USE CASES FOR EFFICIENT INTEGRATION OF SMART HOMES PV

Richard TOKLE SCHYTTE
Powel AS/NTNU – Norway
Richard.Schytte@Powel.no

Kjell SAND
SINTEF/NTNU – Norway
Kjell.Sand@Sintef.no

Rolf Erlend GRUNDT
Agder Energi AS - Norway
Rolf.Erlend.Grundt@ae.no

ABSTRACT

In Norway there is an increased interest in utilizing photovoltaic generation of electricity (PV) in building installations. As many parts of the LV distribution system in Norway are rather weak, large influx of PV might introduce both voltage quality problems as well as feeder overloads. As the observability of the LV distribution systems will increase due to the deployment of smart meters and new sensors/instrumentation in MV/LV substations, these technologies can be applied in smart house and micro grids concepts to maximize PV hosting capacities and to reduce the need for traditional grid measures (lines/cables, increased transformer ratings etc.). A set of use cases has been developed for this purpose and their technical and economic potential have been analysed by a set of simulation models as presented in this paper.

INTRODUCTION

In Norway approximately 40% of the total energy consumption is in households and buildings. Energy consumption is an increasingly discussed topic, with focus on new building standards, energy efficiency requirements and integration of distributed renewable energy generation. In so-called “zero energy” and “energy plus” buildings local generation is indispensable [1].

Several Norwegian utilities are experiencing an increasing number of requests for grid-connected PV in the low voltage grid, due to incentive programs, new building standards and declining PV investment costs. Grid-Connected PV may cause major challenges for the voltage quality and thermal capacity, especially in weak rural grids [2].

The new challenges for the grid might be solved by traditional grid investments to reinforce the grids, but also new Smart Grid technologies might be a cost effective alternative to traditional solutions. A Smart Grid utilizes information from instrumentation and sensors in the distribution grid, substations and end-customers. This information in combination with Smart Grid management concepts such as Micro Grids and Home or Building Automation (Smart House/Smart Buildings) contributes to optimally manage and coordinate resources within the relevant restrictions – e.g. the voltage quality requirements. As voltage quality is the most important barrier for grid connected PV in Norway, the paper focus on use cases for voltage quality management [2].

PV POTENTIAL IN NORWAY

The potential for PV generation of electricity is largest in areas around the Equator, and diminishing the northern and southern latitudes. So, in principle PV generation should not be of that great interest in Norway where the main population centres are found around 60°N. But as measurements show that the expected annual PV potential in the southern part of Norway (see figure 1) amounts to 1240 kWh/m^2, the potential is of technical interest. The figure shows the measured monthly generation for the years 2005 and 2011 as well as the estimations from PVGIS – a solar photovoltaic energy calculator [2-3].

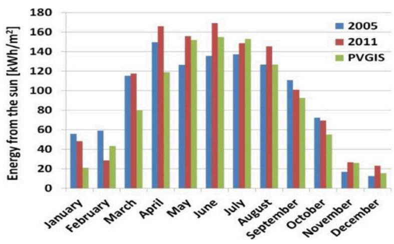


Figure 1 PV generation measurement results – Southern Norway compared with PVGIS estimates [2].

The PVGIS tool seems to underestimate the potential. The relatively cold climate as well as reflection from snow in parts of the year improve the PV panels' efficiency and might explain some of the deviation.

The potential is so promising that incentive schemes have been introduced for building integrated PV (BIPV). The incentives are designed as PV investment support while surplus generation will be traded according to market conditions (e.g. spot market prices) - no feed-in tariffs are yet introduced in Norway.

VOLTAGE QUALITY – A BARRIER FOR PV INTEGRATION

A large part (approx. 70%) of the Norwegian LV distribution system is designed as a 230 V IT system i.e. the line voltage is 230 V. Combined with long distances in rural areas investigations performed by SINTEF Energy Research [4] indicate a high percentage of low voltage networks in Norway have a relatively low short circuit capacity - between 40 and 50 % of the low voltage networks seem to have a higher impedance than the IEC EMC reference impedance [5].

