ADVANCED POWER CONVERTER FOR UNIVERSAL AND FLEXIBLE POWER MANAGEMENT IN FUTURE ELECTRICITY NETWORK

Florin IOV[1], Frede BLAABJERG[1], Roger BASSETT[2], Jon CLARE[3], Alfred RUFER[4], Stefano SAVIO[5]
Peter BILLER[6], Paul TAYLOR[7], Brigitte SNEYERS[8]
1) Aalborg University, Denmark, fi@iet.aau.dk, fbl@iet.aau.dk
2) Areva T&D Technology Centre, United Kingdom, roger.bassett@areva-td.com
3) University of Nottingham, United Kingdom, jon.clare@nottingham.ac.uk
4) Ecole Polytechnique Federale Lausanne, Switzerland, alfred.rufer@epfl.ch
5) Università degli Studi di Genova, Italy, stefano@die.unige.it
6) ABB (Secheron), Switzerland, peter.biller@ch.abb.com
7) Dynex Semiconductor, United Kingdom, paul_taylor@dynexsemi.com
8) European Power Electronics Association EPE, Belgium, bsneyers@vub.ac.be

ABSTRACT

More "green" power provided by Distributed Generation will enter into the European electricity network in the near future. In order to control the power flow and to ensure proper and secure operation of this future grid, with an increased level of the renewable power, new power electronic converters for grid connection of renewable sources will be needed. These power converters must be able to provide intelligent power management as well as ancillary services. This paper presents the overall structure and the control aspects of an advanced power converter for universal and flexible power management in the future European electricity network.

INTRODUCTION

The establishment of a new paradigm for electricity networks in Europe in which there is large-scale integration of distributed energy resources is major element of the key strategic objective of the EU to secure a supply of energy that is clean sustainable and economical [1]. The impact of this will be to reduce dependence on fossil fuels and reduce climate change and pollution, which are of concern to all European citizens. In the new system, large numbers of small and medium sized generators and energy storage elements are interconnected through a fully interactive intelligent electricity network.

In order to reach this goal, the entire architecture of the electricity network must be redesigned and the information and communication technologies (ICT) will be the key factor [2]. New features added by ICT and ICT-based applications such as universal connectivity, services over internet and web, distributed intelligence, advanced fault handling, intelligent load shedding etc will transform the existing electrical grid into a smart one.

Among the different architectures of the future electricity systems three conceptual models are of interest [1]: Micro-grids, an "Internet" model and Active Networks supported by ICT. A possible layout of such an active network is shown in Fig. 1. Distributed Generation (DG) will increase the number of power input nodes and will provide a bidirectional power flow through the network.

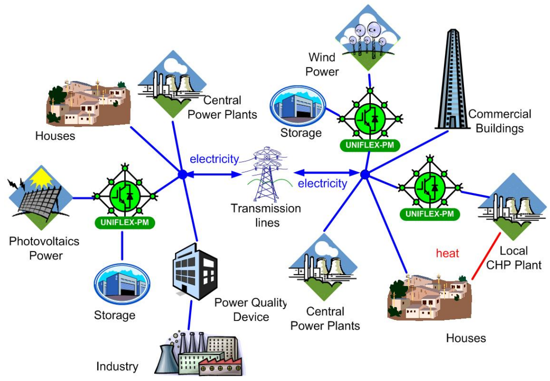

Fig. 1. Possible architecture of an active network with distributed/on-site generation and fully integrated network management.

New power electronics systems will control this power flow and also will provide flexible DG interfaces to the network. The work presented in this paper is part of a research project (UNIFLEX-PM) supported by the European Community under the 6th Framework Programme with focus on the development of key enabling technologies to reach the DG objectives. The main objectives in this project are to research and experimentally verify new, modular power conversion architecture for universal application in the Future European Electricity Network. The target is to establish technology that provides lower cost power electronics to network architects and owners and facilitates the connection of a broader range of distributed generation sources [3].

First this paper will make a review of the existing European grid codes for renewable systems with focus on MV and HV levels. Then, the general structure of the UNIFLEX-PM system as well as the control issues related with its subsystems will be presented.

