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Bottom-up organisation of the distribution grids for effective large-scale DER integration

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Abstract**:** The integration of renewable energy generation, the increasing number of storage systems and controllable loads (collectively referred to as "active" devices) are creating voltage and frequency issues in the operation of distribution grids and calling for new approaches in order to allow safe, coherent and efficient operation. The idea is the decoupling of the grid frequency between upstream and downstream grids and even between grid segments at the same voltage. The grid frequency variation provides all information needed to control the grids[1]. The technical implementation of the frequency decoupling between the upstream distribution grid and neighboring lower voltage segments is performed by AC/DC/AC converters (Frequency Decoupling Smart Transformer - FDST), allowing frequency variation in the downstream grid segments, for active power flow regulation, harmonized control and energy management of generators, controllable loads and available storage capacity. Furthermore, voltage regulation may be performed at the point of connection of the Frequency Decoupling Smart Transformer and throughout the grid by the distributed active power electronic devices.

In the currently proposed concept, the actual grid frequency value itself is used as a means to communicate a predefined "message" to all "listening" grid connected active devices and manage the demand and generation of electricity without a technical solution based on Information Communication Technology (ICT). The ICT solution brings in requirements, such as the need of new specific communication infrastructure between the Distribution Grid Operator (DSO) and the producers, aggregators, consumers/prosumers.

In fact, the independently applied per microgrid grid frequency control concept will be the underlying "security net", so that the microgrid frequency does not deviate outside the allowable values, for example 49.8 to 50.2Hz. Within the previously mentioned frequency window, the balancing through energy exchanges inside a microgrid, performed by energy management concepts (such as aggregators, prosumers, peer to peer exchanges etc.) will be allowed only at longer time scales (normal operation minutes). While at short timescales (up to seconds) near and outside the allowable frequency window the balancing will be ensured by the proposed concept.

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[1] The main part of this work was submitted for patent application and the application concept description and claims were published on Feb. 1st 2018, with application number reference: WO2018020297.

Keywords: Smart grids, microgrids, power electronics, frequency conversion, control systems, smart transformers, variable frequency control, aggregation.

Οργάνωση από την βάση προς τα πάνω των δικτύων διανομής για μαζική και αποτελεσματική ενσωμάτωση Διεσπαρμένων Ενεργειακών Πόρων (ΔΕΠ)

Περίληψη: Η ενσωμάτωση της παραγωγής ανανεώσιμων πηγών ενέργειας, ο αυξανόμενος αριθμός συστημάτων αποθήκευσης και τα ελεγχόμενα φορτία (όλα μαζί ονομαζόμενα «ενεργές» συσκευές) δημιουργούν ζητήματα τάσης και συχνότητας στη λειτουργία των δικτύων διανομής και απαιτούν νέες προσεγγίσεις για την ασφαλή, συνεκτική και αποδοτική λειτουργία. Η βασική ιδέα είναι η αποσύνδεση της συχνότητας δικτύου μεταξύ των ανάντη και κατάντη δικτύων και ακόμη και μεταξύ τμημάτων του δικτύου με την ίδια τάση. Η μεταβολή της συχνότητας του δικτύου παρέχει όλες τις πληροφορίες που απαιτούνται για τον έλεγχο των δικτύων[2]. Η τεχνική υλοποίηση της αποσύνδεσης της συχνότητας λειτουργίας μεταξύ του ανάντη δικτύου διανομής και των γειτονικών τμημάτων χαμηλότερης τάσης εκτελείται από μετατροπείς AC / DC / AC (Smart Transformer Decoupling Smart Transformer - FDST), επιτρέποντας τη μεταβολή της συχνότητας στα κατάντη τμήματα δικτύου για τη ρύθμιση της ροής ενεργού ισχύος, εναρμονισμένο έλεγχο και διαχείριση ενέργειας των γεννητριών, ελεγχόμενων φορτίων και διαθέσιμης χωρητικότητας σε αποθηκευτικά μέσα. Επιπλέον, η ρύθμιση της τάσης μπορεί να πραγματοποιηθεί στο σημείο σύνδεσης του έξυπνου μετασχηματιστή αποσύνδεσης συχνότητας και σε όλο το δίκτυο από τις διεσπαρμένες «ενεργές» ηλεκτρονικές συσκευές ισχύος.

Στην τρέχουσα προτεινόμενη ιδέα η ίδια η τιμή συχνότητας του δικτύου χρησιμοποιείται ως μέσο επικοινωνίας ενός προκαθορισμένου «μηνύματος» σε όλες τις «ενεργές» συσκευές που συνδέονται με το δίκτυο για τη διαχείριση της ζήτησης και της παραγωγής ηλεκτρικής ενέργειας χωρίς τεχνική λύση βασισμένη στην Τεχνολογία Πληροφοριών και Επικοινωνιών (ΤΠΕ). Η λύση ΤΠΕ φέρνει απαιτήσεις, όπως η ανάγκη για νέα ειδική υποδομή επικοινωνίας μεταξύ του Διαχειριστή του Δικτύου Διανομής (DSO) και των παραγωγών, των καταναλωτών/παραγωγών και ομάδες αυτών (aggregation).

