POWER FACTOR STUDY ON NET METERING SITE AND Q-CONTROL FROM SOLAR PV SYSTEMS IN BANGLADESH

REPORT

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EXECUTIVE SUMMARY

Motivation for the Analysis

Poor power factors have been reported for medium voltage consumers which have large PV systems and participate in net metering scheme in Bangladesh. The current regulation establishes penalties for medium voltage consumers with monthly average power factors below 0.95, to be paid per 0.01 p.u. of power factor. And, in case the monthly power factor is below 0.75 for three consecutive months, the consumer can be disconnected from the grid.

The need therefore arises to analyse and quantify the impact of different shares of solar PV generation on an industry's reactive power (Q) drawn from grid as well as on its power factor at the connection point. This quantification considers the current method used for calculating the power factor in Bangladesh, which is based on the lumpsum of the customer's active power and the lumpsum of the reactive power for each month.

Summary of Results

Data from an ice production industry in Bangladesh participating in net metering is used for the analysis. The impact of different shares of solar photovoltaic (PV) system generation on the industry's power factor is analysed. A base case (with no reactive power provision from the PV system, i.e. PV system with a constant power factor of 1) is compared to cases in which the PV is operated with the reactive power control modes of (a) constant power factor, (b) reactive power provision based on reactive power setpoints received (goal: control reactive power at the grid connection point, reducing it to zero when possible) and (c) reactive power provision based on voltage.

The results indicated that there is no real issue on the reactive power balance when a PV system is operated in the distribution grid.
However, the current procedure of metering the power factor was shown to be not very suitable with net-metering schemes.

An overview table comparing main findings regarding reactive power drawn from grid as well as the suitability of power factor calculation method when applying each mode is given next.

PV operation mode	Impact on industry's reactive power (Q) drawn from grid	Suitability of current power factor calculation method to the operation mode
Base case: PV operating with no Q provision	PV system generates no reactive power and therefore has no impact in the reactive power drawn from the grid.	The current method to determine power factor will already fail (i.e. result in penalties due to a power factor below 0.95) for small shares of PV production (above 10% of the industry's energy consumption).
Constant power factor of 0.95 (over-excited)	Reactive power can be well compensated with this method (PV will even provide Q to the grid in certain times). However, providing Q to the grid might lead to over-voltages and might thus be undesirable.	The current method to determine power factor will only fail for very high shares of PV production (above 90% of the industry's energy consumption).
Q provision based on reactive power setpoints received.	Reactive power flows (and thus losses) are considerably reduced in this mode. Reactive power drawn from grid is reduced to zero whenever possible.	The current method to determine power factor fails at around a 40 % share of solar generation on the energy consumption.
Q provision based on voltage (Volt-var)	In this mode, the voltage will be stabilized with minimum amount of reactive power.	This mode is not suitable to be used with the existing method to determine the power factor, as typically reactive power is consumed in reverse flow operation in order to reduce the voltage.

Recommendations

First of all, consumer loads (e.g. induction machines) should always be compensated to a power factor above 0.95. This can be done with conventional compensation methods (such as capacitor banks) or with the PV inverter, if this has STATCOM capability.

In case high power factor penalties due to large PV systems occur, a short term solution is to set the power factor of the PV systems to 0.95 (overexcited).

On the medium-term, it is recommended to require different reactive power control capabilities for PV systems (e.g. Q(U)). Requiring the capability does not imply that it will necessarily be used. It should be up to the distribution company to request which specific type of control and setting is most beneficial for each system (e.g. depending on local reactive power balance). For larger systems (e.g. above 100 kW), the PV inverter should be able to control (within its capabilities) the reactive power at the grid connection point.

Furthermore, it is recommended to change the algorithm for determining the power factor used for deciding on penalties. The power factor should be calculated based on the maximum demand (both kW and kvar). This method is internationally commonly used. It assures, that even in the worst case, the power factor of the load is compensated and allows for more freedom in controlling the reactive power of the PV system (e.g. for voltage control).

1. INTRODUCTION

Poor power factors have been reported for medium voltage consumers which have large PV systems and participate in net metering scheme in Bangladesh. The current regulation establishes penalties for medium voltage consumers with monthly average power factors below 0.95, to be paid per 0.01 p.u. of power factor. And, in case the monthly power factor is below 0.75 for three consecutive months, the consumer can be disconnected from the grid. The current method used for calculating the power factor is based on the lumpsum of the customer's active power and the lumpsum of the reactive power for each month.

The main objective of this study is to analyse the impact of photovoltaic (PV) systems on the power factor of industries with net metering. This is done for the current situation where typically no reactive power support from the PV system is provided as well as cases in which the PV systems operate with different reactive power control modes.

For this, a case study analysis is conducted using data from an industry in Bangladesh. In this analysis, the base case (no reactive power provision from the PV system, i.e. PV system with a constant power factor of 1) is compared to cases in which the PV is operated with the reactive power control modes of constant power factor, reactive power provision based on reactive power setpoints received and reactive power provision based on voltage. The impact of these control modes on the industry is compared using two perspectives: the active and reactive power balance for each hour (representing the actual flows including reverse flows), as well as from the perspective of the calculated power factor for one month, when using the month's lumpsum of active power and reactive power. This means that normal flows and reverse flows resulting from high PV generation will be summed (with opposite signs). Recommendations on reactive power control modes as well as power factor calculation methods are provided as a conclusion, based on the study's results.

2. CAPABILITY OF REACTIVE POWER PROVISION FROM PV INVERTERS

In the past, bulk system voltage regulation was provided almost entirely by synchronous generators. With increasing shares of renewable generation in power systems, the need arises for these units to contribute with voltage and reactive power regulation.

The contribution depends on the size of the renewable generation plant, voltage level of the connection, as well as on the needs of the local voltage. With increasing shares of solar PV systems also in the distribution level, it is becoming common good practice to demand generators connected to the medium and low voltage distribution grid the capability of operating at least at off-unity power factor.

2.1 REACTIVE POWER RANGE

Typically, grid codes specify a required reactive power range as a precondition to get connected. The grid operator can then usually decide what exact reactive power behaviour (reactive power control mode) is required from each generator. The mode is operated within the required range in the grid code.

A simple and common reactive power range requirement is to realize a certain power factor range. In most cases this is either between cosφ = 0.95 underexcited and cosφ = 0.95 overexcited, or cosφ = 0.90 respectively[1]. Furthermore, in many countries, units are not required to provide any reactive power when operating below 10% or 20 % of their rated active power output.

Most inverters for PV generators on the market can fulfil those requirements and it is even technically possible for inverter-based generators to go beyond that (see Figure 1). For example, inverters are capable of providing reactive power support at zero power (similar to a STATCOM). However, this functionality is not commonly used in the industry, as PV inverters are typically disconnected from the grid at night and therefore their reactive power capability is not available.

In Figure 1, figure (a) shows the normal operating range of an inverter (area I) as well as an example of a requirement for operation in the cos φ = 0.90 range (blue lines) with no required reactive power provision for operation below 10% of rated active power (blue triangular area). Figure 1 (b) shows further capabilities of a modern inverter, including the provision of reactive power at zero active power (similar to a STATCOM).