INTERCONNECTION REQUIREMENTS FOR RES

Few European countries have at this moment dedicated grid codes addressed to interconnection requirements of Renewable Energy Sources (RES) and in most of the cases these requirements reflects the penetration of renewable sources into the electrical network or a future development is prepared with these demands. Among all kind of renewable sources only wind power and PV installations have specific requirements. Recently, specific interconnection requirements for Combined Heat and Power plants with power ratings of 1.5 MW or more were issued in Denmark [4] with the main target in increasing the control possibilities of these small units from the system operator point of view.

The renewable sources in the Great Britain's transmission grid code can be identified under different names e.g. DC Converters, Power Park Modules, Non-synchronous generating units, etc. The interconnection requirements in this case are addressed to power control ability, voltage quality and fault ride-through capabilities [5]. However, for connection of embedded generators below a certain power level e.g. 30 MW the Distribution System Operators (DSO) in particular regions shall be contacted.

Different DSOs exist in Germany and the general rules for interconnection at the DS level are defined in [6]. It can be noticed that there are no specific requirements for renewable energy sources. Moreover in Germany the generating units in the MV/LV distribution systems "are usually not utilized for the provision of system services" [6].

A document detailing the minimal interconnection requirements for wind turbines has been published officially in October 2006 in Spain [7]. This document addressed just two topics namely fault ride-through capabilities and reactive power/voltage control during the fault and it applies to all operators connected to the main transmission grid. However according with [13] "REE is considering including wind plant connected" at the distribution system level. On the other hand in Spain the PV systems have interconnection requirements for voltages up to 1kV defined in [8]. However in this case the PV systems shall not provide system services.

Special interconnection requirements for wind power addressed specifically at both MV and HV levels are issued in Denmark [9], [10] and Ireland [11], [12].

Examining these various grid codes it can be noticed that the requirements for wind power cover a wide range of voltage levels from medium voltage to very high voltage while the connection demands for PV installations have focus only on the low voltage level particularly in low voltage distribution networks (domestic applications). The requirements are also different for these two renewable systems. PV systems have specific demands regarding power quality and safety and protection functions e.g. response to abnormal utility conditions, direct current injection and grounding. On the other hand, the grid codes for wind power address issues that make the wind farms operate as a conventional power plant into the electrical network. These requirements have focus on power controllability, power quality, fault ride-through capability and grid support during network disturbances. According to several references e.g. [13] in some of the cases these requirements are onerous.

All considered grid codes require fault ride-through capabilities for wind turbines. Voltage profiles are given specifying the depth of the voltage dip and the clearance time as well [3]. However, in some of the grid codes the calculation of the voltage during all types of unsymmetrical faults is very well defined e.g. Ireland, while others do not define clearly this procedure.

Germany and Spain requires grid support during faults by reactive current injection up to 100% from the rated current [7]. This demand is difficult to be achieved by some of the wind turbine concepts e.g. active stall wind turbine with directly grid connected squirrel-cage induction generator. However, the Doubly Fed Induction Generator-based wind turbines will inject just the rated current of the partial scale power converter placed in the rotor circuit, which is 20%-30% from the generator's rated power. Moving to the wind farm level any wind turbine concept can meet this requirement if the wind farm is connected through a Voltage Source Converter based DC-Link Transmission System to the electrical network.

In order to cope with the network stability issues all grid codes require the curtailment of the produced power and other control signals available for System Operators (SO) [3]. However, the ability of controlling the produced power based on the SO demands is currently provided only by large wind farms. In future a major challenge will be to make this feature available also to small units.

An increased level of renewable power into the electrical network will determine interconnection requirements for all renewable sources similar with those for wind power. Therefore, any renewable system will have to fulfill the grid codes without major changes in the control algorithms as well as in the hardware structure. Thus, a universal and flexible power converter is the key element in grid integration of the renewable sources.

