Final report of the FRS project on TUT's activities and achievements: June 1st 2016 - December 31st 2018

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This is a brief overview of the activities and deliverables of Tampere University of Technology (TUT) in the FSR project. More details of the project deliverables are available in specific reports listed below and publications listed at the end of this report.

Activities and deliverables of the year 2016 have been reported already in January 2017 and activities during the period 1.1. -31.5.2017 in June 2017, during the period 1.6.-31.12.2017 in January 2018 and during the period 1.1.-30.6.2018 in June 2018. Deliverables are in line with the project plan and are enumerated in here only shortly. The specific project reports distributed in January 2017, the four previous overview reports and the main deliverables are as follows:

- Report: PV generator power fluctuations under measured climatic conditions (Seppo Valkealahti)
- Report: Review of grid code requirements for solar photovoltaic systems (Ontrei Raipala and Sami Repo)
- Report: Energy-storage point-of-connection in PV energy systems (Teuvo Suntio and Jussi Sihvo)
- Report: Distributed maximum power point tracking architectures to mitigate effects of PV generator mismatching (Jyri Kivimäki)
- H2020 project proposal was filed during 2016 by the TUT solar power research team related to flow batteries and PV power production and the preparation of a second H2020 project proposal was started in 2017 by Assistant Professor Tuomas Messo. It was later concluded that it was not possible to include TUT in that proposal due to too high number of existing partners. However, based on contacts obtained during 2017, TUT is now actively participating on proposal intended for 2019 H2020 call.
- Overview report on activities and deliverables of TUT in 2016.
- Overview report on activities and deliverables of TUT on the reporting period 1.6.2016 – 31.5.2017.
- Overview report on activities and deliverables of TUT on the reporting period 1.6.2016 – 31.12.2017.

- Overview report on activities and deliverables of TUT on the reporting period 1.6.2016 – 30.6.2018.
- Workshop with companies on the future market needs and technology development scenarios of power systems in Aalto University on 22.3.2018.
- Tutkimusprojektin tulosseminaari; Business Finland, Porkkalankatu 1, Helsinki, 15.11.2018.
- Steering group of the project had 9 meeting as follows: 2.9.2016, 10.1.2017, 10.4.2017, 16.8.2017, 22.11.2017, 17.1.2018, 24.5.2018, 3.10.2018 and 29.3.2019.
- Advisory board of the project had 6 meeting as follows: 4.10.2016, 17.1.2017, 3.5.2017, 30.8.2017, 7.2.2018 and 15.11.2018.
- 22 journal papers have been published on solar PV systems during the period from 1.6.2016 to 31.12.2018.
- 38 conference papers have been published/presented on solar PV systems during the period from 1.6.2016 to 31.12.2018.
- In addition, 7 more journal and 9 conference paper manuscripts on solar PV systems have been submitted during the year 2018 for publication.

The research focus in TUT for the year 2018 was in connecting energy storage systems in parallel with solar PV power plants to mitigate power quality and stability problems and to find the means to improve reliable and efficient operation of PV generator and converter in conventional grid feeding mode as well as in grid forming mode for micro-grids. Also a workshop was held on the future market needs and technology development scenarios of power systems on 22.3.2018 and a public dissemination seminar on 15.11.2018. In the funding application for the years 2017 – 2018, the associated research tasks were as follow.

Task 1.1 Power stability and quality requirements
Task 1.2 Balance of power grid
Task 1.3 Balance, control and operation of micro grids (research started in 2017)
Task 1.4 Design, control and operation of next generation solar PV inverters including storages
Task 2.1 Maintaining stability in PV powered micro grids (research started in 2017)
Task 2.3 Parallel Operation of Grid inverters (research started in 2017)
Task 4.1 Reliable and efficient operation of PV power generator
Task 5.1 Market, system and technology development scenarios of utility scale PV power production
Task 5.2 Future scenarios of electric power prosumers

Status overview of the research work at TUT related to the goals and deliverables set by Tekes in the funding decision is reported down below. Specific results and research findings are reported in detail in the publications listed at the end of this document.

1. Tekes funding decision: Tavoitteena on analysoida sähkövoimajärjestelmän asettamat tehotasapainoon ja sähkön laatuun liittyvät vaatimukset aurinkokennovoimaloilla ja ennakoida tulevaisuuden vaatimuksia.

Partial shading caused by moving cloud shadows is the dominating source of fast PV generator power fluctuations. Irradiance and PV generator power fluctuations caused by moving cloud shadows have been analyzed based on the measurements conducted with the TUT Solar PV Power Station Research Plant. It has been operational since summer 2011 and a measurement database has been collected continuously with 10 Hz sampling frequency. It contains all climatic measurements and measurements conducted with 24 pairs of PV module irradiance and temperature sensors located around the PV plant and a set of electrical measurements.

In Finland as in most of the Europe and other similar climatic conditions, half cloudy days occur more frequently than the other weather types and they cause, accordingly, major fluctuations to the produced PV power. All the characteristics of irradiance transitions have been analyzed comprehensively including shading strength, velocity, speed and duration of transition as well as their annual, daily etc. occurrence. A mathematical parametrization of the irradiance transition characteristics has been also created, which enables to simulate and model various effects of transitions on the PV generator operation. All the irradiance related scientific findings have been published by the end of 2016.

Systematic analyses of the mismatch and maximum power point tracking failure power losses caused by irradiance transition on different spatial and electrical PV generator layouts have been conducted since summer 2016. Results related to the PV generator mismatch losses have been reported for the project consortium and published in scientific papers in 2017. Most of the research work related to multiple maximum power points (MPP), and their occurrence and tracking failure of the global MPPs has been completed in 2017 and all the main finding have been published In journals.

Weather conditions vary considerably around the globe and clear sky sunny days, half cloudy days or overcast cloudy days can dominate the solar irradiance conditions in many areas. Daily solar irradiance fluctuations vary a lot from day to day and the average daily time of power fluctuations is of importance on PV power production stability and power quality point of view (Fig. 1). One common way to limit fluctuations of the PV power fed to the grid is to apply ramp rate limits, typically of the order of 10%/min set by electricity companies. Time of ramps with decreasing or increasing PV output power higher that 10 %/min of the power plant nominal power was found to be daily from few minutes up to 4 hours. The average daily time of these ramps is over 100 minutes in Finland. PV power fluctuations caused by cloud shading are smoothed by the spatial area of the PV generator compared to point irradiance measurement and an improved spatial smoothing method has been developed and tested to model power fluctuations of different PV generator layouts. In addition, state of the art compensation strategies of PV power fluctuation with energy storage systems (ESS) have been tested and further developed. Accordingly, basic energy and power requirements for ESS have been analyzed to compensate fluctuations of PV power fed to the grid.

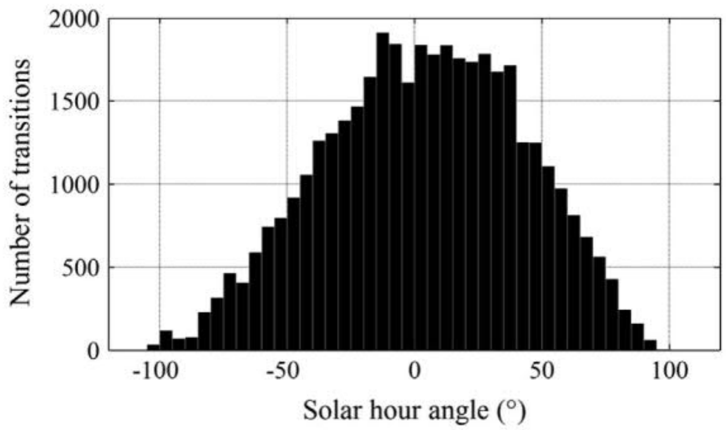


Figure 1. The daily distribution of the recognized irradiance transitions during 13 summertime months.