Η πρόταση της αποσύνδεσης της συχνότητας από το ανάντη δίκτυο και ο ανεξάρτητος έλεγχος της συχνότητας των κατάντη δικτύων (μικροδικτύων) από τον υποσταθμό ΜΤ/ΧΤ υλοποιεί ένα στιβαρό "δίχτυ ασφαλείας", έτσι ώστε η συχνότητα του μικροδικτύου να μην αποκλίνει εκτός των επιτρεπόμενων τιμών, για παράδειγμα 49,8 έως 50,2Hz. Εντός του προαναφερθέντος παραθύρου συχνότητας, δύναται να εκτελείται εξισορρόπηση μέσω ενεργειακών ανταλλαγών μέσα σ’ ένα μικροδίκτυο, που θα δύνανται να

[2] Το κύριο μέρος αυτής της εργασίας υποβλήθηκε σε αίτηση διπλώματος ευρεσιτεχνίας και η περιγραφή της έννοιας εφαρμογής και οι αξιώσεις δημοσιεύθηκαν την 1η Φεβρουαρίου 2018, με αριθμό αναφοράς αίτησης: W02018020297.

υλοποιούνται μέσω συντονισμού διαδικασιών ενεργειακής διαχείρισης (όπως ανταλλαγές μεταξύ ομάδων καταναλωτών/παραγωγών (aggregation), ανταλλαγές μεταξύ καταναλωτών και παραγωγών (peer to peer), κ.λπ.) που θα εφαρμόζονται σε χρονικές κλίμακες λεπτών της ώρας. Ενώ σε βραχείες χρονικές κλίμακες (ως και δευτερόλεπτα) κοντά και έξω από το επιτρεπόμενο παράθυρο συχνότητας η εξισορρόπηση θα εξασφαλίζεται από την παρουσιαζόμενη ιδέα.

1. Introduction

The integration of renewable energy generation, the increasing number of storage systems and controllable loads are creating voltage issues in the operation of distribution grids and raise issues that new approaches are needed in order to allow safe, coherent and coordinated operation. The distribution grids are changing [1] and the implementation of a concept that would allow coherent control and self-regulation within grid segments and microgrids and coordinated control of power exchange between adjacent microgrids is crucial. A Low Voltage (LV) grid segment is considered as part of a microgrid [2, 3] that may have more than one grid segments.

The key idea is that the variation of the grid frequency provides all information needed to control the LV grid. The frequency increases in times of excess generation, while it decreases in times of lack of local power availability [4, 5].

The transformation of the distribution grids from passive to active grids is in progress. At this point in time, there is no reliable, simple and effective technical method to control, integrate and organize LV grid segments and microgrids, interconnected to the upstream distribution grid, without the use of Information Communication Technology (ICT) based infrastructure for point to point communication between the grid operator and the energy producer, employing mobile cellular network communications, SCADA solutions and hierarchical Multi-Agent System (MAS) control systems to manage the progressively large number of active devices connected to the LV grids and multi-microgrids. Several research teams have suggested and developed concepts for centralized and decentralized Multi-Agent System based applications using frequency control and load shedding to stabilize the operation of islanded microgrids and also for interconnected microgrids to the upstream grid [6, 7, 8, 9, 10]. A company named, “Easy Smart Grid” was granted in October 2016 a European patent, with the equivalent US patents pending. They have developed an ICT based price communication technology (meters and controllers), allowing the development of real time trading platforms for energy and flexibility in islanded grids, microgrids or grid cells by coding a price signal onto the grid frequency [11]. The latter patent concept is not varying the actual grid frequency itself on the LV grid segment or microgrid as proposed in the currently presented concept.

In the currently proposed concept, the actual frequency value itself is used as a means of communicating a signal to all "listening" LV grid connected devices and manage the demand and generation of electricity without a technical solution based on Information Communication Technology (ICT) which brings in requirements, such as the need of new specific communication infrastructure between the Distribution Grid Operator (DSO) and the consumer/prosumer (consumers are usually called prosumers, if they also have their own RES generation/storage). Furthermore, the avoidance of the ICT based control solution at the LV grid provides advantages such as enhanced data security, absence of latency, robustness and reliable operation, as well as optimized existing infrastructure usage. For individual LV grid segments and microgrids the possibility of riding through short upstream grid interruptions can be realized, provided adequate generation and storage resources are in place.

The proposed LV smart grid (microgrid) control methodology makes use of a Frequency Decoupling Smart Transformer (FDST - AC/DC/AC converter), as defined later in the article, at the Medium Voltage/Low Voltage (MV/LV) connection point, replacing the traditional transformer, by converting the voltage from MV to LV, while decoupling the frequency between the MV and LV sides and managing downstream connected devices through grid frequency variation. Through the frequency variation on the LV side it is proposed to control the output of generators such as PV systems, small wind turbines, other generators, the input/output of storage systems, including Electric Vehicles and controllable loads. The communication with all the controllable active devices will be through frequency monitoring by all these devices, that will have a common algorithm of grid frequency versus active power response (as in Table I of the concept proposed) and therefore no new communication infrastructure is required for this action. The information communicated to the Distribution System Operator (DSO) from the smart meters, within the existing channels of metering schemes, could be relayed to the FDST by the DSO. This information will help the FDST to validate its management to the LV side and further allow the FDST to correct for voltage implementing energy management and power control according to the local LV grid (microgrid). Further the communication between the DSO and the FDST besides the control of this FDST will allow the coordinated control of several FDSTs by the DSO that may make use of resources of individual microgrids (as defined here the LV grid downstream of the FDST) to support adjacent ones.

Recently, energy management concepts and realizations in microgids with blockchain technology were presented to provide "prosumers" and consumers to exchange energy in peer to peer mode without the interference of the distribution system operator (LO3ENERGY, https://lo3energy.com). Frequency Decoupling Smart Transformer technical implementations when realized would suffer from latency and or reliability issues in communication solution. The Frequency Decoupling Smart Transformer concept offers a reliable and latency-free solution by exploiting the grid frequency.