[1] The terms under and over excited technically only apply to synchronous generators, however they are also often used for inverters to characterize explicitly whether reactive power is generated or consumed. The associated sign to the generation and consumption depends on the sign convention chosen. In the passive sign convention generation is negative

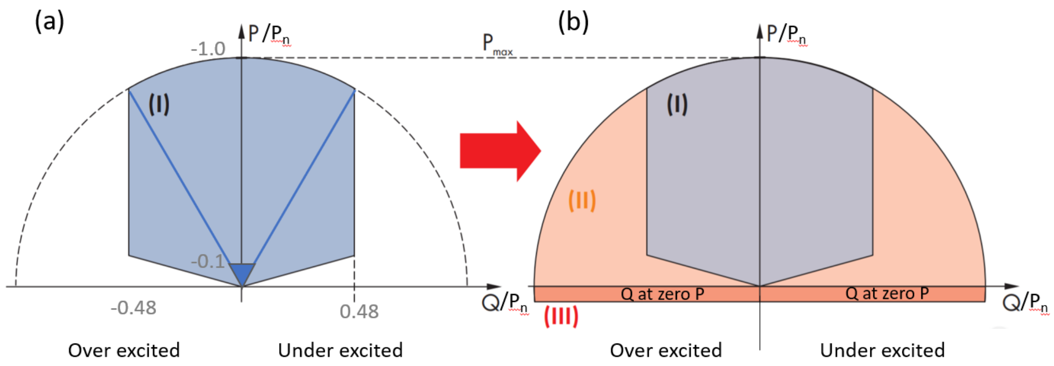


Figure 1: Inverter operating ranges: (a) (I) Normal operating range and requirement for operation in the cos φ = 0.90 range (blue) with no required provision of Q when below 10% of rated active power (blue area); (b) (II) Extended operating range with cos φ = 0 (over excited) to cos φ = 0 (under excited); (III) Reactive power provision outside of feed-in operation. Passive sign convention is used (generation is negative). Adapted from source: SMA Q on Demand 24/7.

Limiting the reactive power requirements to a certain power factor range is a common simplification and mostly used in distribution grid codes or grid codes applicable to small generators. It is possible to issue stricter requirements, as the actual capability curves for reactive power in most generators are not limited to a certain power factor. Figure 1 displays this for a modern PV inverter, where reactive current is mainly limited by the current limit of the inverter and the software controls.

Inverters used for solar PV plants can provide reactive power capability at partial output, but the reactive power capability at full power requires the inverter to be oversized (larger for the same plant kW rating) in order to provide full active and reactive current.

2.2 REACTIVE POWER CONTROL MODES

The reactive power ranges described in the previous section require generators to be able to provide a certain amount of reactive power depending on active power output and voltage at the connection point. This in itself does not yet require reactive power control modes, which are set in a separate requirement. The main control modes are:

- Fixed reactive power contribution (either fixed cosφ or fixed Q, this includes reactive power setpoints by remote control);
- Reactive power contribution dependent on voltage (cosφ(U) or Q(U));
- Reactive power contribution dependent on active power output (cosφ(P) or Q(P));

For PV plants connected to the medium or low voltage distribution grid, it is recommended to require the capability to operate in the following reactive power control modes:

1. Fixed power factor and
2. At least one active power based and one voltage-based characteristic:

- cosφ(U) or cosφ(P) (recommended for connection level of 10 kV and below)
- Q(U) or Q(P) (recommended for connection level above 10 kV).

For example, in Germany, all generators connected to the low voltage level are required to be able to realize fixed cos φ as well as a cos φ(P) characteristic. Generators above 4.6 kVA are also required to be capable of Q(U) operation.

Common practice is to require generators to be capable to implement more than one, or all, control modes. The grid operator will then decide which mode should be activated based on local grid conditions, and may often also change the control mode as required. For the characteristics-based approaches (cosφ(U), Q(U) cosφ(P) and Q(P)), the grid operator will choose the characteristic used. Examples are given in Figure 2.

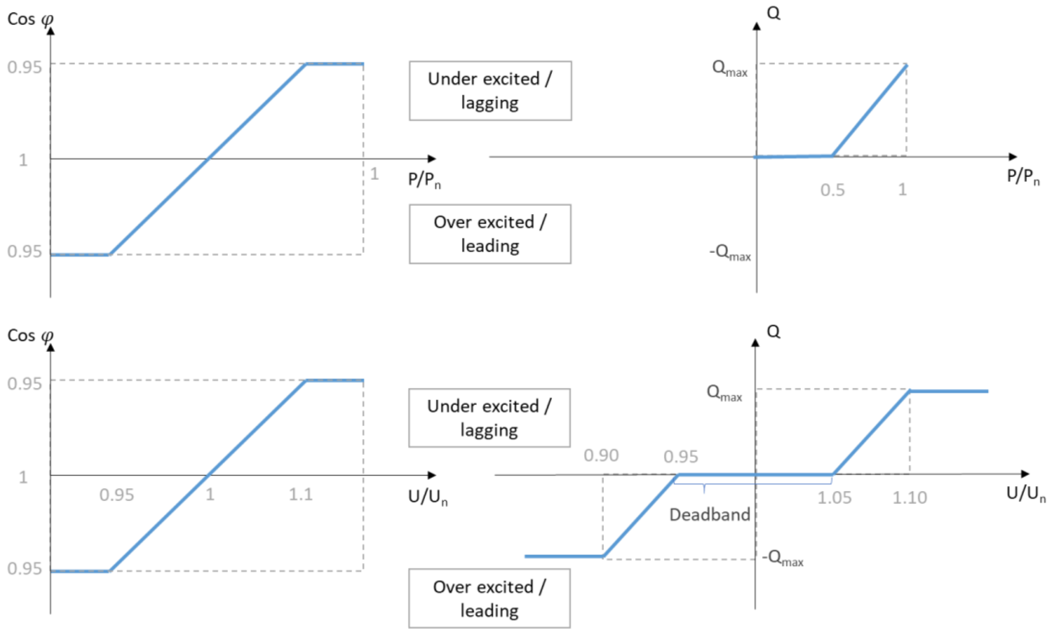


Figure 2: Examples of characteristics of different reactive power control modes. Top row: cosφ(P) and Q(P) modes. Bottom row: cosφ(U) and Q(U) modes.

By requiring the **capability for reactive power provision** early on, the grid operator has the option to later ask units to **enable a reactive power behaviour** in case any problem that requires it appears in the grid at a later point in time.

3. CASE STUDY: ANALYSIS OF Q-CONTROL SUPPORT FROM PV SYSTEMS TO NET METERING SITE

3.1 SELECTED PILOT SITE

3.1.1 Ice Production Industry

The selected pilot site consists of an ice production industry, located in Khulna, Bangladesh. The average load during on-peak hours (17h-22h) and during off-peak hours, as well as the month average power factor can be seen in Figure 3 and Figure 4, respectively.

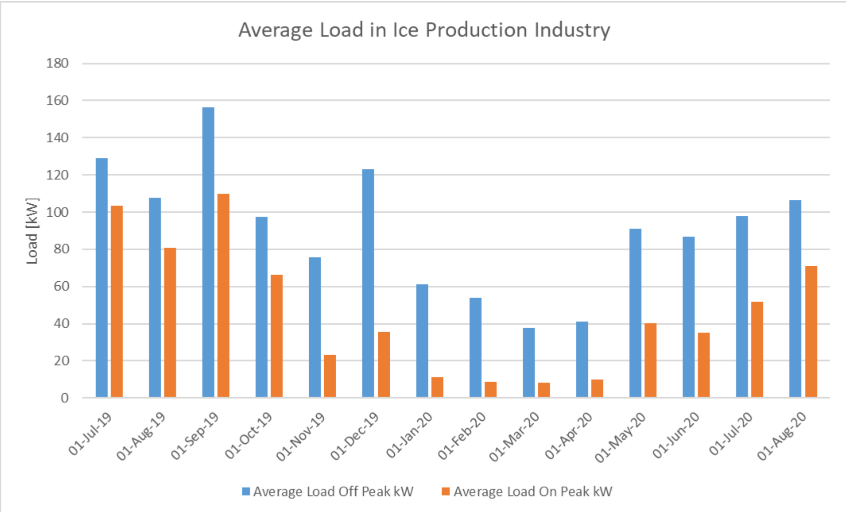


Figure 3: Month average load during peak and off peak hours.