One research focus in 2017 was in ESS requirements for compensating the PV power production and power fluctuation with respects to the day ahead and in day electric spot market practices and terms. The energy, power, etc. requirements have been studied for an energy storage system in a solar PV plant to feed the power to the grid meeting the electricity spot markets practices. An ideal PV energy production forecast was assumed to be available to define a reference power of the system for the studied imbalance settlement periods and the energy produced by the PV generator was set to be equal to the energy fed to the grid during each imbalance settlement period (Fig. 2). The analysis was done for 0.1, 1 and 10 MW PV plants using the existing irradiance measurements of the Tampere University of Technology solar PV power station research plant.

Energy capacity requirement for ESS was directly proportional to the PV plant size so that for a typical 60 min Imbalance Settlement Period (ISP) on the electricity market the ESS needs to be able to deliver the PV plant nominal power for 0.36 h (Fig. 3). This result is in line with earlier studies on the ESS energy capacity requirements to compensate PV power plant fluctuations with respect to different ramp rate limits. The capacity requirement decrease slightly with increasing PV plant size due to increased spatial smoothing of power fluctuations with increasing PV plant area. The probability density distributions of the ESS energy and power capacity requirements for the studied PV generator sizes revealed that periods of high and fast irradiance fluctuations took place during a small portion of time of the year and caused the highest requirements. The high requirements are caused by periods (days) of plentiful irradiance and power fluctuations taking place rarely. Therefore, the required energy storage capacity could be downscaled considerably, for example, by sacrificing some produced energy during periods of high number of fluctuations to meet the market terms or by paying the cost of some imbalance on the market.

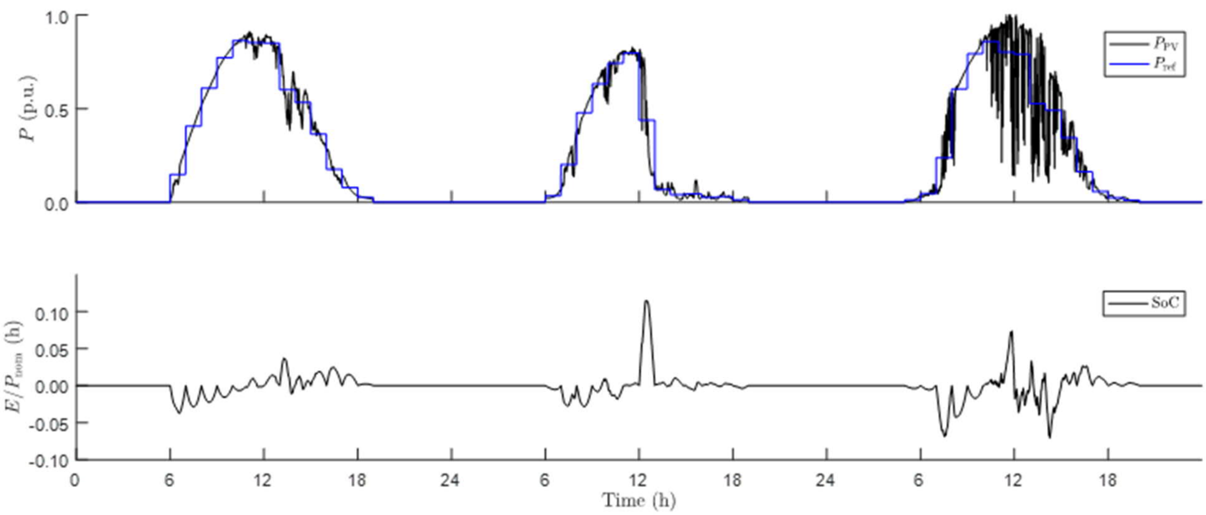


Figure 2. On top is the PV generator output power and the power fed to the grid, i.e., the reference power for state of charge, and down below is the state of charge of ESS during three days from April 11 to 13th in 2015.

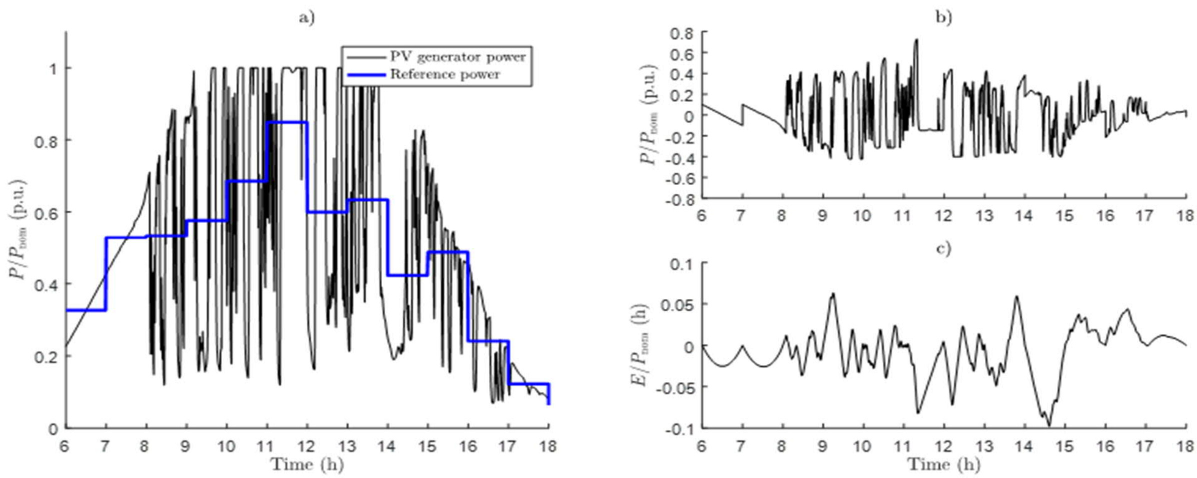


Figure 3. a) 10 MW PV generator power and the grid feeding reference power with 60 min ISP, b) the corresponding power taken from the ESS and c) the energy stored in ESS (state of charge) on 17th of June 2015.

Daily energy cycled through the ESS was 11 % of the annual energy production of the studied PV generators, i.e. directly proportional to the generator size. The amount of cycled energy follows closely the seasonal variation of irradiation and available PV power having peak values on early summertime. However, a considerable portion of the produces energy pass through the ESS all along the year.

Under certain conditions, global horizontal irradiance (GHI) can exceed the clear sky irradiance. This phenomenon is generally known as cloud enhancement, as it is usually associated with partly cloudy days. It has been reported to reach extreme values of over 1800 W/m^2, which is much more than the extraterrestrial irradiance above the atmosphere. The events are typically some minutes long, but they can last up to 30 minutes. The phenomenon is commonly known but poorly understood and can have considerable effects on the operation of PV systems. Therefore, we have analyzed this phenomenon based on our measurement database. In Fig. 4 is an example of the cloud enhancement phenomenon in Tampere region reaching higher irradiance values than the nominal clear sky value of around 900 W/m^2 on that moment. The enhanced irradiance was found to be up to 1.5 times the nominal clear sky value and the enhancement areas can cover PV generators for a long period of time, i.e., be quite large covering PV generators of all sizes. PV generators are also affected by the enhanced irradiance several hundreds of time annually.

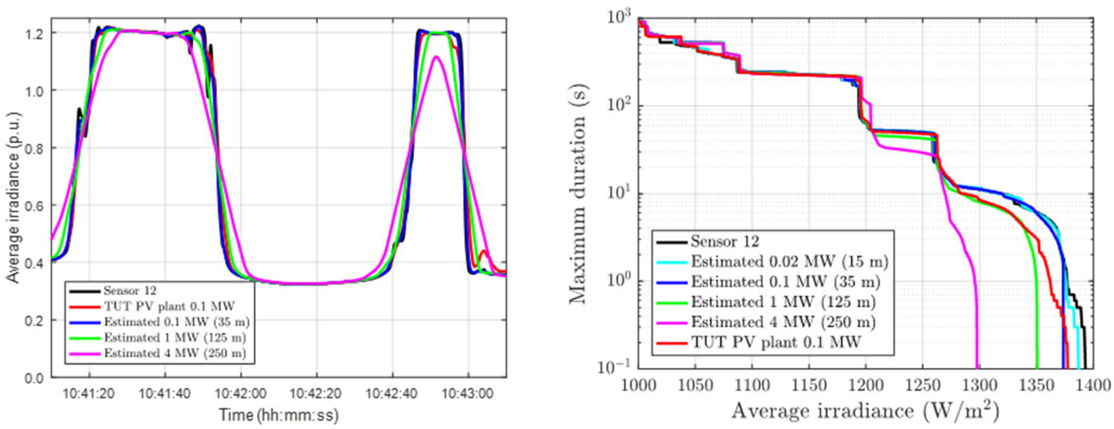


Figure 4. On the left is an example of cloud enhancement effect on different PV generator sizes. On the right is the maximum duration of the enhanced irradiance over different PV generator sizes during 23 summer months from 2014 to 2018.