The control through the grid frequency would allow balancing of microgrids in short timescales and cooperate with other energy management concepts, such as peer to peer energy exchanges, at longer time scale.

In fact, the variable grid frequency control concept proposed here would be the underlying "security net", so that the microgrid frequency does not deviate outside the allowable values, for example 49.8 to 50.2Hz. Within the previously mentioned frequency window all blockchain managed peer to peer energy exchanges or virtual power plants operation will be allowed, but when the grid frequency excurses outside this window then the "security net" takes over and all "active" devices connected to the grid monitoring the frequency would have to alter their behavior to restore the instantaneous power balance and thus the frequency of the microgrid.

Furthermore, in all above energy management schemes the grid frequency could serve as the information to manage any individuals or groups of aggregated consumers and prosumers by programming local active devices to exchange power according to the plan of each aggregator within the allowable frequency window.

2. Background

In the JOULE III European Union (EU) funded project, 20 years ago, titled: "Photovoltaic system technology development for the gradual penetration of photovoltaics into island grids", contract number JOR3-CT97-0158, the frequency droop concept was proposed, implemented and tested in CRES's (Pikermi, Greece) islanded microgrid for power control and energy management of grid connected PV inverters. The frequency of the microgrid was varied by the grid forming diesel generator allowing control of grid connected power generators (Photovoltaic inverters) through the grid frequency without direct communication link. The Maximum Power Point Tracking (MPPT) control code of a grid-connected PV inverter was modified to reduce its output as the grid frequency was increased from 50 to 54 Hz [12].

Furthermore, during the realization of the EU funded projects, PV-MODE, JOR3-CT98-0244 and MORE, JOR3CT98-0215, from 1999 to 2002, the permanently islanded microgrid, in the island of Kythnos in Greece, was developed and is still in operation since March 2001.

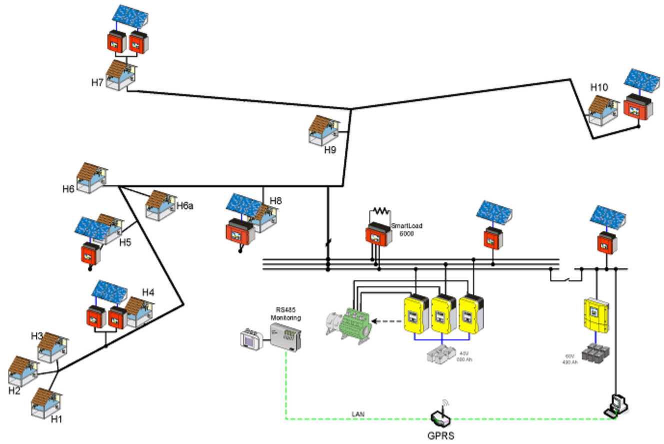

Fig. 1. Single line schematic diagram of Gaidouromantra microgrid, Kythnos island.

The permanently islanded microgrid is used to electrify a settlement of vacation houses in Gaidouromantra (Figure 1) [13]. The Gaidouromantra microgrid electrifies 12 vacation houses and one control room in a small valley in Kythnos. The microgrid and safety specifications for the house connections respect the technical specifications of the Public Power Corporation, which is the local electricity utility. The Gaidouromantra microgrid and the microgrid of CRES at Pikermi, Greece, were also fitted with frequency sensing distributed intelligent load controllers [13] at the point of connection of houses or non-critical loads, while the distributed grid-connected PV inverters were equipped with a power output de-rating control logic, according to the grid frequency (droop control). The grid is formed by SMA bi-directional battery inverters that vary the grid frequency depending on battery stored energy and power availability. Through the frequency variation, according to the State Of Charge (SOC) of the batteries, it was possible to manage the resources by load shedding or PV inverter power de-rating. In the specific microgrid the frequency is used as communication signal between the power units in order to manage the generated/consumed energy, to stabilize the microgrid operation and to extend the battery lifetime [14, 15].

Later, the SELFSYNCTM control method [16, 17, 18] was developed and proved stable operation of multiple grid forming inverters in grid-connected or islanded operation modes through voltage and frequency droop control, enabling synchronization and load sharing of inverters without communication.

Recently, a variable frequency smart transformer was proposed in the European FP7 supported project titled: HEART [19, 20]. It is based on a modular architecture of units composed of power electronics converters that will be able to manage the energy and the information flows among sources and loads in the distribution area with the goal of decoupling it from the rest of the bulk power system.

3. NOVEL GRID ORGANIZATION CONCEPT

The large integration of renewable energy sources (RES), active distributed energy resources (storage) and controllable loads in the electricity networks is imposing key operational, technical and economic challenges and barriers. These are voltage regulation issues, especially in rural areas but increasingly in urban grids. Traditional grid reinforcement is the preferred solution to increase the hosting capacity for RES in the distribution grids, while control and management of controllable devices is usually realized through point to point communication, mainly through mobile telephony and internet communication solutions.

The aim of this concept is to allow the increase of RES generator accepting capacity and enhance load management in the distribution grids, without new physical communication infrastructure, enhancing the associated environmental, economic and operational benefits, while contributing to the transformation of the networks to active, self-organized smart grids with minimized curtailment of RES generator production through storage management and power sharing between adjacent grid segments within a "Microgrid" or several microgrids and even in coordinated exchange of power flow through the upstream distribution and transmission system. The integration of Distributed Energy Resources (DER), such as RES generators, storage and controllable loads in the grids will increase dramatically in the near future, leading consequently to the dramatic increase of communication flows and data processing volumes, while data security and operation robustness issues will immerge.

