IMPROVED GRID INTERACTION OF PHOTOVOLTAICS USING SMART MICRO-INVERTERS

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SUMMARY

Small-scale solar photovoltaic (PV) generators are a popular choice for renewable energy supply in residential and small commercial applications, because of good possibility of roof utilization and building integration. Solar PV is also one of the least controllable RES due to intermittency of prime mover. A major industry driver is improving energy harvest efficiency through better maximum power point tracking (MPPT). In grid-connected applications an inverter is required as a conversion and grid synchronization interface. The improvement in MPPT efficiency and system reliability, as well as some practical installation and maintenance issues have lead to a decrease in inverter size and increase in modularity. With technological improvements and cost reduction, module-integrated inverters or micro-inverters are becoming a preferred choice in residential installations.

The SELECT+ is a joint doctoral research program in the area of sustainable energy technologies, sponsored by European Commission. "Positive energy house" is a name given to the project of 2012 that unified a variety of research topics, including the one presented in this thesis. The project contribution is aimed at conceptual development and practical implementation of *net positive energy building*. The grid-connected solar PV generators are instrumental to this task.

The problem of high PV penetration scenarios in residential LV grids forms the backbone of this research. The research goal is to provide a solution for increasing the PV grid hosting capacity, while avoiding changes in the grid infrastructure itself. More specifically, the objective is to develop a new control method of PV inverter in order to prevent overvoltage. The micro-inverter is selected as the most suitable inverter niche to carry out the solution implementation and meet the following objectives: contribute the technical

development of net positive energy house, with a distributed solution that can be seamlessly integrated within the built environment; from sustainability aspect the solution must consider not only the new PV systems, but also the possibility of retrofitting the old systems instead of replacing them; the solution should support the DSOs by increasing their remote monitoring and control capacities in LV grids; the solution should support/increase the inverter reliability.

The grid is generally not designed for high PV penetration scenarios. The expansion of distributed generation technically required the enabling of grid connection, first at medium voltage level, and with full market liberalization, at low voltage (LV) level as well. The market liberalization created the conditions for both businesses and individuals to participate in the electricity supply, therefore making the distributed generation even more dispersed. The consumer was given the chance to produce electricity, hence the term "prosumer" was coined. The distributed generation has changed the power flow from unidirectional to bidirectional in a grid that was designed to operate as unidirectional. Increasing wind and PV-based generators practically means increasing the presence of intermittent, uncontrollable prime movers. Reducing fossil and nuclear fuels practically means reducing controllable prime movers and losing synchronous generator rotating inertia which is desirable to have in situations with destabilized power system. The frequency and voltage control is then contradictorily becoming more dependent on the uncontrollable prime movers. The intermittent renewable energy sources mostly cannot be synchronously coupled to the grid as conventional sources. They require power electronic converters as a coupling and synchronization interface. The bidirectional power flow along with increasing presence of power electronics converters creates a new supply-demand interaction which is impacting the power quality, control and protection in new ways that yet need to be investigated before large-scale implementation can take place.

Attractive incentives and shift of the building energy efficiency towards net zero paradigm are promoting fast expansion of distributed PV capacities in residential LV grids. This causes suboptimal inverter-grid interaction and power quality deterioration. The overvoltage due to exceeded grid hosting capacity is one of the most immediate problems in large-scale integration of PV. The random process of single-phase PV deployment to three-phase LV grid creates voltage unbalance, which, combined with limited hosting capacity, increases chances for overvoltage. The overvoltage can cause significant feed-in losses due to inverter being frequently disconnected by its overvoltage protection system. Most PV inverters deployed to date only have basic functionalities such as power output maximization and protective disconnection in case of grid disturbance.

The term "smart inverter" signifies the introduction of new control capabilities that exceed the basic ones in order to optimize between grid operational requirements and feed-in power maximization. Of special interest are reactive power support and active power curtailment. To make the transition towards smart inverters, the old inverters either have to be replaced or retrofitted. Retrofit can be a more sustainable option, especially if it can be done only by software intervention ("soft retrofit"). Large-scale software retrofits are already a reality. The policy makers issue technical recommendations to avoid inverter replacement at all cost. Software retrofit can be challenging from the design-for-reliability aspect, especially for micro-inverters, due to their outdoor application and direct exposure to the environment. The capability of accessing the inverter remotely is essential for a cost-efficient software retrofit.

The active power curtailment is recognized as a retrofit-friendly voltage control method for micro-inverters in LV grids. The retrofit is an important aspect of smart inverter implementation, hence it was made on of the objectives of this thesis. The key criteria of sustainable retrofit is established in Chapter 5: control strategy, reliability and warranty, availability of remote access, and grid interaction between old and new inverters. The active power has a much more dominant effect on voltage control in LV networks and is more retrofit-friendly compared to reactive power control.