2. Tekes funding decision: Tavoitteena on löytää kriteerit parhaalle topologialle yhdistää energiavarasto osaksi aurinkovoimalaa ja sen invertteriä sähköverkon tehotasapainon tukemista varten.

2.1 PV inverter with battery storage

A battery storage can be connected directly to the grid using its own DC-AC converter. Moreover, the storage can be used to support the grid by means of voltage and frequency support. However, the topology is not optimal for the integration of PV and electrical storage due to high component count and high complexity of the control system. Therefore, the direct connection was omitted in the early stages of research.

Fig. 5 illustrates the single and double stage topologies, where the storage is connected to the DC link using a separate DC-DC converter. Choosing the right topology depends on various factors, such as power and voltage level of the system, size of the battery and environmental conditions that affect the PV generator's maximum-power-point. Thus, both topologies have their benefits and may be used. Selection between single and double stage topologies is case specific as shortly discussed below.

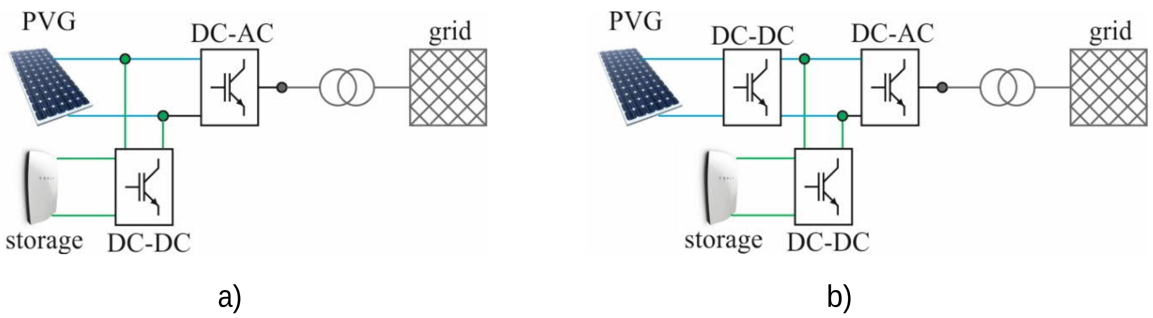


Figure 5. a) Single and b) double stage topologies for PV interfacing energy storage.

The operating range allowed for the PV generator is different in single and double stage topologies. In single stage topology, the minimum voltage of the PV generator is determined by minimum allowed DC link voltage. The DC voltage has to be approximately twice the grid voltage to avoid introducing excessive harmonic currents to the grid. However, this would not be a problem in high power plants where a large number of PV modules are connected in series and the maximum power is obtained naturally at high voltage. The operating range of a single-stage topology is shown in Fig. 6 as the red line. The DC-voltage is changed in steps from the minimum value determined by the grid voltage (120 V_{rms} in this case) up to the maximum value, which is determined by the voltage rating of power electronic switches and the open-circuit voltage of the PV generator. The blue line depicts the achievable voltage range for the double stage topology. The minimum voltage is constrained by losses of the DC-DC converter, and the DC-link voltage limits the maximum voltage. Here a boost-type converter is chosen for its low part count. However, the operating range could be extended by using another type of DC-DC converter capable of Buck-Boost operation, but this would lead to more expensive and complex design. The first criterion in selecting between the single and double stage topologies is the MPP voltage of the PV generator. The operating voltage in single stage topology is mainly limited by the grid voltage, while in the double stage topology the operating voltage is mainly limited by high conversion losses and the voltage level of the DC link. The results were obtained from a hardware-in-the-loop (HIL) simulator, which is currently considered as a state-of-the-art method to simulate power electronics-based power systems.

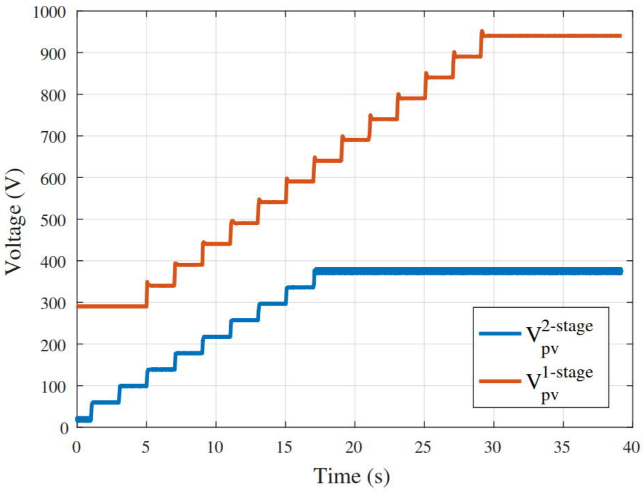
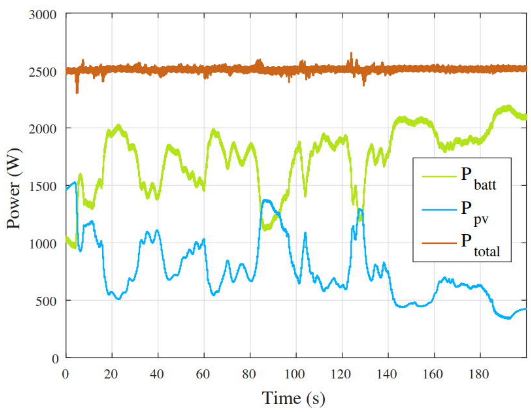


Figure 6. Operating range of the PV generator in single stage topology in red and double stage topology in blue.

The measured irradiance data from TUT's rooftop captured on a half-cloudy day in 12th of July 2016 were used in the HIL-simulator to reproduce the varying power produced by a residential-level PV generator. The battery storage was interfaced using the double stage topology to balance variations in PV power. The goal was to have a constant power flowing to the grid, regardless of the power produced by the PV generator. In this case, the state-of-charge of the battery was assumed to be 50 % to enable both charge and discharge of the battery. The constant power control was achieved by taking a power feedback from the DC-link and processing the error between actual power and its reference value with a discrete control algorithm. It was demonstrated that the method has high potential to level out variations in PV power and to effectively transform the PV inverter to be a constant power source. Moreover, the total harmonic distortion (THD) in grid current remained within acceptable level well below 5 %.

However, the power produced by the inverter has imposed high-frequency noise which may corrupt the grid current THD at higher power levels.