The key elements of this concept are avoiding the new communication infrastructure, the latency and vulnerability in distribution grid segments by controlling in a coordinated manner a very large number of grid connected controllable devices through the grid frequency variation. Through the frequency variation and the information it contains, through the value of frequency, carried by the electricity grid cables which have a direct connection to all grid connected devices, we are avoiding new ICT infrastructure for point to point communication between the control device (FDST) and a very large number of controlled points (all active grid connected devices such as inverters and controllable loads and storage devices).

Any failure of the grid lines leads to a breakdown of communication of the proposed scheme with the FDST but in the case of an ICT based control solution, in addition to that, we are also prone to communication service breakdown, ICT hardware breakdown and to possible voluntary or involuntary interference with the communicated control data (cyber security issues, etc.). Furthermore, the direct control through frequency variation (FDST) avoids issues such as latency in communication and associated grid control issues, eliminates cyber security control and data handling issues and provides higher reliability to the overall electrical system as there are fewer points of failure.

To allow grid frequency variation in distribution grid segments, the downstream operating frequency should be decoupled from the frequency of the medium voltage upstream grid, or even other adjacent grid segments within the same "Microgrid" (Figure 2). Appropriate storage is also proposed between the Medium and Load Voltage grid in order to allow short term storage, optimize power flows through the FDST and allow black start and stand-alone operation depending on conditions and resources. Each grid segment within a microgrid could have a separate Frequency Decoupling Smart Transformer (FDST). By allowing frequency variation, it is possible to realize control and energy management of inverter based generators, controllable loads and battery storage capacity. This way, plug and play functionality, within certain predefined technical limits per connection point, can be applied for new DER units and controllable loads, inside a defined grid segment. This will allow uniform application of a solution within a grid segment per point of user connection without the need for individual assessment every time new resources are added. In practice, the local controllers of all the grid-connected units, such as energy generators, storage and active loads in the "Microgrid", (Figure 2), will have to be able to monitor and respond accordingly to local voltage variation, (already most recent Photovoltaic system inverters have this feature integrated), standardized local droop frequency logic for power control, energy management, black start, etc., allowing for a self-organized "Microgrid" operation.