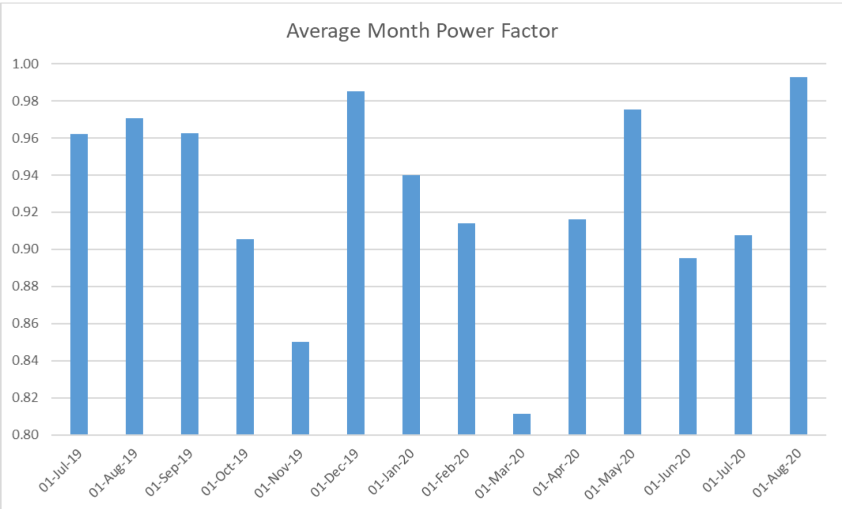


Figure 4: Month average power factor (Y-axis starts from 0.8).

3.2 INDUSTRY LOAD CURVE

Monthly averages are available for the industry load, these include average active power loads on and off-peak as well as a month average power factor, as shown in Section 3.1.1. Hourly measurements of the industry load were not available. Therefore, the industry load curve (hourly load) was estimated based on available substation measurements of the feeder in which the industry is located and the industry's monthly averages. The estimation of the industry load curve will be described next.

3.2.1 Step 1: Feeder data treatment

In this first step, for the nine days of measurements received, missing hourly values were replaced with the average of the existing values of other days for that hour and days which did not fit into the overall pattern were removed. The treated data that will be used to estimate the feeder hourly load curve can be seen in Figure 5.

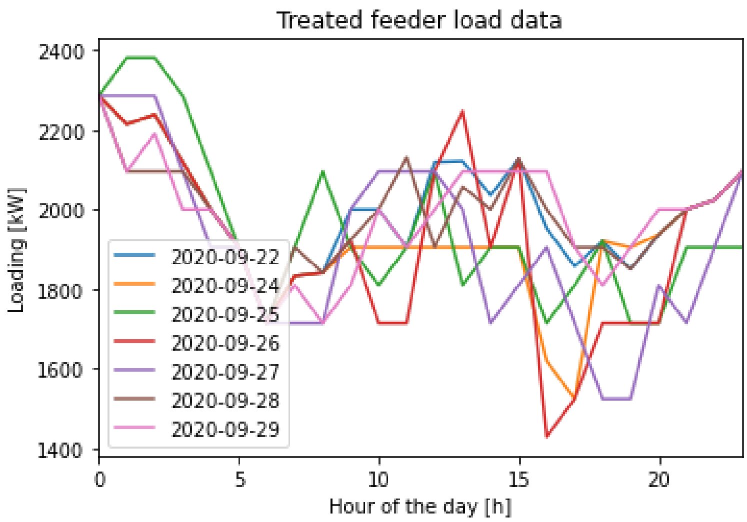


Figure 5: Treated feeder data.

3.2.2 Step 2: Scaling the feeder curves to the industry data

For each day shown in Figure 5, the feeder's average active power load during on-peak and during off-peak hours was calculated. These feeder averages were compared to the industry on and off-peak month averages and a scaling factor calculated for each feeder day. Therefore, using the scaling factor, the curve of each feeder day was scaled to match the industry's peak and off-peak month active power averages.

The industry's reactive power curve was estimated by applying the industry's month average power factor to the estimated hourly values of the industry's active power. This means, that the hourly values of active and reactive power differ between the different days, however the power factor is always the same and equal to the average month power factor from the industry's bill. In Figure 6, the estimated active and reactive power hourly values are shown, scaled from each feeder day shown in Figure 5.

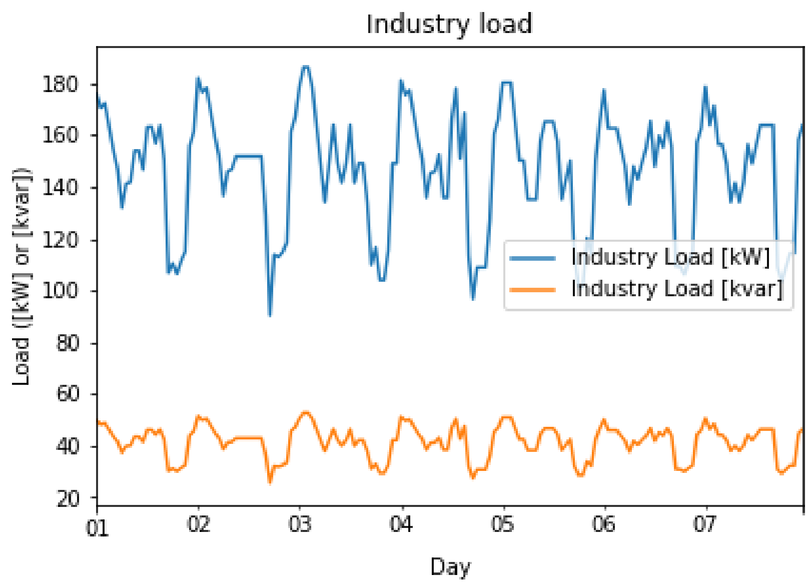


Figure 6: Industry hourly load curve, scaled from the seven days of feeder data and using the average monthly values of the industry for the month of September 2019. (Data for September 2020 was not available).

3.2.3 Step 3: Creating a month profile

In order to calculate the impact of PV on the industry's monthly average power factor, a profile for the industry load for an entire month is needed. This profile was created by simply repeating the seven days profile shown in Figure 6. The resulting industry load profile based on the average data for the month of March (2019) can be seen in Figure 7.

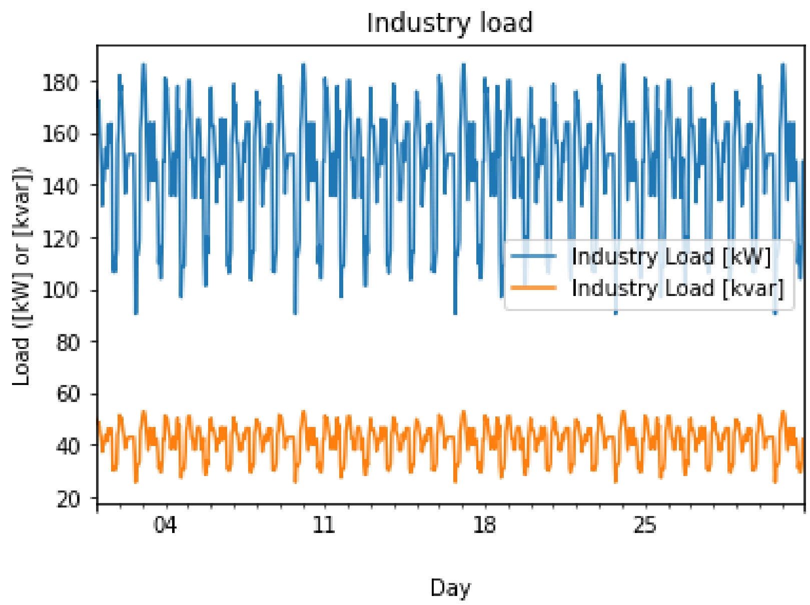


Figure 7: Estimated industry load profile for the month of September.

3.3 SOLAR PV PRODUCTION PROFILE

PV measurement data from a nearby location is available for the months of March to mid June 2019 as well as February 2020. The site's yield (in kWh per kW_{AC}) was calculated for the available months from the characteristics of the PV inverter (27 kW_{AC}/37.8 kW_{DC}). The site yield profile can be used to estimate the energy production of other PV systems in the area, for PV systems of different sizes. As an example, the expected output of a 276 kW_{AC} system is shown in Figure 8 for the sample month of March.