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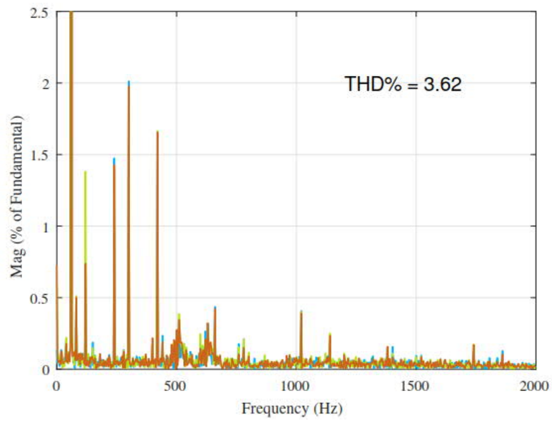


b)

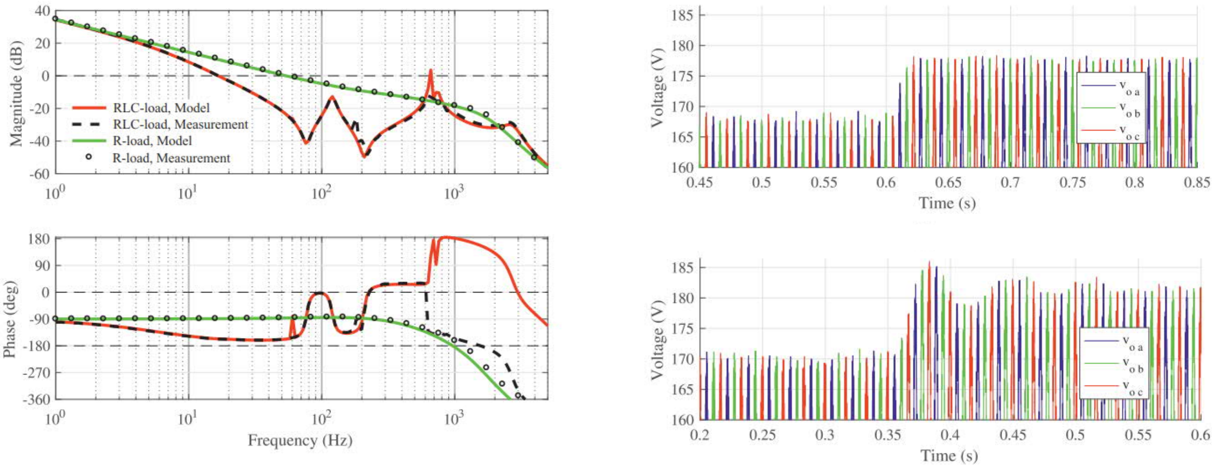
Figure 7. a) Power generated by the PV, absorbed by the battery and fed to the grid. b) Total harmonic distortion of grid currents.

3. Tekes funding decision: Tavoitteena on löytää akkujen lataukseen ja purkamiseen parhaiten soveltuva topologia, joka parantaa ohjattavuutta ja kontrollia sekä sähkön laatua.

3.1 Grid-forming inverter control dynamics

The grid-forming inverter is responsible for generating the AC voltage by itself. Therefore, the inverter is usually tested and designed in the laboratory using a passive load, rather than connecting the converter to the network. Resistive loads have been mainly used for this purpose. The main purpose of the load is to consume the generated power in a safe manner. Moreover, the control performance can be easily tested by connecting or disconnecting extra resistive loads. However, this may easily lead to wrong conclusions on control performance and stability when the inverter is used in actual applications, such as in powering a micro-grid or in supporting a local electrical island.

The developed dynamic model has been used to analyze the control performance of grid-forming inverter with an arbitrary load impedance. The load in a typical micro-grid application (or in grid-forming mode with other parallel inverters) does not resemble a resistor, even though the fundamental power consumption could be modeled this way. Fig. 8 shows the control loop gain of a grid-forming inverter, which was obtained using the developed dynamic model. Such curves are standard tools for design engineers and can reveal important information about the stability of the converter. The developed dynamic model (see Fig. 8a) was found out to be superior in accuracy, i.e., the measured curves overlap with the modeled curves. With sufficient understanding of control theory one can conclude from the red curve that the system has very small stability margin.



a) b)

Figure 8. a) Control loop gains of the grid-forming inverter obtained from the developed dynamic model with two different load impedances. b) Time-domain responses after sudden load changes.

The poor control performance can be predicted using the dynamic model used in Fig. 8a even before the actual inverter is simulated or tested in the laboratory. Time-domain response of the inverter to a sudden load-step is shown in Fig. 8b, where the upper waveform correspond to grid voltages in the resistive load-case and the lower waveforms correspond to the case when the load impedance experience a sharp resonance (only positive part of the waveform is shown for readability). Thus, the use of only resistive loads does not give realistic information on the actual performance of the converter with more challenging loads. With the problematic resonant-type load impedance the grid voltage amplitude oscillates for many fundamental cycles after the load step has occurred. This kind of behavior is unwanted, since it can be amplified by other converters leading to poor power quality or even disconnection and black-out in the micro-grid. However, the control design can be done by taking the load impedance behavior into account, which effectively improves the control performance.

In conclusion, the developed dynamic model of the grid-forming inverter has proven to be an accurate and useful tool in designing robust grid-forming inverters. In fact, usefulness of the dynamic model was demonstrated by selecting a problematic RLC-resonant circuit as the load for the grid-forming inverter. The controllers of the grid-forming inverter were specifically designed for high-performance operation with the problematic load. Fig. 9 shows the step response in inverter output voltage (in synchronous frame) when the load is a resonance RLC-circuit. The dark blue response line corresponds to the initial design where the voltage experiences significant overshoot in respect to the reference value (steady dark line). However, the overshoot can be significantly reduced by using the developed dynamic model as can be seen by inspecting the light blue line waveform.

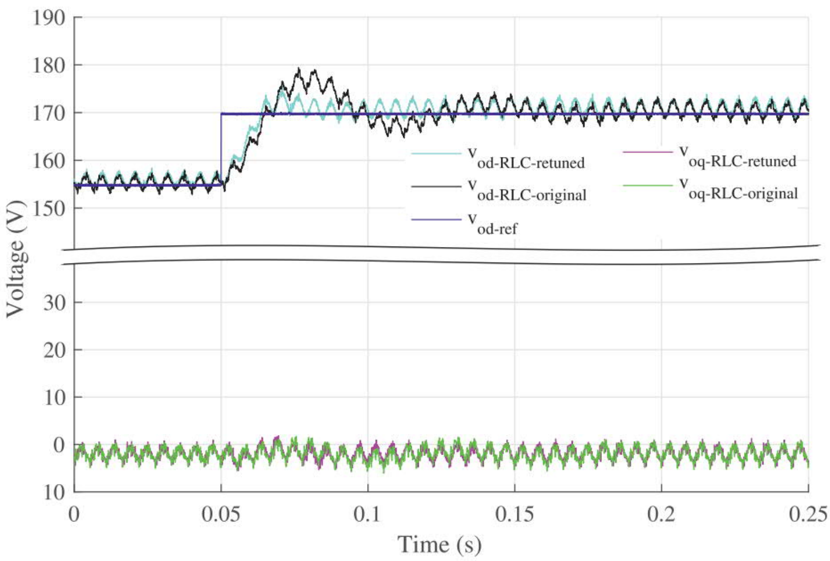


Figure 9. Step response of the grid-forming inverter with problematic RLC-resonant load with original control design (dark blue line) and with specifically tuned control system (light blue).

3.2 Internal impedance of a Li-ion battery pack

The internal impedance of a Li-ion battery can indicate the state-of-charge and state-of-health of the battery. These are the most important parameters from the system perspective. It is essential to know how much energy is remaining in the battery and when the battery reaches its end-of-life. Moreover, in future the internal impedance could be used to differentiate between re-usable and broken battery packs, when second-life batteries become available from the electrical vehicle market for power system applications.

Online measurement method using pseudo-random-sequences (PRBS) has been applied to characterize the internal impedance of a small-scale Li-ion battery pack. The accuracy of the method has been continuously improved during the project. Fig. 10 shows the measured battery impedance in red versus the reference in blue. The reference curve was obtained by using the conventional sine-sweep method.

The goal is to implement the online impedance measurement algorithm as a part of the control routine of the PV inverter, which would give valuable diagnostics information on the state of the battery. The sine-sweep can take up to ten minutes and, therefore, is not applicable for discrete implementation. However, the proposed PRBS-method is most suitable for online implementation due to fact that the injection signal is naturally a two-level discrete signal.