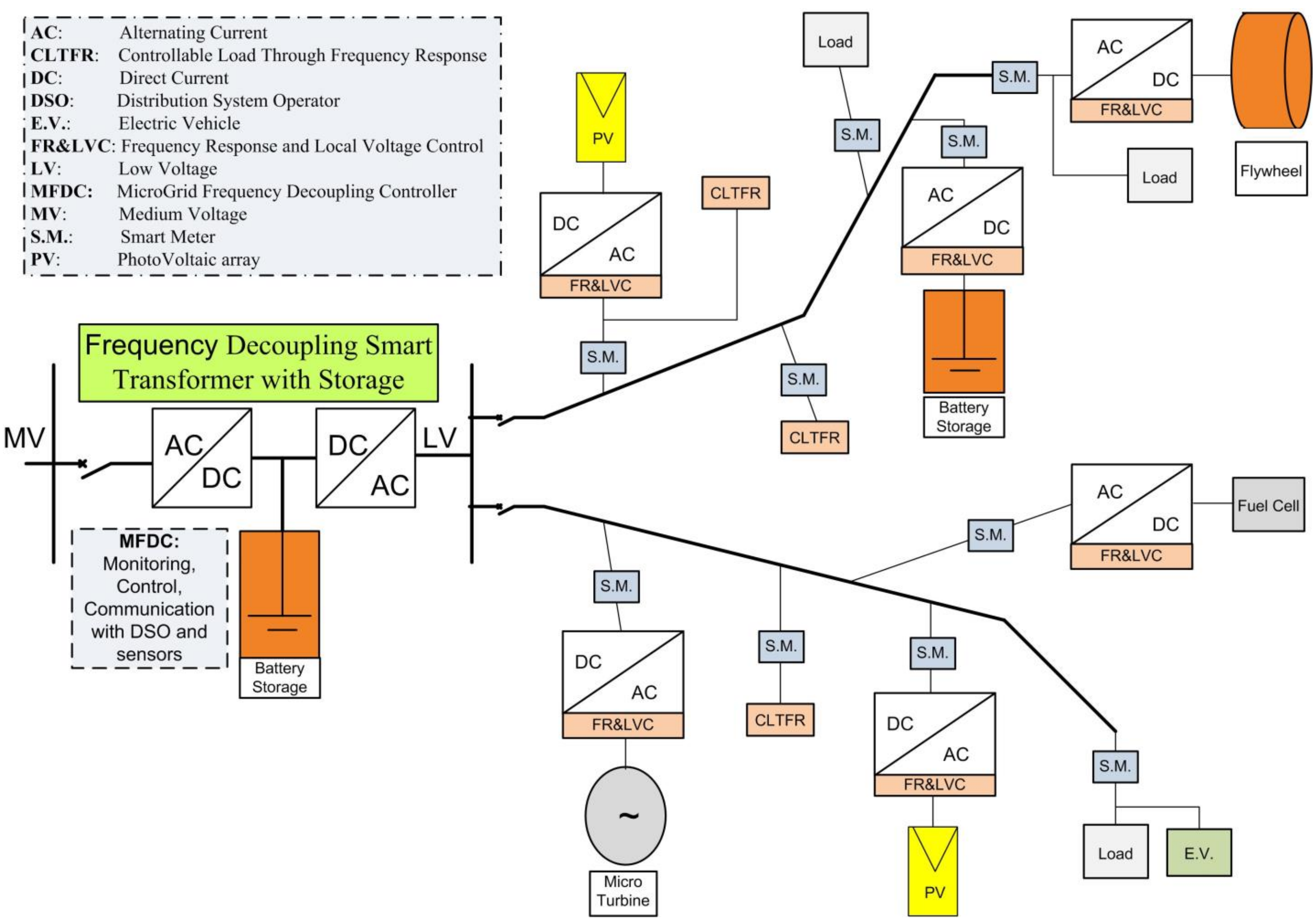

Fig. 2. LV Microgrid example, in this case two grid segments with one Frequency Decoupling Smart Transformer (FDST), in practice it could be one FDST per segment (single line electric diagram)

The distributed active DER units in the "Microgrid" will provide balancing and ancillary services such as voltage, frequency support as well as energy buffering depending on their local voltage situation, the grid frequency and their own operation state/limitations within a self-organized grid segment.
The proposed multi device communication through the grid frequency does not come for free, the frequency decoupling of the "Microgrid" means that an investment has to be made at the MV/LV transformer level but noting that such an investment provides the opportunity to effectively control the integration of new resources and the operation of an incentive based electricity market. For this purpose, a generic concept of two back to back 4-quadrant inverters with communication, monitoring, control and storage integration capabilities, sensors and algorithms for forecasting load, RES generation, implementing a "Frequency Decoupling Smart Transformer" (FDST) is proposed to be developed to serve the new concept, Figure 3.

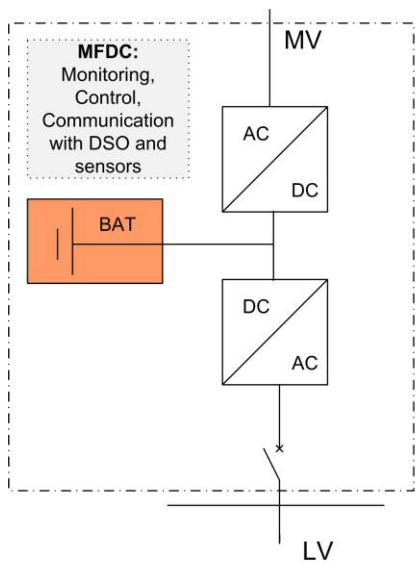

Fig. 3. Microgrid (or Grid Segment) Frequency Decoupler Controller generic concept– "Frequency Decoupling Smart Transformer" with storage (single line electric diagram)

The frequency decoupling solution may also provide the opportunity to the Distribution System Operator to introduce its own storage media (battery bank, flywheel, capacitors, etc), sized appropriately to allow islanded and transitional "Microgrid" operation between islanded and grid-connected modes. The FDST provides benefits for the LV grid network and its stakeholders without the need to revisit the "Microgrid" structure every time new resources are added to it, but only introducing regulations and technical specifications of allowed interconnection of devices per point of connection to the grid by "consumers" or "prosumers". To complete the innovative control solution, grid-connected inverters (generators and storage inverters) would have to monitor the local grid voltage in order to implement locally reactive power support functions. For the operation of the electricity market, demand and generation (in-feeding from storage media as well) response may be incentivized through tariff variation to consumers/prosumers that could be communicated through the value of the grid frequency variation instead of point to point communication “signals”.

This bottom-up self-organization approach could also be followed in the upstream grid implementing a bottom up hierarchically coordinated electrical system. The roadmap of implementation of this concept has at least three steps:

1. In grid segments with low DER unit penetration, the FDST “transformer” will be monitoring and correcting the voltage at the “transformer” connection point, which will have the capacity to vary its voltage level to avoid possible grid voltage excursions outside the accepted voltage operation window.
2. As DER unit penetration increases, the local control devices integrated in the distributed DER units may first respond to the local variation of the voltage, supporting the grid operation.
3. In even higher DER penetration or lack of local power resources at the grid segment level, the “Frequency Decoupling Smart Transformer” (FDST) will be monitoring the flow of power and the voltage variation and will adjust the frequency appropriately in order to regulate the grid segment through all grid connected “active” devices within the accepted operation technical limits. By active devices it is meant, those that monitor the voltage and frequency of the grid at their connection point and are able to perform some functions to contribute in the self-regulation of the grid segment.

Depending on the state of the wider network, where the “Microgrid” is connected, various strategies may be implemented by the Distribution System Operator (DSO), who is in communication and control of all the “Frequency Decoupling Smart Transformers”. The DSO may command the FDST to vary or minimize flow through the “smart transformer” by energizing storage reserves and/or shifting the time of use of loads, inducing temporary islanding of the grid segment or the “Microgrid”. The DSO will operate each FDST node as the last actively controlled point of the downstream grid and implement its monitoring and operational control. As by article 36 of the Electricity Directive, DSOs are not allowed to own, develop, manage or operate energy storage facilities. Although, recently Eurelectric has proposed, due to the urgent operational issues presently on-hand, such as the growth of mainly variable distributed generation connecting at the distribution level, to allow DSOs under certain conditions to own, develop, manage or operate energy storage facilities. Such storage facilities are necessary for the distribution system operator to fulfil its obligations under this regulation for the efficient, reliable and secure operation of the distribution system.