The Norwegian PQ code ("Reg No 1557 30 November 2004 on the quality of supply in the Norwegian power system") has a strict requirement for the supply voltage variation both with respect to integration time and to probability:

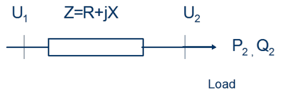
- *all* ***1 min mean values*** *of the supply voltage shall be within ± 10 % of the nominal voltage* ***100 % of the time*** *at all supply terminals in the low voltage network.*

(The main deviations from EN 50160 are indicated in **bold**.)

Though the Norwegian LV distribution systems have a large capacity from a thermal perspective due to the comprehensive use of electricity for space and water heating, the voltage quality aspect might often be the limiting factor for PV integration due to voltage rise problems during the summer months, when PV generation is peaking and the domestic load is usually quite low as air-condition is not commonly used in Norwegian homes.

VOLTAGE QUALITY MANAGEMENT

The voltage drop from an infinite bus to a supply terminal is in principle given in Figure 2 (Thevenin equivalent):



$$\Delta U \approx \frac{1}{|U_2|}(P_2 \cdot R + Q_2 \cdot X)$$

where

U_1, U_2 - feeding end and receiving end voltages
P_2 - net active load (load – local generation)
Q_2 - net reactive load (inductive)
R - supply resistance (short circuit resistance)
X - supply reactance (short circuit reactance)

Figure 2 Voltage drop illustration

In situations of grid-connected PV with a larger generation than the locally consumption of the loads the end-customer will deliver power to the grid. The direction of the current is changed, and so is the voltage drop. The same approximation can be used for surplus generation i.e. PV with negative values for P_2. Q_2 might be negative or positive depending on inverter capabilities and settings and other reactive loads in the installation. Thus, a negative voltage drop indicates a voltage rise.

To manage the supply voltage variations within the PQ code limits, two main dimensioning situations for BIPV are of importance in Norway:

1. Summer peak generation with corresponding small electricity consumption that defines possible high voltage problems (above + 10%)
2. Winter peak load with corresponding small electricity PV generation which defines possible low voltage problems (below – 10%)

As shown in Figure 2, the voltage drop can be controlled be controlling the active power P_2 and/or the reactive power Q_2. (For a given supply the resistance R and the reactance X are constant.) In installations combining loads and PV to avoid too high voltages (situation 1), it is optimal to maximize local active power consumption as well as to "consume" reactive power i.e. inductive behaviour. To avoid too low voltages with no active power PV generation (situation 2) it is optimal to maximize local reactive power "generation" i.e. capacitive behaviour.

It should be noted that in LV distribution systems in Norway, the short circuit impedance R/X is >> 1 for most supply terminals, indicating that installation active power control is more effective than reactive power control.

In addition to PV inverter controls and building energy management controls for voltage management, transformer tap-changer devices, and special voltage conditioner devices might be used [2]. In this paper the use cases do not address the use of voltage conditioners.

USE CASES FOR INTEGRATION OF PV

In the project, four main use cases for integration of local PV generation have been developed as listed below [2]. The list also indicates the sub use cases/scenarios:

1. Monitoring and visualization of actual generation and consumption for manual load control or manual change of Home Energy Management System (HEMS) settings
2. Estimation and visualization of tomorrows estimated generation for manual change of Home Energy Management System settings
3. Local voltage control with smart house technologies.
   - Inverter reactive power compensation
   - Control of active feed-in power with domestic consumption control
4. Micro grid voltage control with coordination of several smart houses.
   - Inverter controlled reactive power compensation in smart houses
   - Control of active feed-in power from the connected smart houses with domestic consumption
   - Transformer On-Load-Tap-Changer (OLTC) in the MV/LV substation

The overall objective of the described use cases is to contribute to cost efficient integration of PV.