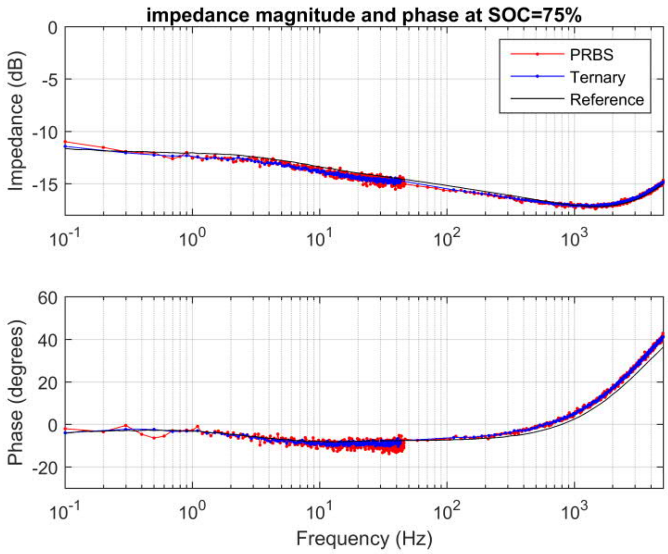


Figure 10. Measured internal impedance of a Li-ion battery pack using the conventional sine-sweep method (in blue) and the PRBS-method (in red).

Online impedance measurement method has been experimented during a research visit of MSc Jussi Sihvo at Aalborg University, Aalborg, Denmark. The measurement setup is unique, since there is no need to disconnect the battery from the circuit for testing, but the battery can be measured under normal stress and temperature conditions. Such measurement, if applied over long-term, will provide highly useful data on the aging mechanisms of Li-ion batteries. As a positive side-effect the diagnostics and monitoring tools integrated to DC-DC chargers and inverters can be made smarter and more accurate.

3.3 Dynamic model of PV inverter with battery storage

Small-signal dynamic model of PV inverter has been completed, which includes the battery storage and its interfacing DC-DC converter according to the one-stage topology presented in Fig. 11. However, the model could be directly applied for the two-stage topology by simply replacing the PV generator admittance Y_{pv} with the output admittance of an upstream DC-DC, which may be used if PV generator voltage is low.

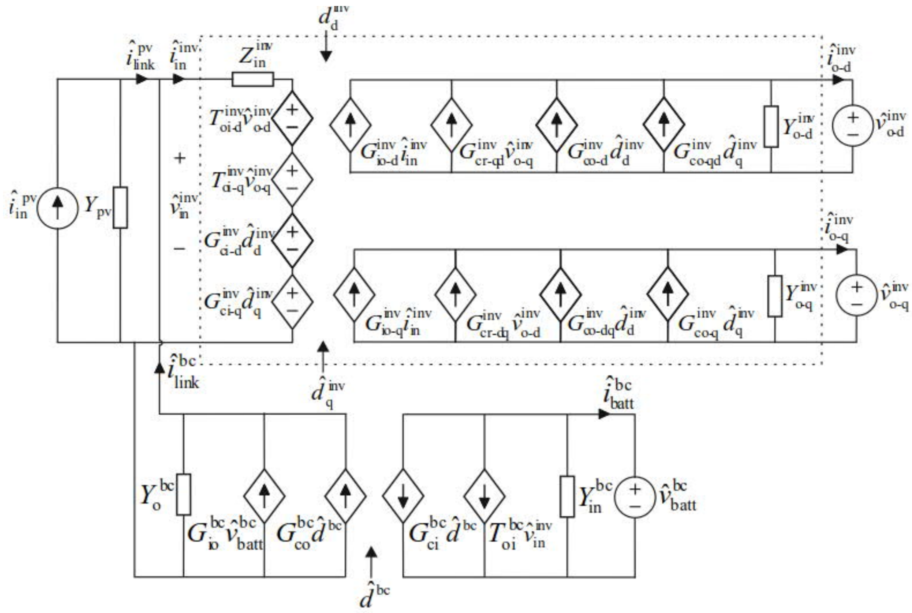


Figure 11. Overview of the complete PV inverter dynamic model with battery storage and DC-DC interfacing converter.

Figure 12a shows some results of the developed model as frequency responses in various operating point. Such frequency responses can be used for accurate design of robust controllers that necessitate the stability of the grid-connected PV inverter. It is evident that the model accuracy is very high, since the model (dotted lines) corresponds with the measured frequency responses (solid lines) very well over a wide frequency range.

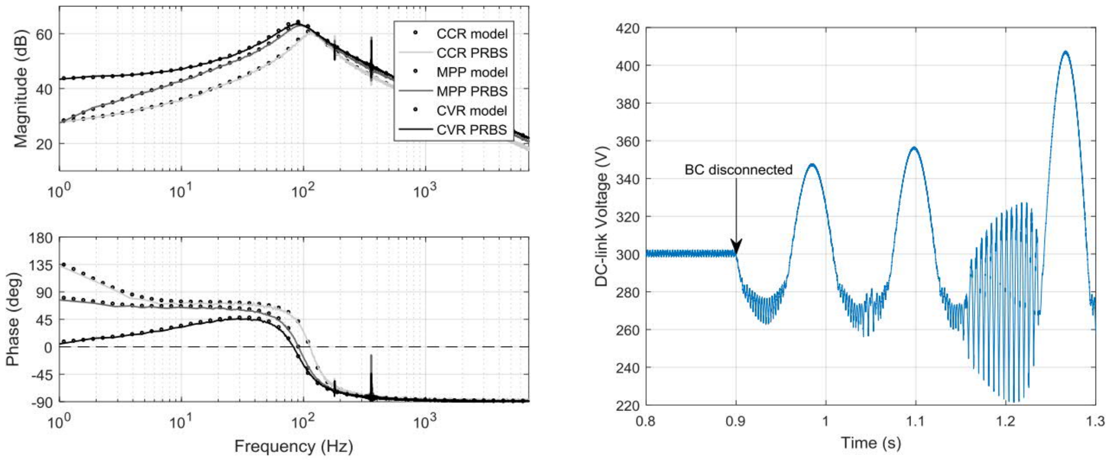
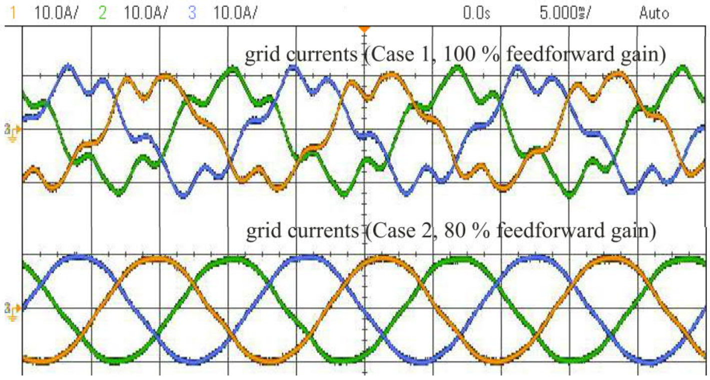


Figure 12. a) Dynamic model of the grid-connected PV inverter with battery storage, represented as a frequency response. b) DC-link voltage of the PV inverter begins oscillating due to unstable control system.

The dynamic model can be used to predict unstable conditions and to design more robust controllers to avoid power quality problems and potential safety hazards as illustrated in Fig. 12b. The DC-link voltage of the PV inverter starts to oscillate wildly after disconnecting the battery storage. This kind of behavior can be known beforehand by utilizing the dynamic model of Figs. 11 and 12a. A complete dynamic model capable for such accuracy did not exist in literature before.

The dynamic model of the inverter was successfully used to predict power quality problems arising on the grid side. The model was verified with a live inverter at TUT's power electronics research laboratory. It is now fairly well understood in our research group, how interactions between a single PV inverter (with or without storage) and the power system impedance are reflected as power quality problems. Fig. 13a shows a test case when the inverter is connected into a long inductive transmission line and is subjected to different internal control variables. In Case 1 the control parameters are selected in a conventional way, without considering the effect of the transmission line. The currents are highly distorted with multiple harmonic components, which naturally leads to unacceptably low power quality. However, by proper tuning of the inverter control parameters, the resonance can be avoided and the grid currents remain sinusoidal. The optimal performance is illustrated by measurement Case 2.