4. Operational Control

In the not too distant future, the low voltage grid segments and especially urban and semi-urban segments are expected to be dominated by PV systems, small wind generators, μCHP, heat pumps, battery storage systems, electric vehicles, all connected to the grid through an inverter. In addition, the “prosumers” and consumers will be connected to the grid through a smart meter and all buildings will have controllable loads, such that their operation could be deferred through a “signal” when it is considered appropriate and desirable in economic and system level operation related terms. In low voltage grid segments like the ones described previously the operational control will be as follows: grid connected inverters will have to be able to monitor the voltage, current, frequency and to be equipped with local voltage support functions depending on the local situation (Local Voltage Control). At the same time, as the grid is operating at its nominal frequency, of say 50 Hz, the Frequency Decoupling Smart Transformer (FDST) that interconnects the segment to the Medium Voltage, is controlling the power flow and the voltage at the LV side of the transformer in order to counterbalance any unwanted voltage excursions. The FDST, through DSO communication, is also monitoring in real time Voltage, Current of a number of smart meters along the length of the grid segment, provided by the smart metering data communication infrastructure of the Distribution System Operator (Figure 4). The smart meter information is providing a snap shot of the state of the grid segment to the FDST through the DSO and a reiterated validation of the implemented operational control by the FDST.

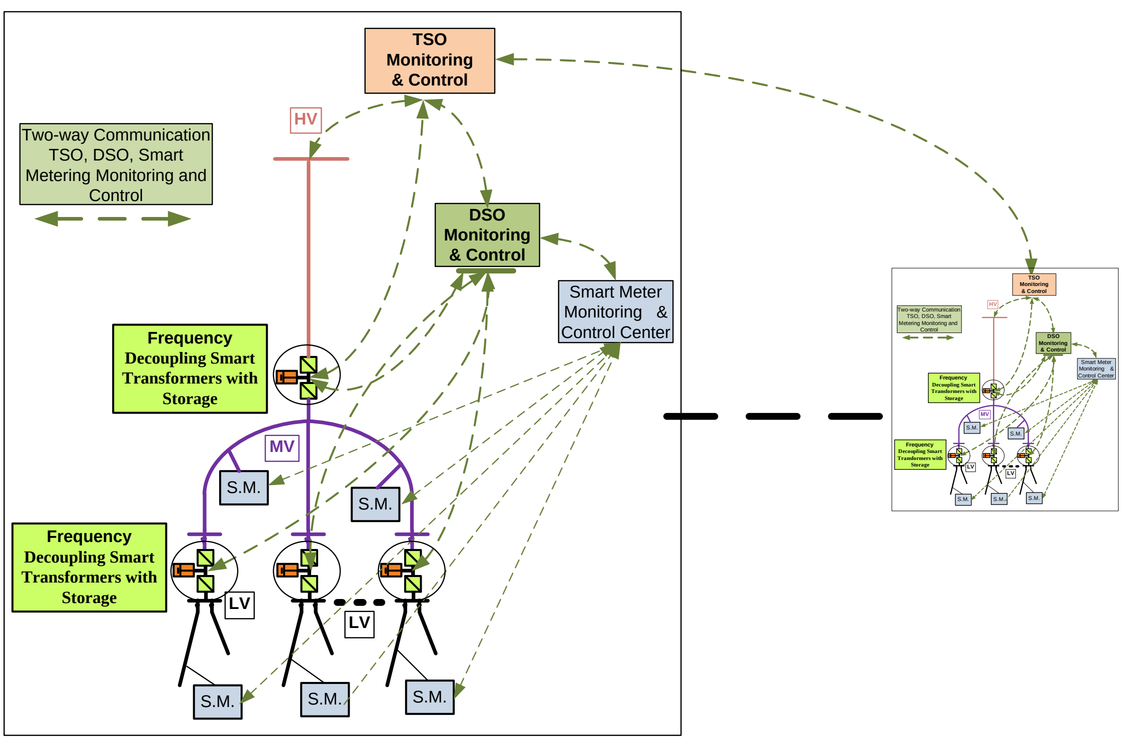

Fig. 4. Operating coordination scheme through communication flows between the Distribution System smart metering control center and Frequency Decoupling Smart Transformers (FDST) at LV and MV levels, as well as coordination between DSOs/TSOs and FDSTs control (single line electric diagrams)

The FDST controllable transformer may operate in voltage control mode, which is particularly useful for long rural feeders, where reactive power control can be often an issue.

Load and RES forecasting and historic data will be also important tools for the DSO in anticipating the grid situations and having the resources available to ride through the potential disruptive events.

Then, at a certain point in time, a situation may be reached where the local voltage compensation of distributed units in the grid segment and the voltage variation at the point of connection of the FDST are not sufficient to keep the voltage in the window of normal operation. Then the FDST through its internal logic and measurements collected will vary the grid segment frequency (see Table I) in order to "signal" active power control to all listening (monitoring) inverter devices and controllable loads to act in a coherent manner in order to stabilize the operation of the segment (Grid Frequency dependent control). Already in Germany all PV system inverters above a certain power level can be controlled with external signals and modulate their active and reactive power. The proposed control concept suggests the avoidance of direct point-to-point communication and the extra investment cost, security, latency, robustness and reliability issues. A grid frequency variation is proposed to control the power generating/absorbing devices. At the same time the grid frequency variation value within the normal frequency operation window (see Table I) can be taken to be the "signal" for tariff changes and/or service charges and credits that electric devices and consumers would monitor and respond accordingly (Demand and Generation Response) with an appropriate compensation incentive. In terms of over-frequency droop response, already for new inverters it is mandated in Germany and elsewhere, to limit their active power output according to the grid frequency increase. For the frequency windows of Table I outside the normal state of operation, the control frequency dependent "signal" is obligatory to follow by all devices for the sake of safe grid operation. It is evident that any newly added generation, storage and load shift flexibility resources will follow the same rules for power exchange as in Table I.