Visualisation

The objective of use cases "1" and "2", regarding visualization, is to increase local utilization of PV. Solarpix [2] has stated that the utilization may increase by 10 % with visualization of estimated generation. PV generation and local consumption often do not coincide.

Thus in hours with surplus generation, electricity is sold the DSO or market player. Normally the customer sells surplus power in the middle of the day and buys in the morning, evening and night.

The use cases utilize available information from AMI (Advanced Metering Infrastructure), PV inverter and weather forecast to inform the HEMS about continuous consumption and generation as well as tomorrows estimated PV generation. Based on these measurements and forecasts the customer can shift domestic consumption to match local generation, and thereby increase the utilization of PV.

Local voltage control

The local voltage management use case "3" is utilizing smart house/ inverter controls to maintain the supply terminal voltage within the PQ code limits. The supply situation is as indicated in Figure 2. The use case utilizes the AMI/Smart meter for voltage measurements and control algorithms in HEMS to control the voltage. HEMS control the PV inverter to compensate with reactive power, and use relays to control domestic consumption. Increased domestic consumption reduces the feed-in active power, and thereby can contribute to control the voltage. The domestic "consumption" controlled is heating of tap water and space heating which constitutes approx. 85% of the annual household consumption in Norway. Also the effect of local energy storage (battery) is investigated in this use case.

Micro grid voltage control

The use case for voltage control in a micro grid with several smart houses connected on the same LV feeder, utilizes the local voltage control mechanisms in the smart houses as well as an OLTC to maintain voltage limits. Figure 3 shows the micro grid topology.

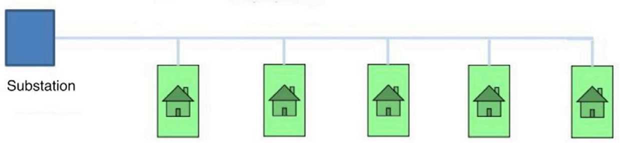


Figure 3 Micro Grid with substation and five smart houses [2]

The objective of the use case is to maintain voltage restrictions, so that a possible need for increased grid capacity can be reduced or delayed.

The smart meter in each smart house measures and reports the voltage level in the feeder. Based on the voltage the Micro grid control system can send control signal to the smart house HEMS and the OLTC controller. Each smart house will also utilize the local voltage control from use case "3" to maintain the voltage limits with reactive power compensation and feed-in active power. The OLTC can control the feeding end supply voltage to optimize voltage profile long the feeder by decreasing the substation voltage in periods of high generation and high voltage problems and vice versa in low voltage situations.

DATA AND SIMULATION MODEL

Data for use case analysis

In the technical simulations performed, real measurement data for consumption and solar irradiation are used (hourly resolution). The high voltage problem simulations used data from June 20th 2013. This day was selected based on the fact that this was a typical sunny summer day with low consumption. The day is assumed to be close to the summer peak. The irradiation data is from the R&D project “Solstrøm på Nett”. The consumption data is from the Smart Grid demonstration project “Demo Steinkjer”. The analysis used a roof top PV installation of 41,5 m^2 per smart house, with an efficiency of 10,5% and pitch angle of 38° giving a generation capacity of 4,7 kWp per house [2].

Simulation Model for use case analyses

To study the technical impact of the use cases, two integrated simulation models for voltage quality and PV generation/consumption simulations have been developed in MATLAB. The first simulation model is for the simulation of a single smart house connected to a typical Norwegian LV feeder i.e. a supply situation equivalent the situation shown in Figure 2. The short circuit impedance is largely determined by the distribution substation transformer and the LV feeder impedance and average Norwegian data have been used giving an R/X~8.

The single smart house model is integrated with a micro grid simulation model, see Figure 3, which consists of a distribution substation, LV feeder connecting several equal smart houses (equal load profiles and PV generation patterns) with an equal distance between the houses. The micro grid controller utilizes single smart house control options as well as MV/LV substation OLTC controls.