The selection of the critical control parameters is based on the impedance model of the PV inverter, which has been derived based on the dynamic model discussed above. The impedance model was verified by laboratory measurements and showed very good accuracy, as can be seen in Fig. 13b.



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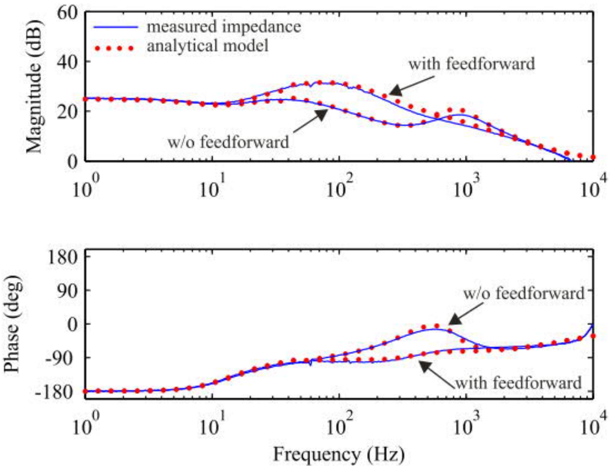

b)

Figure 13. a) Power quality problems arising from wrong and properly tuned inverter control parameters. b) Frequency-domain impedance model and the laboratory measurement.

In future, the amount of power electronic converters, such as PV inverters with integrated storage, will increase dramatically. Thus, the interactions and harmonics caused by inverters are expected to increase. The research has produced significant knowledge on how to analyze power quality and stability in the case of single grid-connected inverter. However, to cope with upcoming stability issues the emphasis should be placed on analyzing and designing multi-inverter systems, where an arbitrary number of power converters are used to feed the power system, such as a local AC micro-grid.

4. Tekes funding decision: Tavoitteena on löytää toteutettavissa olevat ja edulliset tavat monitoroida ja mahdollisesti ohjata PV generaattorin yksittäisten paneelien tai sarjaan kytkettyjen paneelien toimintaa.

Even if the efficiency of the PV cells is high, the PV generator spatial and electrical layout is ideal and the other system parts behave perfectly, partial shading, PV cell degradation and damages, reflections, soiling etc. can reduce the output power of a conventional PV system. These effects lead to the situation where the weakest PV cells determines the output power of the generator by reducing the current through the series-connected cells. Therefore, bypass diodes are connected in parallel with groups of cells to prevent cell failures due to hot spots caused by reverse-biased cells and to prevent excessive power losses. However, the operation of bypass diodes can lead to multiple maxima that hinder the operation of maximum power point (MPP) tracking algorithms and, accordingly, to a need to operate PV inverters over a wide voltage range.

Mismatch and MPP tracking failure energy losses have driven significant interest in distributed power electronics, including micro-inverters, or distributed DC-DC topologies. The conventional conversion approach is a series string of PV panels connected to a central inverter. This approach is efficient and effective only when maximum power point (MPP) current levels of PV cells do not differ from each other significantly. The modular panel-by-panel architectures have been introduced to overcome the reduced energy yield. These approaches allow each panel to operate at its local MPP through distributed controls via implementing global MPPT for traditional centralized inverters, reconfiguring interconnection between PV panels, adaption of module-dedicated DC-DC and DC-AC converters etc.

Research focus has been on analyzing the importance and effects of mismatched operation of PV modules in a PV generator. One of the main causes of mismatch operation of PV modules is partial shading caused by edges of moving cloud shadows. The analyses have shown that PV generator mismatch power losses caused by moving clouds are of marginal importance on the system efficiency point of view and a dynamic optimization of the PV generator operation is not viable in practice. The possible effects caused by false operation of the maximum power point tracking in the case of cloud shading is still under evaluation.

A recent focus in this field is a partial-power processing architectures, in which the parallel configuration allows the converters to process only the mismatch fraction of the total power. The main idea of the concept is to enable module-level DC-DC converters only when differences occur between PV modules or their substrings. That limits the operation time of the converters and therefore, has a positive impact on reliability. Based on the literature survey, the partial-power processing architecture seems to be an attractive solution for mismatching conditions and optimization of the system operation, especially for more stable conditions.

This requires more comprehensive studies about their dynamic behavior. These studies were initiated in latter 2017 by one PhD student. The approach is to utilize the mathematical methods developed by Prof. Spagnuolo at the University of Salerno in Italy with his colleagues. Prof. Spagnuolo visited TUT for three months in autumn 2018 for the joint research effort on this topic. The electrical behavior of PV modules can be modelled based upon the widely used one-diode model of a PV cell that provides the following relationship between the current I and the voltage U of the cell

$$I = I_{ph} - I_o\left(e^{\frac{U+R_S I}{AN_S kT/q}} - 1\right) - \frac{U + R_s I}{R_{sh}},$$

where A is the ideality factor, I_o the dark saturation current, I_{ph} the light-generated current, R_s the series resistance, R_{sh} the shunt resistance and T the operating temperature of the PV cell. Boltzmann constant is represented by k and q is the elementary charge. Especially current and voltage parameters in the equation are strongly dependent on the received irradiance and the operational temperature of the PV cells. Out of these parameters, the parasitic resistances are known to be effected by soiling and PC panel aging and to extract these parameters from the measured data might provide insight to the phenomena and tools for online condition monitoring. With reverse deduction it is actually possible to extract parameter {G, T, A, R_s, R_{sh}} by fitting the one diode model to the measured I-U curves. Parameter G is the received irradiance on the PV panel. In Figs. 14 and 15 are examples of the extracted irradiance and series resistance from one day I-U curve measurements of a single PV panel. These results are first of the kind extracted directly from the measurements showing good potential for developing on online measurement tools.

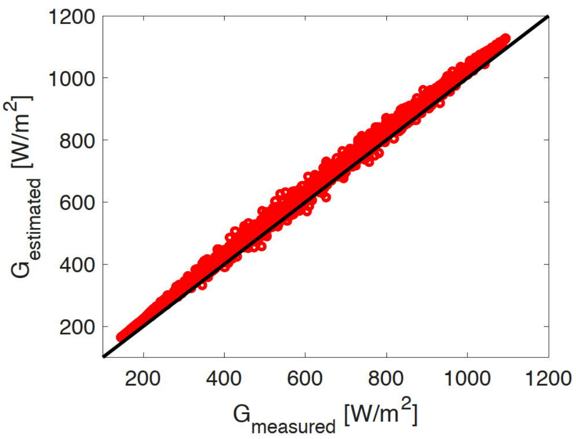

Fig. 14. Scatter plot of the estimated vs. measured irradiances during one-day I-U curve measurements of a PV panel.

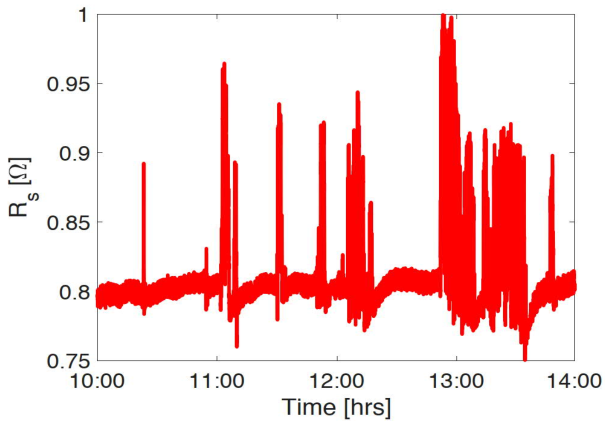

Fig. 15. Identified series resistance from the one-day I-U curve measurements of a PV panel.

5. Tekes funding decision: Tavoitteena on myös saavuttaa tutkimussuunnitelman mukainen tutkijanvaihto sekä tieteellinen julkaisutoiminta.