TABLE I: OPERATION SCENARIOS OF FDST DOWNSTREAM (LV) GRID ACCORDING TO FREQUENCY WINDOWS

Frequency window in Hz	Grid Frequency dependent initiated Actions of Grid-connected devices	Operation state	Operation Colour Code
below than 47.5	Disconnection of loads, generators, etc.	Shutdown	
47.5 – 49.5	100% feed-in of grid-connected generators, Controllable loads off and battery discharging at max allowed rated power	Emergency condition level 2	
49.5 – 49.8	100% feed-in of grid-connected generators, Controllable loads off and battery discharging at 50% of rated power	Emergency condition level 1	
49.8 – 50.2	Allow 100% feed-in of grid-connected generators Charging and Discharging of batteries and controllable loads allowed to operate according to user (aggregators) will within this window	Normal, market procedures are followed	
50.2 – 50.5	Controllable loads allowed on, according to duty cycle and battery charging on	Emergency condition level 1	
50.5 – 51.5	Grid-connected generator active power reduction by 50% per Hz, while Controllable loads on according to duty cycle and battery charging on	Emergency condition level 2	
higher than 51.5	Disconnection of loads, generators, etc.	Shutdown	

Furthermore, the DSO, when the resources and capacity is available, may implement control and energy management strategies from the FDST transformer, such as to minimize flows through the transformer, support adjacent LV grid segments and finally to optimize flows with the upstream higher voltage grid. Therefore, a bottom-up organization approach of the grid is proposed (Figures 2 and 4). Furthermore, the FDST due to its principal of operation and controlled resources will allow simple and smooth connection and disconnection of the LV segment (Microgrids) to the upstream network.
The same concept of frequency decoupling through the FDST controllable transformer can also be applied, with the same logic and organization between the Medium Voltage and High Voltage grid, as it was presented between LV and MV. Between the DSO and Transmission System Operator (TSO) exchange of information is suggested as presented in Figure 4, regarding the state of the MV grid segments, through the HV/MV FDST, for MV customer/prosumer Smart Meter information and other grid monitoring devices. The corresponding control of the HV/MV FDST is implemented as agreed between the TSO or the DSO for a coordinated and optimal operation of the electric system as presented in Figure 4.

5. Microgrid or Grid Segment Frequency Decoupler implementations

The power electronics and storage introduced to the MV/LV transformer site will have the capability for low voltage grid control, monitoring (Microgrid or Grid Segment Frequency Decoupling Controller – MFDC, see Figures 2, 3) and two-way communication capability with the Distribution System Operator. This way the grid segment or "Microgrid" will present itself to the Distribution System Operator as a single controllable entity in the network, simplifying the situation and allowing grid segment management with a very large number of grid connected electric devices. The above proposal does not exclude the collective organization and optimized operation (aggregation), within the grid segment or "Microgrid", for consumers, producers and the associated monitoring and control by Information and Telecommunication applications at the level of buildings, houses, farms, small industry, aggregation of consumers/producers, etc., within the frame of safe operation (regulated by grid code and market operation). In fact, within the usually accepted normal state frequency window of 49.8 – 50.2 Hz (Table 1), the frequency variation controlled by the DSO, will be used as the electricity tariff level "signal", incentivizing the behavior of electricity market participants and anticipating excursions outside the normal operation state. Therefore, the FDST provides a tool to the DSO and electricity market stakeholders for wide application of tariff level response control, within the normal frequency operation window. Outside the normal operation window (Table 1), all active user electric devices would have to follow in an automated mode the emergency level active power control scenarios as presented in Table 1, with appropriate compensation and charges depending on the case.

This innovative concept opens a new field of hardware and control logic development, which moves the last active point of monitoring and control of the Distribution System Operator at the MV/LV Smart Transformer for the entire downstream grid segment (Microgrid). Grid frequency droop control in interconnected grid segments offers control simplification and increased reliability in the communication solution, reducing monitoring, control points and related investments. The addition of new DER units, of predefined capacities depending on the user, the local grid segment or "Microgrid" infrastructure and local electricity consumption, etc., will allow plug and play operation, per customer connection point, due to the underlying control logic of the DER units that does not permit excursions outside preset windows of voltage and frequency.

Appropriate business models would have to be developed in order to give value to the new features offered by the FDST and compensate participating grid connected devices for services offered for frequency, voltage support and other unusual conditions reinstatement. The cost of the FDST transformer is expected to become affordable as the scale of implementation will become important. The applicability and economic potential of this novel concept is extremely large, if we consider that potentially all the MV/LV transformers (as well as at higher voltage level [HV/MV]) could be replaced with the proposed hardware and control package. The current number of MV/LV transformers in Greece is over 160.000 and by extrapolation, this number exceeds the 7 million units in Europe and over 50 million units worldwide.

The implementation example of control strategy, in terms of grid frequency variation (according to Table I and Figure 6), of active power control of generators, controllable loads and the operational behavior of battery charge/discharge cycles is presented in graphic format in figure 6. Positive values for active power mean that generators produce power (injecting) and batteries banks or Electric Vehicles (EV) are discharging (injecting) power, while negative values are only present when loads are consuming power and battery banks and EVs are charging (as loads).