For the different use cases, the models simulate the supply terminal voltages (1 min. maximum r.m.s. voltages) resulting from the load and PV generation data with an hourly time step [2].

RESULTS OF USE CASE ANALYSIS

Technical simulations

Use Case 1 and 2; “Visualization”

The technical simulation of the use cases visualize for the homeowner the estimated irradiation, intraday production, power import from the grid and local consumption. Figure 4 shows the result of the simulations for June 20th and shows that the local production peaks at midday maximizing the export of power from the smart house to the grid. The consumption graph shows that the consumption is peaking in the evening, after sunset. It is possible to shift consumption from both the morning and evening to periods of local production. The homeowner can either plan the consumption or apply so called smart appliances that seek to maximize the local use of PV power e.g. by midday tap water heating [2].

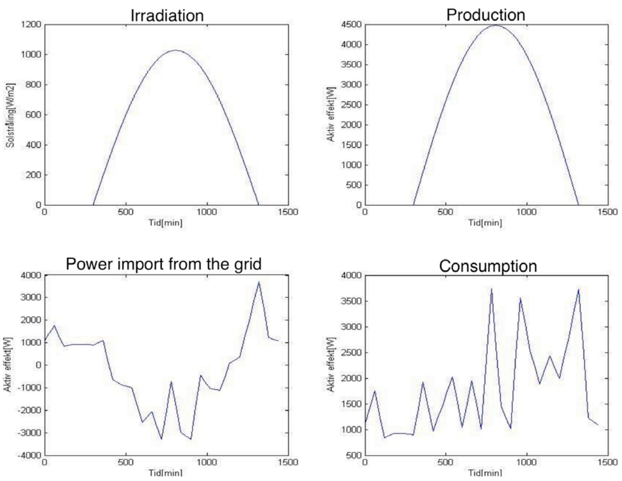


Figure 4 Irradiation, Production, Power import from the grid and local consumption vs. time of day in minutes from midnight [2]

Use Case 3; Local voltage control
The technical simulations of the single smart house supply terminal voltage showed that no voltage restrictions are exceeded even when no control measures were applied. The maximum voltage rise is 3,83% with no local control; 3,8% when applying reactive power control and 2,17% when applying feed-in power control. The simulation results indicate that compensation with reactive power has little effect on the voltage, and that control of feed-in power was more effective to control the voltage [2].

Use case 4; Voltage control with several smart houses
The simulation results showed that the Norwegian Quality Code requirements were exceeded, and a real need for measures was identified. Figure 5 shows the simulation results with different control options for the worst case i.e. the maximum voltage situation. The figure shows that the voltage rise across the feeder is 12 % related the substation when no control measures are applied. Compensation with reactive power has limited impact on the voltage, and the voltage across the feeder is only reduced to 11,5 %. The tap changer option can control the voltage to satisfy the quality code, but there will still be a large voltage deviation along the feeder. Figure 5 shows that it is essential to regulate the voltage by controlling the feed-in active power, by an increased local consumption in periods of high PV generation and low load [2].