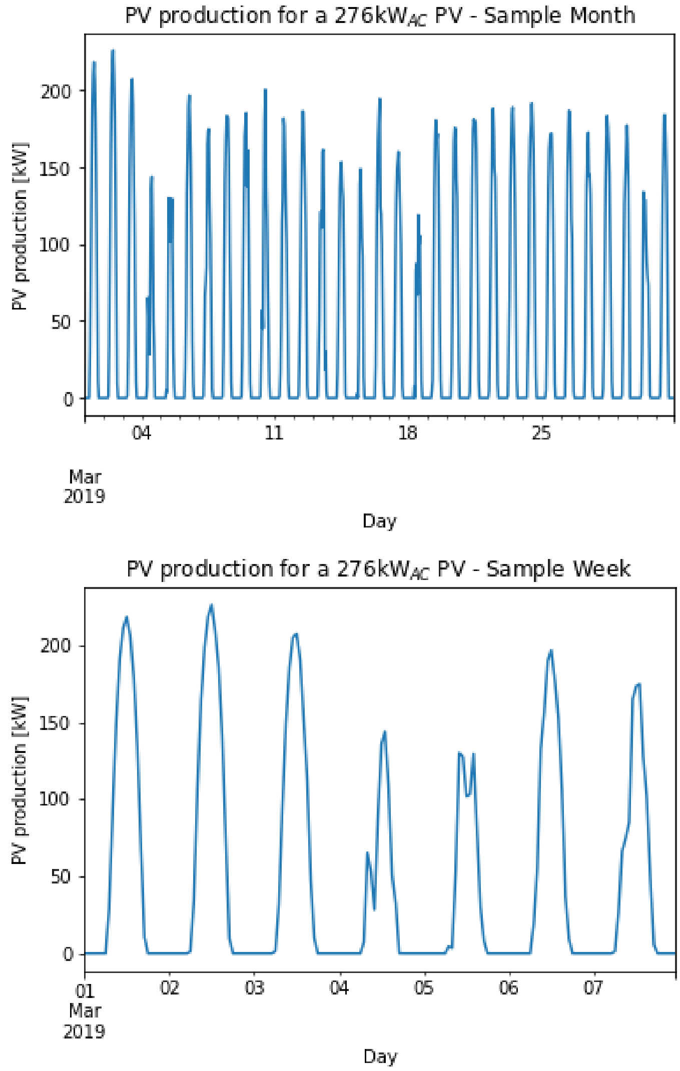


Figure 8: PV production profile for the sample month of March, for a 276 kW_{AC} PV system. Estimated based on measurements received from nearby PV system. Top: full month. Bottom: first week.

The 276 kW_{AC} PV size corresponds to the sum of the industry's maximum load and minimum load. This is recommended as the maximum PV size to be installed in the industry, in order to limit the reverse flow into the grid to the maximum industry load. For example, when the industry is consuming its maximum load, the PV system will supply this load and feed into the grid the equivalent value to the industry's minimum load. When the industry is consuming its minimum load, the PV system will supply this load and feed into the grid the equivalent to the industry's maximum load.

3.4 ANALYSIS OF IMPACT OF Q-CONTROL SUPPORT FROM PV SYSTEMS ON THE INDUSTRY'S POWER FACTOR

In this Section, the impact on the industry's power factor of the provision of reactive power from the PV system under different reactive power control modes is compared.

3.4.1 Base Case: PV system with no reactive power provision

Using the industry load profile calculated for the month of September (as shown in Figure 7) combined with the PV generation profile for a 276 kW_{AC} PV system using the data from March (shown in Figure 8), the load seen from the grid (net load) can be estimated on an hourly basis.

As the base case, the net load when the PV system does not provide reactive power is calculated for the entire month. The PV system thus has a constant power factor of 1. The industry load as well as net load for a sample week can be seen in Figure 9, both for the case without any PV system and for the base case of a PV system with power factor of 1.

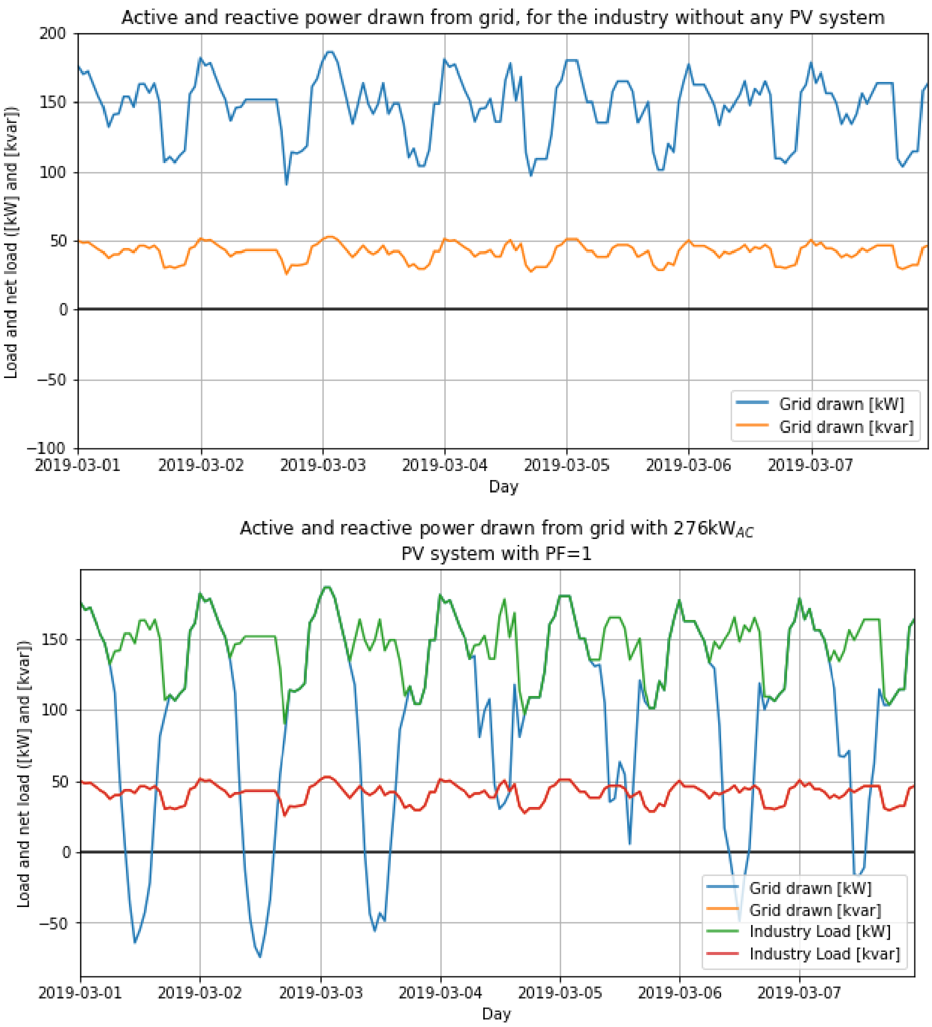
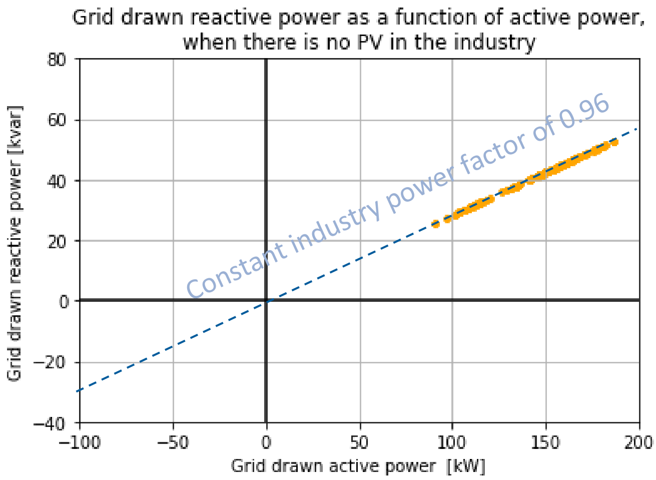


Figure 9: Industry active and reactive loads and active and reactive (net) loads drawn from the grid, when the industry has no PV (top) and has a 276kW$_{AC}$ PV system with constant power factor of 1 (bottom).