5.1 Research exchange

Assistant Professor Tuomas Messo visited Aalborg University in Denmark for three months in 2017. During the three months an online stability analysis tool for grid-connected converters and a new grid synchronization algorithm for unbalanced grid operation were developed. The online stability analysis tool may have significant impact in the field of adaptive tuning of grid-connected power converters, such as photovoltaic inverters. Stability issues are expected to increase when the amount of grid-connected converters increases. The new synchronization algorithm has good potential to reduce the time it takes for a grid-connected inverter to detect a grid fault, such as unbalanced grid voltages.

Collaboration continued in the form of joint PhD course, where Messo was lecturing on impedance measurement techniques in May. Moreover, preparations for research visits of PhD students were made.

Messo also visited the Padova University in Italy for two months from May to June in 2018 and two weeks in DNV-GL in the Netherlands in April in 2018. DNV-GL has extensive laboratories suitable for studying complex dynamic interactions and power quality problems in future power grids. During the visit to DNV-GL new techniques to develop test and verification setups for micro grid and grid-forming inverters were prototyped. A second visit has been agreed to take place in 2019 to extend the work. DNV-GL is also one of the key partners in the H2020 proposal under work, which is aimed for the 2019 call.

Doctoral student Matias Berg visited Padova University for two months in Autumn 2018.. The research group in Padova has extensive knowledge on micro grids and grid-forming inverters, which supported strongly the research work. Many issues with the accuracy of the grid-forming inverter dynamic model were solved during the research visit, such as the damping effect from blanking time.

Doctoral student Jussi Sihvo visited Aalborg University in Denmark. During his visit an online impedance measurement algorithm were been implemented, which will be used to gather valuable data on the impedance behaviour of Li-ion cells under accelerated aging tests. The results are unique on global scale since online impedance measurement of Li-ion batteries have not been previously implemented during aging tests, without disconnecting the battery. Results up to now are promising and TUT has access to unique and precious measurement data, which has been since then used in publications.

In autumn 2017, Professor Giovanni Spagnuolo from the University of Salerno in Italy visited TUT from 2nd to 9th of September. This was a continuum of existing co-operations since 2013, which has leaded to co-supervision of 4 MSc theses, joint publications etc. Professor Spagnuolo worked at TUT for three month as a TUT visiting professor from 1.8.2018 until 31.10.2018. Measuring and monitoring of the operation of PV generators was in focus of research during the visit being closely related to project tasks.

Table: Research exchange.

Visitor	From	To	Duration
2016			
Prof. Tuomas Messo	TUT	Aalborg University, Denmark	3 months
2017			
Prof. Tuomas Messo	TUT	Aalborg University, Denmark	3 months
Prof. Giovanni Spagnuolo	Univ. of Salerno, Italy	TUT	1 week
Prof. Tuomas Messo	TUT	Padova University, Italy	2 months
2018			
PhD Student Jussi Sihvo	TUT	Aalborg University, Denmark	3 months
Prof. Giovanni Spagnuolo	Univ. of Salerno, Italy	TUT	3 months
PhD Student Matias Berg	TUT	Padova University, Italy	2 months
Prof. Tuomas Messo	TUT	DNV-GL, Netherlands	2 weeks
PhD Student Tomi Roinila	TUT	DNL-GL, Netherlands	2 weeks
PhD Student Roni Luhtala	TUT	DNL-GL, Netherlands	2 weeks
IN TOTAL			17,5 months

5.2 Scientific publication

Goal set for the whole consortium was to publish at least 9 journal and 9 conference papers annually. TUT alone has published more than the overall goal during the period 1.6.2016 – 31.6.2018. All publications submitted by TUT after the official start of the project on 1.6.2016 are listed down below. In total, there are 19 published journal papers and 10 journal paper manuscripts under review. Accordingly, 38 papers have been published and presented in conferences and 9 conference paper manuscripts are under review.

Four PhD theses and four MSc theses have been finalized during the research period. The PhD theses were done partly before the project, but closely related to the research themes of this project supporting, especially, the startup of the project. There are currently six PhD theses under supervision based on the research done in the FRS projects and most of them will be completed in 2020.

PhD Theses:

- Aapo Aapro, Factors in active damping design to mitigate grid interactions in three-phase grid-connected photovoltaic inverters, 13.10.2017.
- Kari Lappalainen, Output power variation and mismatch losses of photovoltaic power generators caused by moving clouds, 17.11.2017.
- Jukka Viinamäki, Aspects on designing power electronic converters for PV application, 15.12.2017.
- Jyri Kivimäki, Issues in Design of Maximum-Power-Point-Tracking Control – Power Electronics Perspective, 5.10.2018.

Master Theses:

- Roosa-Maria Sallinen, Integrating an electrical energy storage to a grid-connected photovoltaic system, MSc Thesis, 62 pages, 2017.
- Matias Berg, Dynamics of Grid-Forming Inverter, MSc Thesis, 81 pages, 2017.
- Henrik Alenius, Modeling and electrical emulation of grid impedance for stability studies of grid-connected converters, 82 pages, 2018.
- Jussi Sihvo, Online impedance measurement techniques for Li-ion batteries, 75 pages, 2018.

Journal papers published or under review since summer 2016:

1. K. Lappalainen and S. Valkealahti, Apparent velocity of shadow edges caused by moving clouds, Solar Energy 138 (2016) pp. 47–52.
2. K. Lappalainen and S. Valkealahti, Effects of irradiance transition characteristics on the mismatch losses of different PV array configurations, IET Renewable Power Generation (2016). doi: 10.1049/iet-rpg.2016.0590.
3. K. Lappalainen and S. Valkealahti, Output power variation of different PV array configurations during irradiance transitions caused by moving clouds, Applied Energy, 190 (2017) 902-910.
4. K. Lappalainen and S. Valkealahti, Effects of PV array layout, electrical configuration and geographic orientation on mismatch losses caused by moving clouds, Solar Energy, 144 (2017) 548-555.
5. A. Aapro, T. Messo, T. Roinila and T. Suntio, Effect of active damping on output impedance of three-phase grid-connected converters, IEEE Transactions on Industrial Electronics, 64, 9 (2017) 7532-7541.