Chapter 6 reveals how a micro-inverter modular topology coupled with ICT support can be pushed beyond its current use, in order to deliver high PV penetration neighborhoods, while keeping the grid safe and supporting the inverter reliability. It is implemented as the *Sequential Module-level Tripping* (SMT), a modified overvoltage protection scheme that achieves curtailment on a system level, without modifying the functionality of an individual micro-inverter unit. This makes SMT a more reliable and retrofit-friendly alternative to convention curtailment solution based on active power-voltage droop. The assumption of SMT's design-for-reliability is that reconnection time provides some cool-down to MOSFETs and capacitors, whereas the cool-down resulting from droop-scheme would be less, as it is still a continuous, operating state. The SMT relieves MOSFETs from duty cycle variation allowing them to be engaged only in default MPPT operation. While droop is applicable for all inverter ratings and topologies, the limitation of SMT is that it is economically sensible only for small-sized inverters (250W-500W) which is the domain of micro-inverters.

The algorithm parameters can be configured both locally (single point of common coupling) and over a wide-area (multiple coupling points along the feeder). Locally, these parameters only consider the voltage rise problem from perspective of a single PV system, while wide-area configuration allows the distribution system operator to balance between voltage requirements and energy export at feeder level and coordination with their own protection gear, OLTC transformers, etc. A two-way parameterization is proposed in order to balance between voltage requirements and energy export. One way is to manage the width of the voltage control range while another way is by managing the micro-inverter trip delay time.

The SMT controller is considered in two varieties for two scenarios: software retrofit and hardware retrofit. The software retrofit allows seamless integration with zero cost involved. Given the rising importance of massive smart grid inverter retrofits in the future, the software retrofit should be given priority whenever possible. Most of the micro-inverters available on the market today are sold in package with a data concentrator device, more often called "gateway". They communicate to micro-inverters via mesh radio or power line communication while remote communication with an application is done via ethernet (TCP/IP). The SMT trip delay and voltage control parameters can be assigned to micro-inverters via gateways. The actual voltage monitoring and control loop remains internal to the micro-inverter while the gateway only manages the behavior of micro-inverter, hence the term "feed-in management" is introduced.

There is no unified standard in micro-inverter development platforms and communications used in gateways. Secondly, micro-inverter market is very competitive and from author's industry experience as a system integrator, the manufacturers are generally not open to the idea of sharing their firmware with 3rd party integrators to implement new functionalities. This complicates the idea of unified SMT retrofit for different manufacturers and, depending on the urgency of enabling power curtailment, hardware retrofit would be faster, but more expensive solution. Independence from micro-inverter technology is achieved by adding external slave relays instead of targeting inverter's internal protection switches There is fixed added cost due to dedicated master controller and voltage sensor at the point of common coupling (distribution panel). Furthermore, the slave relays present a growing cost due to inverse economies of scale - the bigger the PV capacity the more relays will be needed.

The SMT algorithm and controller are applied in a 14-bus Dutch residential feeder model and simulated for effects on voltage and feed-in losses. Modeling and simulation is described in Chapter 7. For the proof-of-concept investigation of SMT effectiveness in voltage regulation, a *worst-case scenario*, constant power flow is performed. In this simulation two wide area control schemes are proposed and tested: *branch trip delay* (BD) and *branch-and-bus trip delay* (BBD). The results show that, after applying SMT curtailment, the bus voltage levels are within tolerances compared to massive overvoltage occurring without SMT. Both BD and BBD perform almost identically in flattening the voltage along the feeder and minimizing the distribution losses. However, BBD, being a scheme with greater number of power steps, provides better granularity of control. For consequence this creates smoother voltage ramp, less power curtailment so more generating capacity is preserved throughout the curtailment event. With the application of BD scheme the preserved generation ranges from 25% to 63%, while BBD preserved generation ranges from 38% to 75%.

The BBD as the better performing scheme is then applied in an annual power flow simulation with variable load and generation profiles. In both constant and variable power flow simulations the objective is to mitigate overvoltage using SMT and preserve certain percentage of generation as opposed to 100% power loss. Throughout the year the overvoltage prevention efficiency of SMT is quite high with only a few events out of 515 that it was unable to successfully resolve due to unsynchronized voltage control trigger over multiple buses. A successful PV penetration increase from 5A to 8A per house, for the case of Dutch residential feeder was achieved without changing the grid infrastructure. The wide-area curtailment scheme allows the distribution system operators to optimize between various priorities such as voltage levels vs. total feeder output, economic equality between connected parties, voltage unbalance and curtailment execution time.

The voltage unbalance in synergy with excess generation can additionally escalate the overvoltage problem. The LV grids are inherently more unbalanced due to random placement of single phase loads and generators. Micro-inverters are almost exclusively single phase, and increase the risk of voltage unbalance occurrence. Having a densely deployed remote sensor infrastructure becomes very expensive at LV level due to high number of nodes that need to be covered. Therefore, Chapter 7 also addresses micro-inverter gateways for possibility of exploiting their data aggregation capability and retrofitting them with voltage unbalance monitoring capability. The idea is to bridge the gap for single-phase grid-connected devices that, by their design, have no capability to analyze a three-phase parameter such as voltage unbalance.