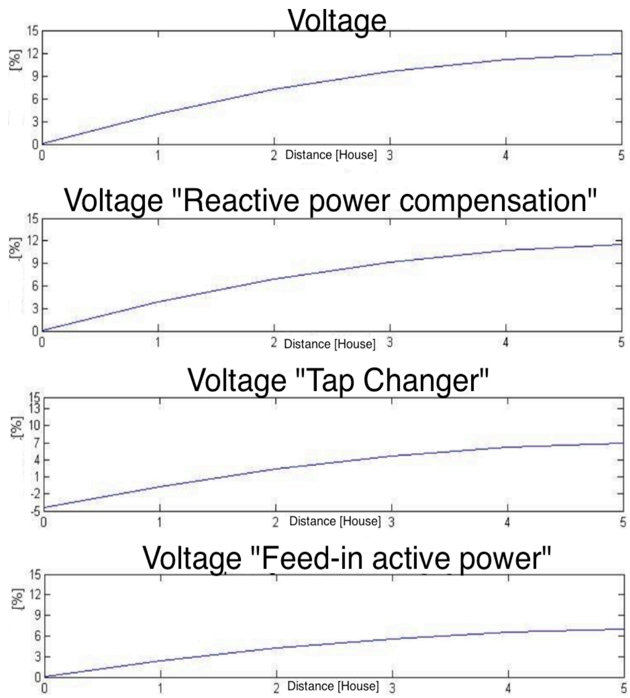


Figure 5 Micro Grid Simulation Results [2]

Economical

The following price assumptions are used in the economic evaluations:

- Grid tariffs 0,36 NOK/kWh
- Electricity price 0,44 NOK/kWh
- PV sales price 0,34 NOK/kWh

The cost of purchasing electricity from grid is higher than selling, so there is also an economic incentive for the PV owner to increase the utilization of PV generation [2].

Use Case 1 and 2 – "Visualization"
The specific economic value of shifting consumption and correspondingly increasing the utilization of local generation is 0,46 NOK/kWh (grid tariff reduction plus reduced net electricity purchase). The typical investment cost for HEMS is 2650 NOK, while AMI is mandatory in Norway from 2019 so there is no extra associated investment cost with AMI [2]. As indicated in Figure 4 it is possible to shift consumption to sunny periods. Shifting approximately 365 kWh/year over the 25-year lifetime can cover the investment cost for the HEMS.

The increased utilization of local generation will also reduce the need for increased grid capacity, and contributes to additional PV installations in the grid without increased grid capacity.

HEMS will enable more functionality than these use cases need, and for that matter it is assumed that the use case will result in a positive contribution.

Use Case 3; Local voltage control
The simulation of use case 3 with integration of a single smart house with PV showed that no voltage restrictions were exceeded. That means that there is no real need for control mechanisms or grid measures to host a single PV smart house on a typical LV distribution feeder.

Use case 4; Voltage control with several smart houses
The technical analyses show a real need for measures. If none of the scenarios in the use case is realized there is a real need for an investment in increased grid capacity. The results of the technical analysis and the associated investment cost for the different alternatives are shown in Table 1. The battery package consists of a 2 kWh battery at each house. There is not associated any investment cost with an increased local consumption by heating, neither installation of AMI and HEMS. The investment cost related HEMS is covered by the visualization case.

Table 1 Micro Grid Analyses results [2]

Alternative	Cost [NOK]	Voltage rise [%]
None	0	12
Increased capacity	197.864	6,0
Reactive compensation	0	11,5
MV/LV OLTC	70.000	7,0
Battery Package	250.000	7,0
Feed-in power control	0	7,0

Based on the comparison of investment costs and impact on the voltage level, control of active feed-in power by an increased local consumption was the most attractive solution. OLTC in the MV/LV substation is financially more attractive than upgrading the grid, while the current investment costs for batteries for are more expensive than upgrading the presented grid. Battery technology may be more interesting in the near future due to expected declining investment costs.

CONCLUSION

PV generation has an interesting potential also in more Artic locations such as Norway. Smart grid and smart house technologies might contribute to cost efficient PV integration and can compete with traditional grid investments. In Norway, especially voltage quality constraints are a dimensioning factor as many supply terminals have grid strength below the EMC reference impedance [5]. The use cases documented in this paper contributes to a cost efficient integration and utilization of PV in the LV grid. As the simulation results shows, the integration of a single smart house with PV on a typical LV feeder will not create a voltage quality problems. But with integration of several smart houses with PV the simulations show that unacceptable voltage rise might occur during summer. The most promising option to solve the voltage quality problems in this case is to maximize local active power consumption through HEMS control action. Use cases utilizing reactive power control options are not effective due to the high R/X relationship for typical LV feeders.

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