In Figure 9, it can be observed that, when compared to the case of the industry without any PV system (top figure), the generation of active power from the PV system contributes to reducing the active power drawn from grid during the day and even reverse the flow, by providing active power to the grid (shown in the bottom figure). In the base case, the PV system generates no reactive power and therefore has no impact in the reactive power drawn from the grid, which is equal to that of the industry load.

The power factor was calculated for every hour of the simulated month. The scatter plot shown in Figure 10 indicates for every hour of the simulated month (one dot for each hour) the proportion of active power drawn from the grid in relation to the reactive power. The top figure indicates a system without any PV and therefore the power factor of every hour is equal to the monthly average power from the industry data (0.96), as expected because this value was used as basis to estimate the industry hourly reactive power. In the bottom figure, it can be seen the impact of having a PV system active power generation reducing the active power drawn from grid without also reducing the reactive power, which will result in a lower (worse) average month power factor. The PV system here only affects the grid drawn active power. It does not affect the industry's grid drawn reactive power, therefore compensation units do not need to be added because of the PV system.



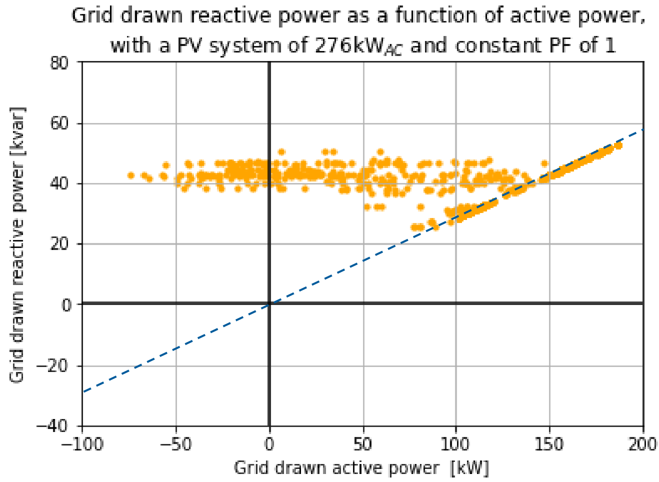


Figure 10: Proportion of grid drawn active power in relation to reactive power, without any PV in the industry (top) and with a PV system with constant power factor of 1 (bottom).

The size of the PV system was varied, resulting in different shares of the industry monthly load covered by the PV system. The impact on the industry power factor for the various PV sizes can be observed in Figure 11, shown as a function of the percentage of the industry monthly load that is covered by each PV system size. The reduction of the industry power factor with higher shares of the load covered by the PV system is shown.

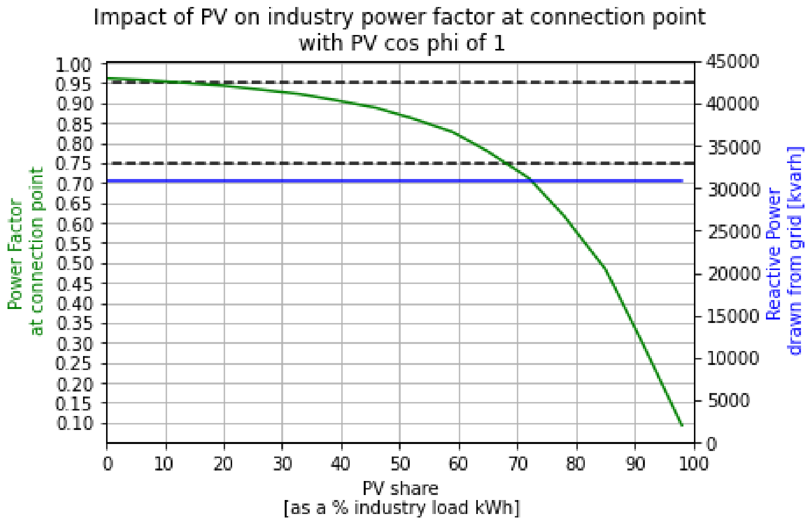


Figure 11: Impact of different PV generation shares to the industry's monthly average power factor, when there is no reactive power provision from the PV system. Green curve: Power factor at connection point. Blue curve: reactive power drawn from grid.

This case shows that, when operating the PV system at a constant power factor of 1.0, the reactive power drawn from the grid is not affected by the PV system, i.e. it is equal to the load's reactive power. However, due to the reduction of active power drawn from the grid (as part of this power is now supplied by the PV system), the current power factor method of calculation would yield penalties for shares of PV system covering only 10% of the industry's monthly load.

3.4.2 Case 1: PV system providing reactive power with a constant power factor of 0.95 over excited

The first case of reactive power control mode analysed is to have the PV system operating with a constant power factor of 0.95 over excited, if the PV active power produced is above 20% of the installed PV capacity. Below 20%, the PV will operate with a power factor of 1.

The industry load as well as net load when the PV system operates with a constant power factor of 0.95 was calculated for the entire month analysed. A sample week can be seen in Figure 12. Reactive power is now being provided by the PV systems and reduces the reactive power drawn from grid, even providing reactive power to the grid at certain times (negative values shown in Figure 12).

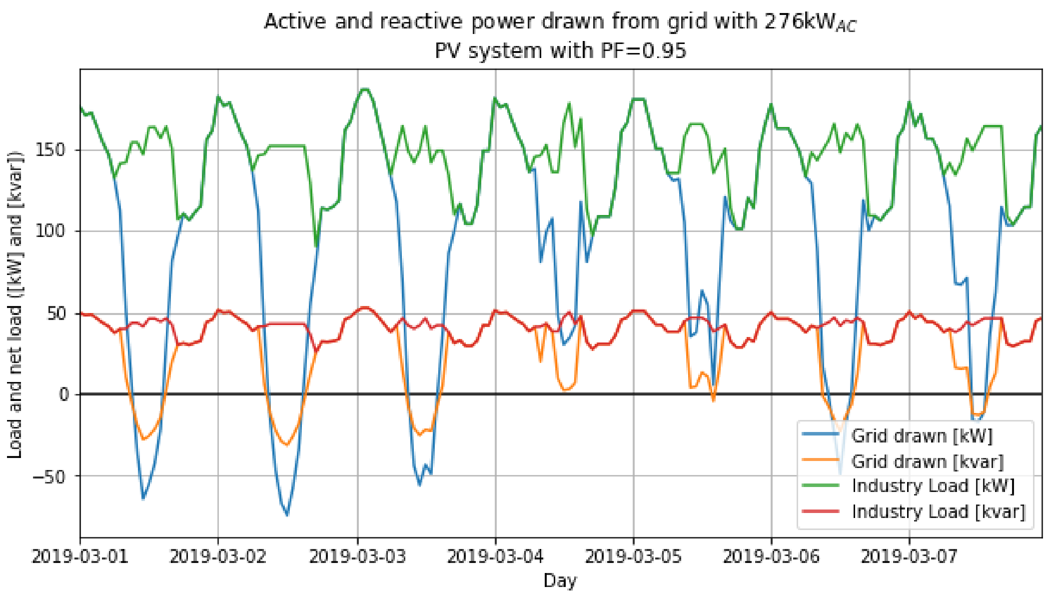


Figure 12: Industry active and reactive loads and active and reactive (net) loads drawn from the grid, when the industry has a 276kW$_{AC}$ PV system operating with constant power factor of 0.95.

The scatter plot shown in Figure 13 indicates for every hour of the simulated month (one dot for each hour) the proportion of active power drawn from the grid in relation to the reactive power. From this it can be seen that the PV system affects the active power drawn from the grid in proportion to the reactive power drawn from the grid. However, overcompensation of reactive power occurs and this might lead to affecting the voltage negatively.