For this purpose Monte Carlo stochastic power flow is simulated for an unbalanced LV grid model. Also an alternative, less computationally and technically demanding method is proposed for implementation of voltage unbalance factor monitoring. The solution proves to be limited by gateway aggregate sample rate and is not precise in extreme unbalance situations. Given the lack of power quality monitoring capability, higher voltage unbalance potential and big presence of single-phase loads in LV networks, it might be a worthwhile, intermediary monitoring solution that can add more value to the already deployed micro-inverter systems.

The Chapter 8 is dedicated to techno-economic analysis. This analysis first considers dynamic active power curtailment as a general category among solutions for overvoltage mitigation and projects its benefit trend for five EU countries. Two trends are identified based on knowledge of supply impedance in the analyzed countries: one trend considers only the resistive impedance part and the other considers the complex impedance expressed as the R/X ratio. According to former trend Poland takes the first place and according to latter, the Netherlands takes the first place and Poland is second in terms of extracting the most benefit out of curtailment. Such trend for Poland can be explained by high supply impedance of dominantly rural LV grid with high voltage variations.

In second part of the techno-economic analysis, an economic advantage of SMT over conventional overvoltage protection is analyzed with a novel annual feed-in loss assessment methodology. This method identifies two types of curtailment events based on their relation with overvoltage events: *preventive curtailment* that actually prevents overvoltage and *wasteful curtailment* that triggers power reduction, but is not a precursor to overvoltage event. This dual approach in treating power curtailment helps determine the true benefit of such action. For the selected Dutch grid scenario, at individual household level, the curtailment has a highly preventive character that doesn't go below 96.8%, while the maximum realized wasteful curtailment is not higher than 0.8kWh annually. On the whole feeder level the SMT brought 77.4% more yield than the overvoltage protection while wasteful curtailment share is insignificant. This translates in 550 kWh energy saving which could easily cover a monthly electricity bill of one household.

The third and the final part of the techno-economic analysis concerns the effects of SMT and droop power curtailment implementation on micro-inverter component reliability. The initially assumed micro-inverter reliability benefits of SMT over droop are investigated using the 217plus^{TM}, a well known reliability prediction methodology for electronic components. The study reveals that, depending on the applied power curtailment method, the interests can be conflicting from design-for-reliability point of view. While SMT might be favored over droop due to being almost 50% more effective in reducing failure rate of electrolytic capacitors, it might significantly increase the failure rate of electromechanical protective relays by 1000%. This conflict can be avoided by making a an early design recommendation: for micro-inverters with active power curtailment capability, SMT should be a more preferred over droop because of the more beneficial impact on DC bus capacitors, provided that AC protective switch is not electromechanical, but a solid state.

The thesis concludes with a hardware-in-the-loop (HIL) validation study of three different voltage support retrofit solutions: droop curtailment, reactive power control and SMT. These software retrofits are evaluated with respect to internal effects on micro-inverter like electrical stress and thermal behavior, as well as effects on the grid voltage magnitude and harmonic contribution. The models are simulated using Typhoon HIL402 real-time simulator: micro-inverter power stage is simulated at 1μs time step on an FPGA chip customized for solving power electronics, while controller is implemented on a dedicated ARM processor.

The SMT implementation can provide the highest and instantaneous grid voltage reduction. Its implementation must ensure that inverter reconnection to grid should not happen at low end of the DC link voltage control range in order to avoid DC undervoltage problems. The SMT provides the greatest positive contribution to internal temperature reduction, but also the greatest negative contribution to DC link electrical stress. SMT is better option if inverter harmonic contribution needs to be eliminated especially for inverter types that do not have active harmonic filtering.

Changing the reactive power reference in an inverter without decoupled active/reactive power control is not possible without comprising reliability and operation according to standard. Also the contribution in lowering grid voltage is 3 times smaller than that of SMT and can be attributed mainly to active power reduction. Since this control approach is acting directly on the PI controller, its characteristics would have to well known before retrofit otherwise large references could push it towards marginal stability/instability. That being said it is unlikely that retrofit could be executed remotely without taking the inverter offline for thorough testing. With respect to harmonics scenario, the reactive power retrofit is hardly worth the risk considering the injected current deterioration and virtually no voltage reduction contribution coming from reactive power change.

The droop curtailment retrofit does not target the PI control directly but rather conditions the output at boost converter level. The boost duty cycle variation has more flexibility than reactive current reference variation. However, the same problem of active-reactive power coupling occurs and the power factor deteriorates as the reactive power tries to compensate the change in active power. This kind of retrofit must ensure that the inverter under consideration has some form of active-reactive power decoupling implemented beforehand. This decoupling cannot be achieved remotely as it either requires hardware modification or complex intervention on controller.

The lowest complexity of SMT implementation makes it most promising for performing the retrofit remotely. However, due to a large number of existing inverter designs and control strategies the SMT does not provide a "one size fits all" answer, but consulting would be required for each inverter design and manufacturer. In terms of thermal performance and harmonic current magnitude reduction, the SMT proved to be the most beneficial retrofit option. The micro-inverters were evaluated as the most suitable inverter niche to carry out the solution implementation and meet the research objectives sustainably, especially due to possibility of industry-proven remote software retrofit and increased system-level reliability.