If RES generators and storage devices do not exceed a nominal capacity, to be defined, at the connection point of the consumer and certain predefined technical limits, a plug and play operation concept of grid-connected devices may be implemented.

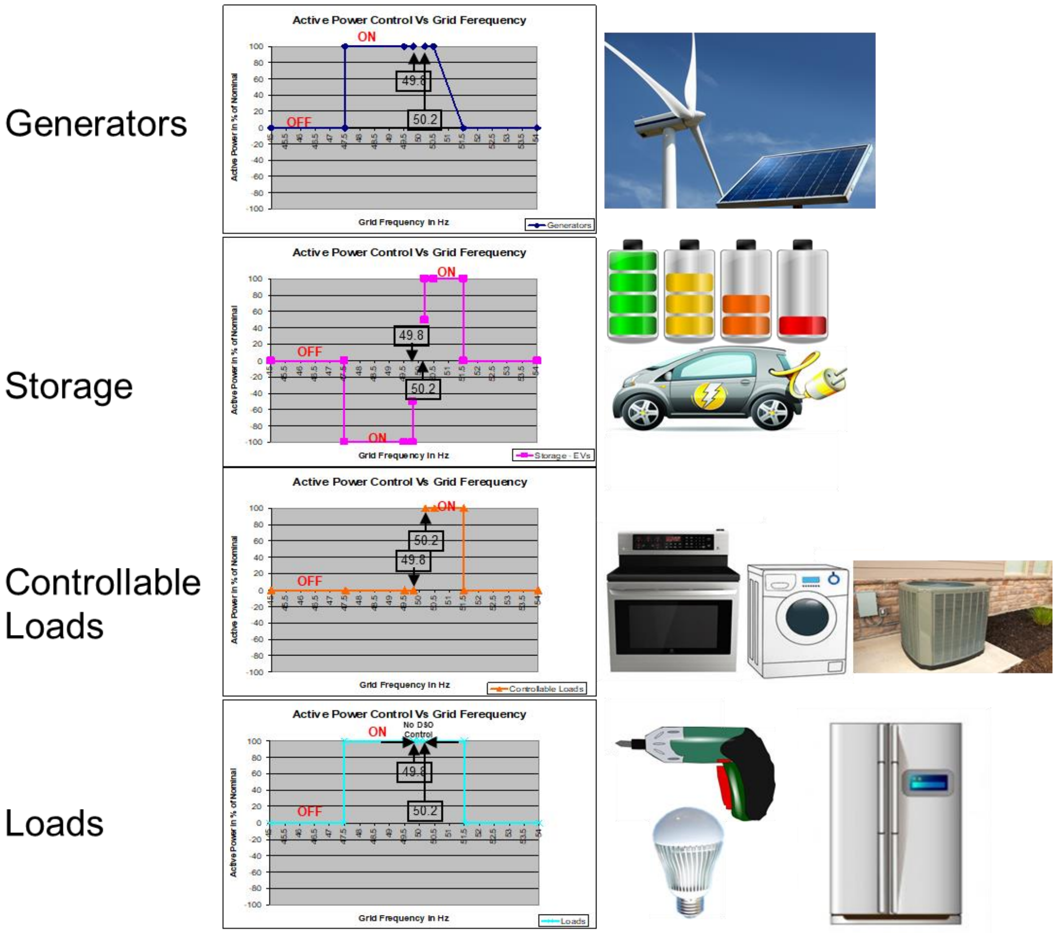

Fig. 6. Active power control strategy according to grid frequency variation (as in Table I) within a LV grid segment

Plug and play operation of "active" (frequency and voltage monitoring) devices is implemented through active power variation according to a potential scenario, frequency window, as presented in Table I and at the same time respecting voltage regulation at all points of the grid segment, through local voltage control logic of "active" distributed interconnected devices. The distributed active grid-connected devices measure the grid frequency variation, local voltage and respond accordingly (ancillary services) as in Table I, regarding active power.

Furthermore, the FDST transformer measures and controls Voltage and Frequency and thus power flow at the MV/LV transformer point.

Alternative grid frequency operation windows, to those of Table I, may be needed, for controlling distributed electrical devices and in order to comply with safety related issues. The controlled distributed grid-connected devices should also adopt new local control logic to operate coherently with the grid frequency variation.

If there is concern for the described frequency variation windows, away from the normal operation state

(49.8 to 50.2 Hz), it is technically possible to implement much tighter frequency windows compared to the ones currently presented in Table I and Figure 6.

6. CONCLUSION

The Frequency Decoupling Smart Transformer (FDST) device, as described in the above presented concept, is designed to control generation, injection and use of energy of a very large number of grid connected devices through the frequency. Furthermore, FDST allows the exploitation of local resources by the DSO for adjacent microgrids (or segments) instead of curtailing generation. The variable grid frequency, within the normal operation frequency window, could be used by aggregators and other energy management applications to manage local active devices and transactions of energy according to each aggregator's plan of action. Any excursion outside the normal operation frequency window is corrected by the "security net" concept presented in this paper. This control concept through the grid frequency is characterized by high reliability, security, lack of latency and robustness and does not need any new communication infrastructure in the LV distribution grids (microgrids). The bottom-up self-organization approach could also be followed in the upstream grid implementing a bottom-up hierarchically controlled electrical system.

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