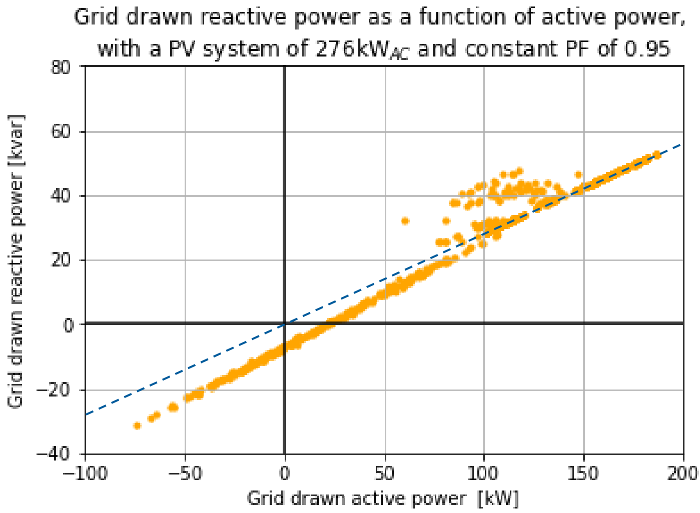


Figure 13: Proportion of grid drawn/injected active power in relation to reactive power, for the case of a 276kW$_{AC}$ PV system in the industry operating with constant power factor of 0.95. Dotted line represents the power factor of 0.96 from the industry load without PV.

The size of the PV system was varied, resulting in different shares of the industry monthly load covered by the PV system. The impact on the industry power factor for the various PV sizes can be observed in Figure 14.

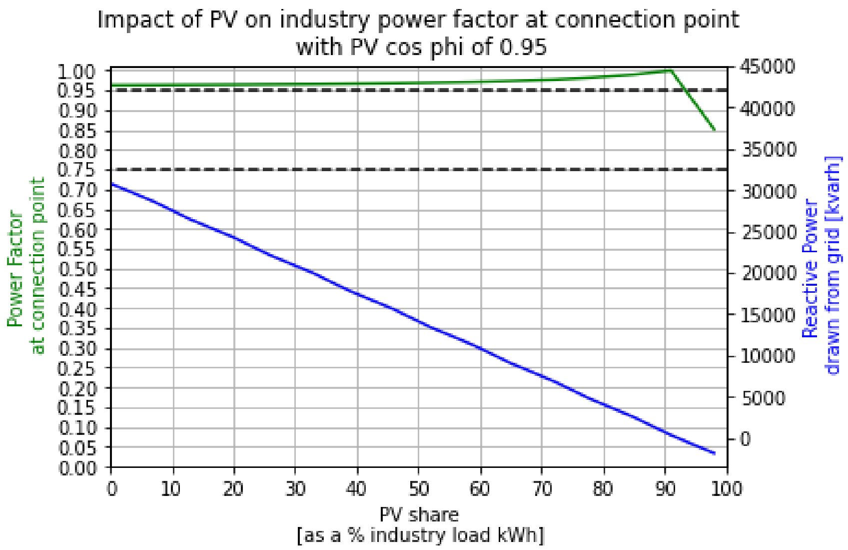


Figure 14: Impact of different PV generation shares to the industry's monthly average power factor, when the PV system operates with a constant power factor of 0.95. Green curve: Power factor at connection point. Blue curve: reactive power drawn from grid.

From Figure 14 a clear improvement in the industry's monthly average power factor can be observed, when compared to the base case in which the PV system operates with a constant power factor of 1 (i.e., no reactive power provision). Under the current regulatory conditions, penalties (for power factor below 0.95) would only occur for shares of PV system covering more than 90% of the industry's monthly load.

3.4.3 Case 2: PV system providing reactive power based reactive power required at the industry's connection point

The second case of reactive power control mode analysed is to have the PV system providing as much reactive power as needed to cover the industry load (assuming measurements at the connection point are received as setpoints), limited to a maximum reactive power of 33 % of the installed active power (following the reactive power capability curve of many PV inverters and requested by many international grid codes). This is only applicable if the PV active power produced is above 20% of the installed PV capacity. Below 20%, the PV will operate with a power factor of 1.

The industry load as well as net load when the PV system operates with this reactive power control mode was calculated for the entire month analysed. A sample week can be seen in Figure 15. Reactive power is now being provided by the PV systems aiming to reduce the reactive power drawn from grid to zero, when possible without exceeding the reactive power limit of 33 % of the installed active power.

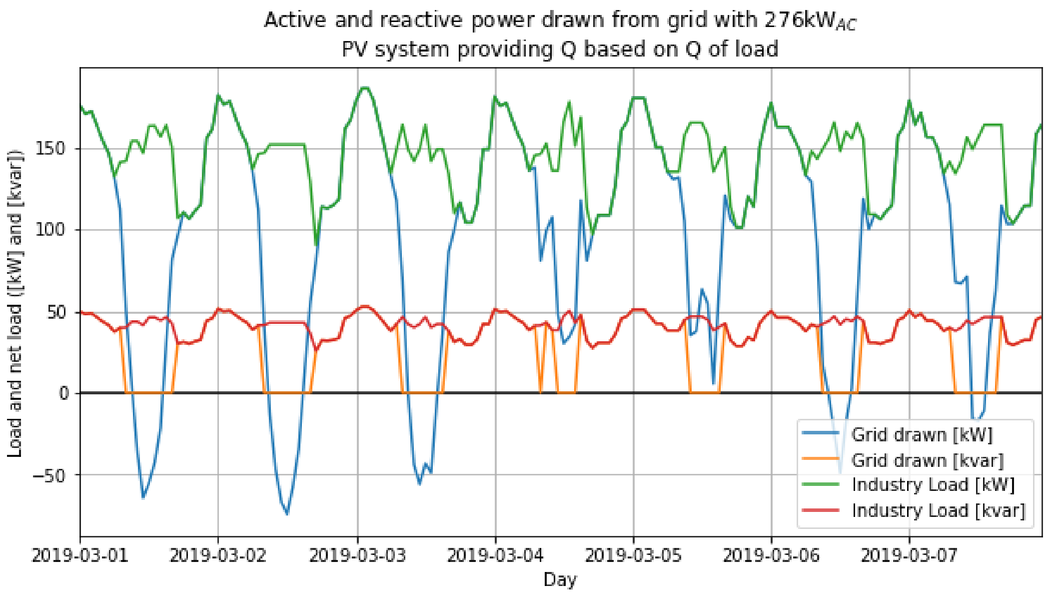


Figure 15: Industry active and reactive loads and active and reactive (net) loads drawn from the grid, when the industry has a 276kW$_{AC}$ PV system operating with a reactive power control mode based on the load's reactive power requirements.

The scatter plot of active power drawn from the grid in relation to the reactive power is shown in Figure 16. It can be observed that many points have been moved to the grid drawn reactive power of zero (which corresponds to a industry power factor of 1). Most of the remaining points correspond either to hours in which there is no PV production (no sunlight) and therefore the PV does not modify the industry power factor of 0.96 or for hours when the PV active power is smaller than 20 % of the installed PV system size and therefore no reactive power is generated (PV operates with a power factor of 1).

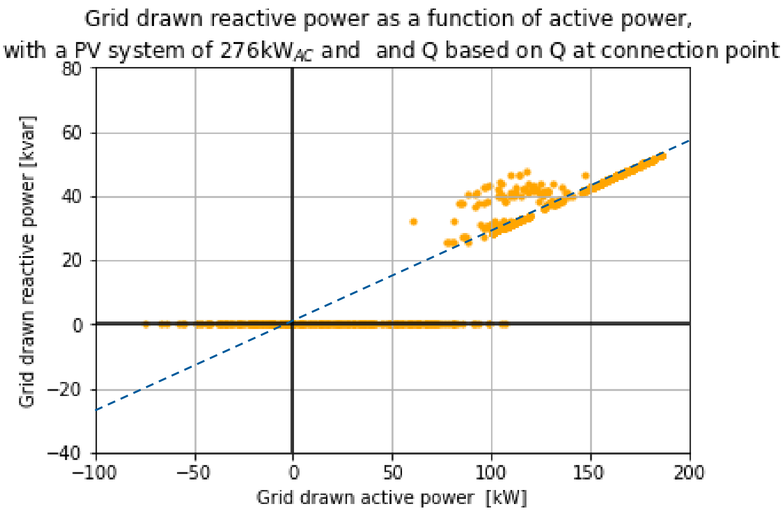


Figure 16: Proportion of grid drawn/injected active power in relation to reactive power, for the case of a 276kW$_{AC}$ PV system in the industry operating with a reactive power control mode based on the reactive power required by the industry load.