6. J. Kivimäki, et al., Revisited perturbation frequency design guideline for direct fixed-step maximum power point tracking algorithms, IEEE Trans. Ind. Electronics, 64, 6 (2017) 4601-4609.
7. J. Kivimäki, S. Kolesnik, M. Sitbon, T. Suntio and A. Kuperman, Design guidelines for multi-loop perturbative maximum power tracking algorithms, IEEE Trans. Power Electronics, 33, 2 (2018) 1284-1293.
8. M. Järvelä and S. Valkealahti, Ideal operation of a photovoltaic power plant equipped with an energy storage system on electricity market, Applied Sciences, 7, 7 (2017) 749, p.1-13.
9. K. Lappalainen and S. Valkealahti, Photovoltaic mismatch losses caused by moving clouds, Solar Energy, 158 (2017) 455-461.
10. J. Viinamäki, T. Suntio and A. Kuperman, Grid-forming-mode operation of boost-power-stage converter in PV-generator-interfacing application, Energies, 10, 1033 (2017) 1-23.
11. T. Suntio, T. Messo, A. Aapro, J. Kivimäki and A. Kuperman, Review of PV generator as an input source for power electronic converters, Energies, 10, 1076 (2017) 1-25.
12. S. Kolesnik, M. Sitbon, E. Batzelis, T. Suntio and A. Kuperman, Solar irradiation independent expression from photovoltaic maximum power line, IEEE Journal of Photovoltaics, 7, 5 (2017) 1416-1420.
13. T. Roinila, T. Messo and E. Santi, MIMO-identification techniques for rapid impedance-based stability assessment of three-phase systems in DQ-domain, IEEE Transactions on Power Electronics, 33, 5 (2018) 4015-4022.
14. R. Luhtala, T. Roinila and T. Messo, Implementation of real-time impedance-based stability assessment of grid-connected systems using MIMO-identification techniques, IEEE Transactions on Industry Applications, DOI: 10.1109/TIA.2018.2826998.
15. T. Roinila and T. Messo, Online Grid-Impedance Measurement Using Ternary-Sequence Injection, IEEE Transactions on Industry Applications, DOI: 10.1109/TIA.2018.2825938.
16. T. Suntio, On dynamic modeling of PCM-controlled converters – Buck converter as an example, IEEE Transactions on Power Electronics, 33, 6 (2018) 5502-5518.
17. A. Kuperman, M. Sitbon, M. lineykin, T. Suntio and S. Schacham, On-line dynamic conductance estimation based maximum power point tracking of photovoltaic generators, Energy Conversion and Management, 166 (2018) 687-696.
18. T. Suntio, Load-resistor-affected dynamic models in control design of switched-mode converters, EPE Journal, 2018, pp. 1-10, DOI:10.1080/09398368.2018.1467657.
19. T. Suntio, Dynamic modeling and analysis of PCM-controlled DCM-operating buck converter – A Reexamination, Energies, vol. 11, issue 5, no. 1267 (2018) 1-18.
20. R.-M. Sallinen and T. Messo, The Combined Source-Effect of Photovoltaic Generator and Bi-Directional DC-DC Battery Charger on Inverter Control Dynamics, IET Journal of Engineering, (accepted for publication)
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22. T. Roinila, R. Luhtala and T. Messo, Hardware-in-the-Loop Methods for Real-Time Frequency-Response Measurements of on-Board Power Distribution Systems, Transactions on Industrial Electronics, (early access)
23. R. Luhtala, H. Alenius, T. Roinila and T. Messo, Adaptive Power-Factor Correction Based on Real-Time Grid Inductance Estimation, Transactions on Energy Conversion, (under review)
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25. T. Messo, R. Luhtala, A. Aapro and T. Roinila, Accurate Impedance Model of Grid-Connected Inverter for Small-Signal Stability Assessment in High-Impedance Grids, IEEJ Journal of Industry Applications, (open-access, accepted for publication).
26. K. Lappalainen, P. Manganiello, G. Spagnuolo, S. Valkealahti, An Algorithm for the Virtual Sensing of Photovoltaic Module Operating Parameters, IEEE Journal of Photovoltaics, (under review).
27. K. Lappalainen and S. Valkealahti, Number of maximum power points in PV arrays during cloud partial shadings, Applied Energy, (under review).
28. M. Järvelä, K. Lappalainen and S. Valkealahti, Characteristics of the cloud enhancement phenomenon and PV power plants, Solar Energy, (under review).
29. K. Lappalainen and S. Valkealahti, Fluctuation of the PV array maximum power point voltage during irradiance transitions caused by clouds, IET Renewable Power Generation, (under review).

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2. T. Messo, A. Aapro, T. Suntio and T. Roinila, Design of grid-voltage feedforward to increase impedance of grid-connected three-phase inverters with LCL-filter, IPEMC 2016-ECCE Asia, 2016, Hefei, China, pp. 1-8.
3. A. Aapro, T. Messo and T. Suntio, Effect of single-current-feedback active damping on the output impedance of grid-connected inverter, EPE ECCE Europe, 2016, Karlsruhe, Germany, pp. 1-10.
4. J. Viinamäki, J. Jokipii and T. Suntio, Improving double-line frequency voltage ripple rejection capability of DC/DC converter in grid-connected two-stage PV inverter using DC-link voltage feedforward, EPE ECCE Europe, 2016, Karlsruhe, Germany, pp. 1-10.
5. P. Pakonen, A. Hilden, T. Suntio and P. Verho, Grid-connected PV-power-plant-induced power quality problems – Experimental evidence, EPE ECCE Europe, 2016, Karlsruhe, Germany, pp. 1-10.

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7. J. Kivimäki and T. Suntio, Determining maximum MPP-tracking sampling frequency for input-voltage-controlled PV interfacing converter, IEEE ECCE, 2016, Milwaukee, WI, USA.
8. A. Aapro, T. Messo and T. Suntio, Output impedance of grid-connected converter with active damping and feed-forward schemes, IEEE IECON, 2016, Florence, Italy, pp. 2361-2366.
9. J. Kivimäki, T. Suntio and A. Kuperman, Sampling frequency design to optimizing MPP-tracking performance for open-loop-operated converters, IEEE IECON, 2016, Florence, Italy, pp. 3093-3098.
10. Y. Basha, M. Sitbon, S. Schachman, S. Lineykin, T. Suntio and A. Kuperman, Robust maximum power point tracking of renewable energy generators, IET RPG Conf., London, UK, 2016.
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12. T. Reinikka, R. Luhtala, T. Roinila and T. Messo, Implementation of online impedance measurements setup for three-phase grid-connected inverters, Automaatiopäivät, 2016, Vaasa, Finland, pp. 1-6.
13. K. Lappalainen and S. Valkealahti, Simulation Resolution of PV System Studies under Partial Shading Conditions, 33nd European Photovoltaic Solar Energy Conference and Exhibition (33nd EU PVSEC), 25–29 September, 2017, Amsterdam, The Netherlands.
14. J. Kivimäki, T. Suntio and A. Kuperman, Factors affecting validity of PVG-Power settling time estimation in designing MPP-tracking perturbation frequency, IEEE IECON, Peijing, P. R. China, 2017.
15. T. Messo, R. Luhtala, D. Yang, T. Roinila, X. Wang and F. Blaabjerg, Real-time impedance-based stability assessment of grid converter interactions, 2017 IEEE 18th Workshop on Control and Modeling for Power Electronics, Stanford, USA, July 9-12, 2017.
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22. G. Petrone, S. Romanelli, G. Spagnuolo and S. Valkealahti, Photovoltaic Plant Cloud Shadowing and Energy Drops in Northern Europe, the IEEE International Conference on Industrial Technology 2018 (IEEE ICIT 2018), Lyon, France, 20 – 22 February, 2018, 1055-1060.
23. T. Messo, A. Aapro and T. Roinila, Design of Grid Voltage Feedforward for High-Impedance Grids using DQ-Impedance Model, International Power Electronics Conference, IPEC 2018 ECCE Asia, Niigata, Japan, May 20-24, pp- 1-8, 2018.
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25. M. Berg, T. Messo and T. Suntio, Frequency Response Analysis of Load Effect on Dynamics of Grid-Forming Inverter, International Power Electronics Conference, IPEC 2018 ECCE Asia, Niigata, Japan, May 20-24, pp. 1-8, 2018.
26. R. Luhtala, T. Roinila and T. Messo, Adaptive Control of Grid-Voltage Feedforward for Grid-Connected Inverters based on Real-Time Identification of Impedance-Based Stability Margins, International Power Electronics Conference, IPEC 2018 ECCE Asia, Niigata, Japan, May 20-24, pp. 1-8, 2018.
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30. T. Reinikka, R. Luhtala, H. Alenius, T. Roinila and T. Messo, PHIL Test Bench for Real-Time MIMO-Identification Methods of Complex Power Grid, 18th IFAC Symposium on System Identification, SYSID 2018, Stockholm, Sweden, 9-11.7, 2018.
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39. G. Spagnuolo, K. Lappalainen, S. Valkealahti and P. Manganiello, Identification and Diagnosis of a Photovoltaic Module by Outdoor Measurements, 13th IEEE PES PowerTech Conference, Milano, Italy, June 23-27, 2019 (accected).
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41. K. Lappalainen and S. Valkealahti, Experimental verification of a method to model the operation of PV modules during irradiance transitions, ELECTRIMACS 2019 - The 13th international conference of the IMACS TC1 Committee, Salerno, Italy, May 21-23, 2019 (accepted).
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46. M. Berg, P. Mattavelli and T. Messo, Dead time impact on AC-side small-signal stability of power electronic systems, IEEE Workshop on Control and Modeling for Power Electronics, IEEE COMPEL 2019, Toronto, Canada, (under review)
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