UNIFLEX-PM SYSTEM

The main target of the UNIFLEX-PM system is to provide a universal and flexible power electronic interface for grid connection of RES including storage facilities. A possible structure of the UNIFLEX-PM system is shown in Fig. 2.

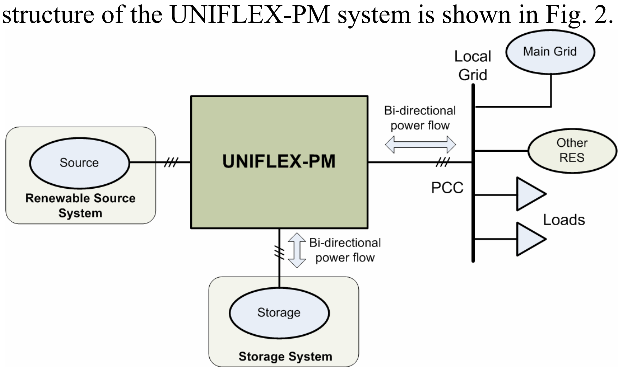

Fig. 2. Structure of the UNIFLEX-PM system for grid connection of RES including storage facilities.

The system comprises of a renewable energy source connected to an AC/DC power converter to a common DC bus-bar. Since the only renewable source able to support bi-directional power flow is the PEM fuel cell, this power converter must be able to support just a unidirectional

power flow. A storage system is also connected to the DC bus-bar. The structure of the power converter in this case depends on the type of the storage element. It can be an AC to DC conversion stage or just a DC to DC one. The grid connection is made through a power converter which can also have a modular approach.
The power rating of the system is around 5 MW (e.g. 1 MW/module) with a rated voltage in the PCC of 10-20 kV. This voltage level is very common in most of the distribution systems in the European countries. However, using a transformer with high voltage on the primary side a connection to the transmission system is possible.

Renewable Source System

Basically any renewable source can be used in this system. However, the structure of the generator side converter as well as its control will be determined by this source.
In wind applications the power converter and its control are determined by the generator type. The general structure of the UNIFLEX-PM system can be used in a full scale power converter based wind turbine. Therefore, mainly three generators types can be used in this case namely synchronous generator with field winding, permanent magnet generator and squirrel cage induction generator.
The synchronous generator will require a diode bridge rectifier and an additional fully controlled power converter for the field winding. The permanent magnet generator is used in direct driven wind turbines and two conversion stages are required. First an AC/DC power stage based on voltage source power converter will assure the variable speed operation then a DC/DC power stage will keep the DC-link voltage fixed on the common DC-bus. Finally, the squirrel-cage induction generator is using a fully controlled power converter without any additional power stages.
In each case generators with multiple stator windings can be used and thus the efficiency is increased at low power production.
In most of the biomass Combined Heat and Power plants an electrical system similar with that from wind turbines can be used.
A PV source will require a DC to DC conversion stage as well as a fuel cell system.
In all cases the control of the generator side converter has as main goal to optimize the maximum power extraction and to assure the optimum operation point of the generator.

Energy Storage System

Energy Storage Systems are in a continuous development and new improvements in cost, efficiency, control algorithms, etc. is added constantly. Each technology has advantages and drawbacks and choosing a particular technology implies several factors e.g. renewable energy source and the corresponding power conversion topology; grid connection requirements; overall cost of generation and storage; environmental and social aspects.
Some storage technologies are constrained by environmental or safety considerations. Solenoidal configurations for Superconducting Magnetic Energy Storage produces external magnetic field and an exclusion zone around the units is required. Lead acid batteries require planning of handling and transport of the electrolyte while Compressed Air Energy Storage requires a suitable site for the reservoir.
Thus, the energy storage technology must be chosen in agreement with the renewable energy source and basically the following issues must be taken into account:

- **Functionality of the energy storage system versus time response**. In order to compensate for load-levelling policies a medium term storage capacity is needed while power quality issues will require a very short term storage capacity.
- **Area or volume of the storage system compared with RES**. Some of the storage technologies require a relative large area or volume therefore the selection of the storage technology must take this aspect into account.
- **Decoupling of the storage capacity and power rating**. Some storage technologies e.g. advanced batteries like REDOX can offer this feature and can make the entire system much more flexible.
- **Relatively long life time** ca. 20 years which is typical for example for most of the wind turbines.
- **Low Maintenance**.