The size of the PV system was varied. The impact on the industry power factor for the various PV sizes can be observed in Figure 17.

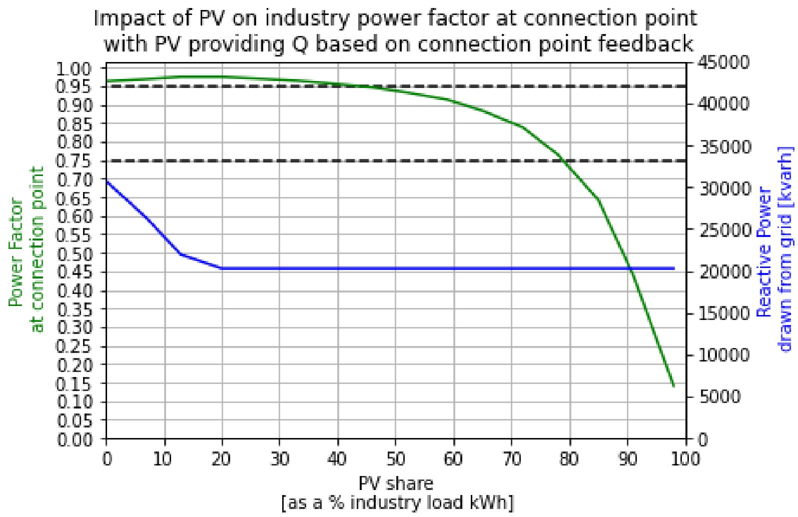


Figure 17: Impact of different PV generation shares to the industry's monthly average power factor, when the PV system operates with a reactive power control mode based on the reactive power required by the industry load. Green curve: Power factor at connection point. Blue curve: reactive power drawn from grid.

From Figure 17 it can be seen that, for PV systems sized to cover 20 % of the industry's load and above, the reactive power of the load during the hours when the PV system is generating is already covered (the PV system does not produce more than needed to cover the industry's load in this control mode). Therefore, the reactive power still drawn from grid will correspond to that needed to cover the industry load outside the PV system's production hours. With this constant reactive power drawn from the grid and a decreasing active power drawn from grid (due to the increasing PV production) the resulting monthly average power factor reduces. Under the current regulatory conditions, penalties (for power factor below 0.95) would occur for shares of PV system covering 45 % of the industry's monthly load.

3.4.4 Case 3: PV system providing reactive power based on voltage (volt-var)

The third case of reactive power control mode analysed is to have the PV system providing reactive power as a function of the voltage. This mode enables the PV system to contribute to maintaining the voltage between recommended values at the connection point. This behaviour is especially important in the case of high shares of PV in the distribution system, as these can have the effect of increasing the voltage at the end of the feeder above desired levels.

Because no voltage data was available for the analysed industry, the reaction of the PV system's reactive power control was set based on the net active power of the grid (active power drawn from grid), as shown in Figure 18. Typically, the voltage will be lower when there is low active power generation from the PV system (i.e. high active power energy drawn from the grid). In this case, the PV system can support (increase) the voltage by generating reactive power. Analogously, the voltage will increase at the connection point of the industry at times with high active power generation from the PV system (i.e. low active power energy drawn from the grid, or even reverse flow situations). In this case, the PV system can support (reduce) the voltage by consuming reactive power. Therefore, the reactive power response of the PV based on voltage can be emulated by using the grid drawn active power as an indicative of expected voltage status. This emulation is sufficient for the purpose of this analysis, however, for further analysis of this method, it is strongly recommended to use voltage measurements of the PV site.

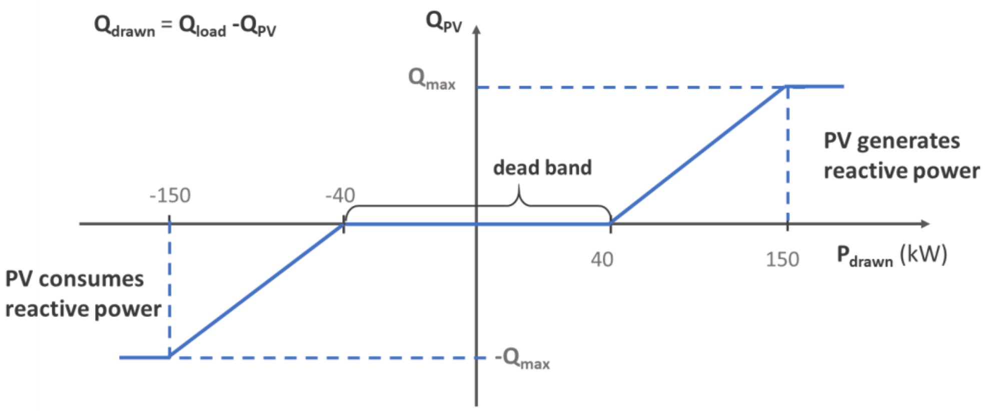


Figure 18: $Q_{PV}(P_{drawn\ from\ grid})$ characteristic applied to the PV in order to emulate Q(U).

The maximum reactive power of the PV system corresponds to 33 % of the installed active power (following the reactive power capability of many PV inverters). This reactive power output is only applicable if the PV active power produced is above 20% of the installed PV capacity. Below 20%, the PV will operate with a power factor of 1. The dead band chosen for the PV's response was 40 kW.

The industry load as well as net load when the PV system operates with this reactive power control mode was calculated for the entire month analysed. A sample week can be seen in Figure 19. As displayed, the PV's reactive power response is only activated when the grid drawn active power is outside the dead band (represented by the dotted lines).

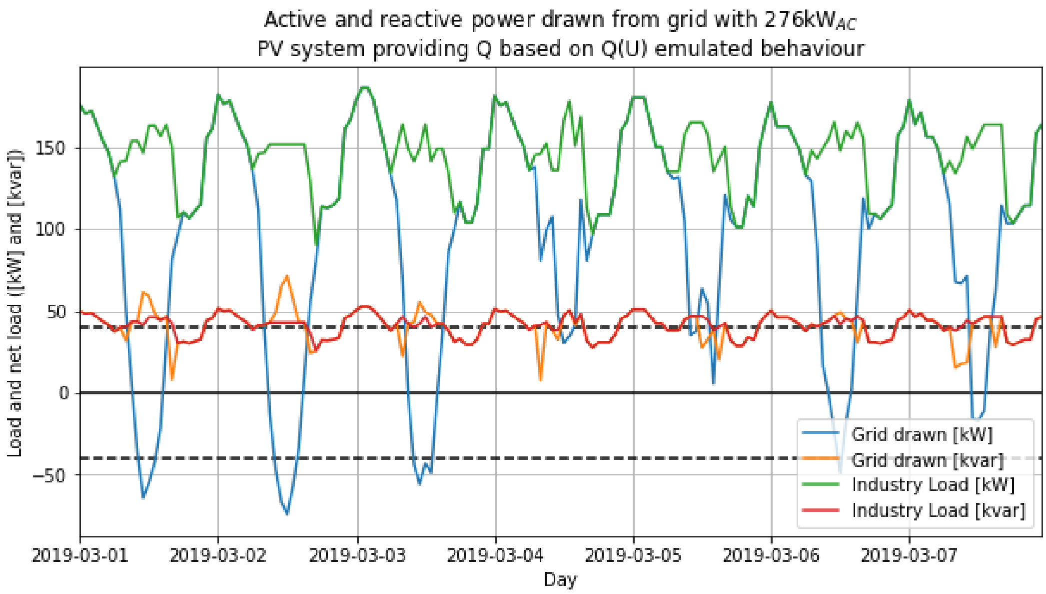


Figure 19: Industry active and reactive loads and active and reactive (net) loads drawn from the grid, when the industry has a 276kW$_{AC}$ PV system operating with a reactive power control mode based on (emulated) voltage.

