	Inv	++	+
	SG	++		SG	++	SG	+	SG	++	SG	++	
	DFIG	+										
	IG	-		IG	-	IG	no	IG	-	IG	-	
Improvement of Voltage Quality	Inv	++	++	Inv	++	Inv	++	Inv	++	Inv	++	-
	SG	no		SG	no	SG	no	SG	no	SG	no	
	DFIG	+										
	IG	no		IG	no	IG	no	IG	no	IG	no	
Black Start	Inv	+	+	Inv	+	Inv	no	Inv	++	Inv	++	no
	SG	+		SG	+	SG		SG	+	SG	+	
	DFIG	-										
	IG	no		IG	no	IG		IG	no	IG	no	
Islanded Operation	Inv	+	+	Inv	+	Inv	no	Inv	++	Inv	++	no
	SG	+		SG	+	SG		SG	++	SG	++	
	DFIG	-										
	IG	no		IG	no	IG		IG	no	IG	no	
Fault-Ride-Through	Inv	++	++	Inv	++	Inv	++	Inv	++	Inv	++	-
	SG	-		SG	-	SG	-	SG	-	SG	-	
	DFIG	+										
	IG	--		IG	--	IG	--	IG	--	IG	--	

Legend

Grid Coupling Technology
- IG directly-coupled induction generators
- SG directly-coupled synchronous generators
- DFIG doubly-fed induction generators
- Inv inverters (including inverter-coupled IG and SG)

- ++ indicates very good capabilities
- + indicates good capabilities
- - indicates little capabilities
- -- indicates very little capabilities
- no indicates that this is not possible without additional external equipment

5 CONCLUSIONS

With the increase of the penetration of DER new ancillary services, esp. at the distribution network, become possible. In order to substitute conventional power plants it is necessary to utilise the capabilities of DER for network operation. Their aggregation in the framework of VPPs simplifies the control of a large number of DER of small size and different characteristics. The presented results of the assessment of technological control capabilities of DER integrated in a VPP show substantial potentials of DER to provide the future ancillary services. Especially, inverter-coupled DER can provide many, mostly unused, features.

An economic analysis apart from this paper has shown that frequency control by WTGs, PV systems and hydro power plants seems not to be attractive due to their low marginal costs. However, electricity-driven CCHP plants, controllable loads as well as storage units principally installed for other services are economically very attractive. Generally, the comparably low technological capabilities of IG-coupled DER make them not very attractive for many of the ancillary services. Also the inflexibility of active power control of thermal-driven CCHP plants reduces their economic attractiveness for many services. Apart from these two categories, the others are very attractive economically because of many inherent capabilities which are not exploited at present because of the lack of appropriate incentives.

Also driven by the cost reductions of ICT, DER integrated in VPPs are expected to build a supporting role of the future sustainable electricity supply and the future network operation.

In addition to the presented work, simplified models are developed which are representative for a large variety of DER and which allow the simulation of a large quantity of integrated DER with the analysed control capabilities. These can be implemented in different network analysis tools for simulations of the network operation actively supported by DER. In addition to the qualitative results of the presented assessment, these models allow numeric simulations with quantitative results.

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More information on the project is available on: www.fenix-project.org.

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