The structure of the storage side power converter is related to the type of the storage technology used. This power converter shall be able to support a bidirectional power flow. Its control has focus on optimizing the storage/extraction of energy in the storage element.

Grid Interface

The grid side converter is the key element in respect with the interconnection of the UNIFLEX-PM system to the electrical network. It shall be able to transfer the renewable power to the grid, to meet the grid code requirements and to keep the system connected over a wide range of operating conditions e.g. faults, island operation, etc. Moreover, ancillary services such as voltage control and black-start capability must be provided. A paralleled structure will improve the overall efficiency of the system and will also improve its redundancy.
Voltage and current measurement for each phase in the Point of Common Coupling (PCC) must be available for the converter control. A hardware protection for power switches e.g. high-speed fuses as well a software protection can be used.
The control algorithm of the grid interface must be able to handle unsymmetrical faults, to inject full reactive current during grid faults and to operate both in grid connected- and islanding mode.
The structure of this control shall include advanced Phase Locked Loop structures in order to cope with unsymmetrical and unbalanced voltages, fast current control in each phase and advanced control techniques for active/reactive power e.g. injection of negative sequence of the voltage
The steady state performances are given mainly by the

switching frequency and flicker content of the produced power. Voltage quality parameters e.g. harmonic compatibility levels, Total Harmonic Distortion, etc. shall meet the requirements from EN 61000-2-4 standard. Flicker emission can be improved by using the storage system.

Overall Control and Energy Management

The entire control of the UNIFLEX-PM system comprises basically two levels of control namely the control associated with each subsystem and the overall control including the energy management.

The overall control shall include the several modules/functions. Power/frequency control including primary control shall provide the balancing of the instantaneous power consumption and the production in the whole area as well as the secondary control for balancing the power production and demand within the regional zones. The power production shall follow the power set-point imposed by the Distribution System Operator (DSO) and Transmission System Operator (TSO).

Voltage control is controlling the voltage in the whole area. This control shall follow the system operator demands for reactive power. Moreover the control must be able to regulate the voltage in islanding mode.

Advanced grid monitoring techniques e.g. detection of islanding and estimation of the distance to fault must be included. The detection of islanding is used to change the priorities in controlling the frequency and the voltage in the PCC while the estimation of the distance to fault can be used to change the control strategy during faults. For example when a fault is detected near the PCC the grid interface cannot provide grid support while the distance to the fault is relatively large the grid interface can inject 100% reactive current.

Short term and medium term estimation of the power production based on meteorological data e.g. wind prediction, solar irradiation, etc. can be used in spot market as well as by the DSO/TSO for balancing the system.

Energy management with the main target in optimizing the power production and energy storage based on actual and estimated power production, grid conditions and system operator demands shall also be included. Optimizing the operation of the paralleled power modules based on the actual production can be another function provided by this module.

Circuit breakers must be used for overall protection of the system. Communication protocols and data exchange with the system operators must be provided as well as voltage and current measurement in the PCC.

CONCLUSIONS

In order to facilitate a high penetration of DG in the future European electricity network advanced power electronic converters are needed. These converters shall be able to provide an intelligent management of the renewable sources including storage technologies as well as system services. Currently, all existing solutions are addressed to particular technologies and a universal and flexible power converter is needed. This paper presents the structure and the related control of such a power converter. This power converter has a modular architecture based on Medium Frequency transformer isolation modules incorporating advanced magnetic and insulating materials. This modular approach leads to high reliability and low cost. Connection at different voltage levels and powers is made possible by series/parallel connection of modules. This power conversion system can connect different sources and/or loads including energy storage with different characteristics and power flow requirements. Advanced control strategies to control the local converter energy storage and energy flow together with global control to manage the interaction with the grid/loads/storage elements are also included.

Acknowledgments

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