The scatter plot of active power drawn from the grid in relation to the reactive power is shown in Figure 20. This reflects the curve shown in Figure 18. For example, at times with higher active power energy drawn from the grid (due to lower PV generation), the voltage is expected to decrease, and therefore, the modelled reactive power response from the PV system will generate more reactive power of the PV, reducing the reactive power drawn from the grid in order support and increase the voltage.

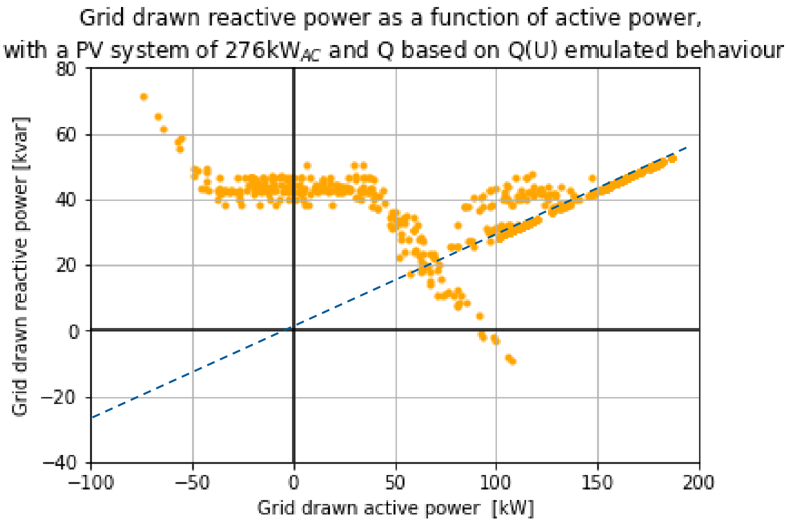


Figure 20: Proportion of grid drawn/injected active power in relation to reactive power, for the case of a 276kW$_{AC}$ PV system in the industry operating with a reactive power control mode based on emulated voltage.

The size of the PV system was varied. The impact on the industry power factor for the various PV sizes can be observed in Figure 21.

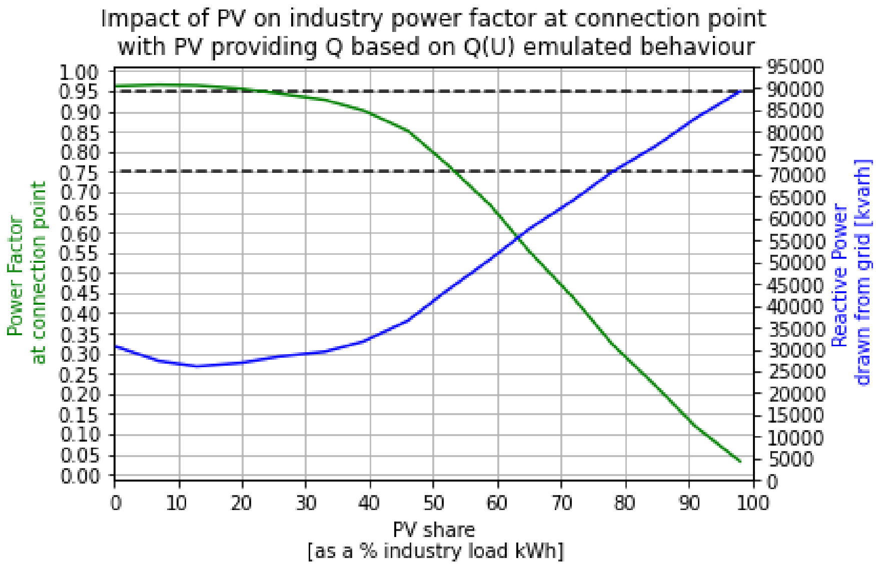


Figure 21: Impact of different PV generation shares to the industry's monthly average power factor, when the PV system operates with a reactive power control mode based on emulated voltage. Green curve: Power factor at connection point. Blue curve: reactive power drawn from grid.

This reactive power control mode directly aims to provide voltage support. For low PV shares (which decrease the grid drawn active power without reverse flows occurring), the PV system will be producing reactive power to increase the voltage therefore reducing the grid drawn reactive power ($Q_{drawn} = Q_{load} - Q_{PV}$ and Q_{PV} is positive). For higher shares of PV in the system reverse flows begin to occur and with increasing magnitude, and therefore the PV system's reactive power control responds by consuming more reactive power in order to reduce the voltage., leading to the eventual increase of the grid drawn reactive power ($Q_{drawn} = Q_{load} - Q_{PV}$ and Q_{PV} is negative). The increase of grid drawn reactive power in combination with the decrease of the grid drawn active power results in low power factors for the industry, when the power factor is calculated by using the sum of hourly active and reactive powers (reverse flows with a negative sign).

Under the current regulatory conditions, penalties (for power factor below 0.95) would occur for shares of PV system covering 25 % of the industry's monthly load.

4. SUMMARY OF CHALLENGES AND RECOMMENDATIONS

4.1 SUMMARY OF CHALLENGES

The impact on an industry's power factor when having PV systems providing reactive power under different control modes was analysed, for different shares of PV generation in relation to the industry's energy consumption. The method used for the industry's power factor calculation is based on the lumpsum of the industry's monthly power drawn from the grid (active and reactive power). This method reflects what is being applied in Bangladesh currently. The key findings of this study are:

1. When operating the PV system at a constant power factor of 1.0
   - The PV system generates no reactive power and therefore has no impact in the reactive power drawn from the grid.
   - However, the current method to determine power factor will already fail (i.e. result in penalties due to a power factor below 0.95) for small shares of PV production (shares above 10% of the industry's energy consumption).
2. When operating the PV system overexcited (e.g. constant power factor of 0.95)
   - The reactive power can be well compensated and will even provide reactive power to the grid in certain times.
   - The current method to determine power factor will only fail for very high shares of PV production (above 90% of the industry's energy consumption).
   - Providing reactive power to the grid in reverse flow situation might lead to over-voltages and might thus be undesirable.
3. Another solution is to control reactive power at the grid connection point (reducing it to zero, when possible). With this control mode:
   - Reactive power flows (and thus losses) are considerably reduced.
   - However, the current method to determine power factor fails at around a 40 % share of solar generation on the energy consumption.
4. Other favourable controls such as Q(U) (also known as VoltVar) will stabilize the voltage with minimum amount of reactive power, however this mode is not suitable to be used with the existing method to determine the power factor, as typically reactive power is consumed in reverse flow operation in order to reduce the voltage.

As observed from the active and reactive scatter plots, there is no real issue on the reactive power balance when a PV system is operated in the distribution grid. However, the current procedure of metering the power factor is not very suitable with net-metering schemes, and therefore it is recommended to be modified. Recommendations are summarised in the next section.

4.2 RECOMMENDATIONS

4.2.1 Short Term

- Consumer loads (e.g. induction machines) should always be compensated to a power factor above 0.95. This can be done with conventional compensation methods (such as capacitor banks) or if the inverter has STATCOM capability.
- In case high power factor penalties due to large PV systems occur, the power factor of the PV systems can be set to 0.95 (overexcited).

4.2.2 Medium Term

- Different reactive power control capabilities should be required for PV systems (e.g. Q(U)). Requiring the capability does not imply that it will necessarily be used (as explained next).
- It should be up to the distribution company to request which specific type of control and setting is most beneficial for each system (e.g. depending on local reactive power balance).
- For larger systems (e.g. above 100 kW), the PV inverter should be able to control (within its capabilities) the reactive power at the grid connection point.
- **The algorithm to determine the power factor used for deciding on penalties is recommended to be changed.** The power factor should be calculated based on the maximum demand (both kW and kvar). This method is internationally commonly used. It assures, that even in the worst case, the power factor of the load is compensated and allows for more freedom in controlling the reactive power of the PV system (e.g. for voltage control).