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Impacts of high penetration of PV in distribution grids and mitigation strategies.

Semester Thesis

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Zürich, August 2013
Special acknowledgements to the Foundation of Education and European Culture for its kind support during the course of my Master studies, part of which is the present Semester Thesis.
Abstract

Over the last few years renewable energy technologies are getting increasing interest due to the rising environmental awareness and potential depletion of conventional energy resources. The most of the renewable energy potential lies in distributed generation and especially photovoltaics (PV) which are subsidized quite often by the government for residential installation.

Despite the benefits of high PV penetration, high penetration might lead to several technical issues sourcing from the fact that distribution grids were not originally designed to carry generation. The focus of the project is to study such technical limitations potentially occurring during steady state while assuming symmetrical three-phase operation.

The first part of this project is dedicated to the theoretical study of these constraints and relevant mitigation strategies. In the second part, we focus on the mitigation scenarios of storage and conductor upgrading. An optimization algorithm is implemented in order to investigate the impact on PV energy yield. The algorithm suggests optimal location and sizing of batteries. Finally, an interpretation of the simulation results is presented.
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1 Introduction

Over the last years renewable energy technologies are getting increasing interest due to the rising environmental awareness and potential depletion of conventional energy resources. The most of the renewable energy potential lies in distributed generation, a term which implies the installation of renewable energy sources to the distribution grid (low voltage grid) thus leading to reduced congestions and power losses [26], [2]. Specifically photovoltaics (PV) are highly suitable for distributed generation considering that they are relatively easily installed, they produce no greenhouse gas emissions during their lifetime and their input energy is abundant. These reasons have contributed into them being quite often subsidized by the government for retail use meaning the residential installation supported by many EU countries’ government[5].

At the same time, high penetration of PV in a low voltage grid can be the cause of several technical issues sourcing from the fact that distribution grids were not originally designed to carry generation. The focus of the project is to study such technical limitations potentially occurring during steady state while assuming symmetrical three-phase operation.

The first part of this project is dedicated to the theoretical study of these constraints and relevant mitigation strategies. In the second part, we focus on the mitigation scenarios of storage and conductor upgrading and an optimization algorithm is implemented in order to investigate the impact on PV energy yield. The implementation of an optimization algorithm which considers voltage and thermal limits and derives the optimal location and sizing of batteries is the second goal of the project. The algorithm implemented simulates a variety of scenarios which are based on a benchmark low voltage grid located in Affoltern, Zurich. Real life weather data are used to derive the photovoltaic generation. A two-well model of the lead-acid batteries is used as storage model and a thermal model of a transformer simulates its hot spot temperature. The interpretation of the simulation results takes place at the third part of the project.

2 Limitations on PV penetration

Despite its huge theoretical potential, photovoltaics’ high penetration is hindered by certain technical constraints related to the operation of the electrical power system and the ratings of the electrical components [2]. Distribution systems were originally designed to facilitate the flow of power from the generation to the consumers through successively decreasing voltage levels. The challenge that distributed generation introduces derives from the opposite power flow that it creates, i.e. from the distribution level towards the MV/LV feeder.
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The problems that can be caused by high penetration of PV in the system vary from overvoltages and voltage unbalances to power quality, protection and stability issues. Out of all the potential technical issues created due to the high penetration of PV, the objective of this semester project is to focus on the technical issues created during the steady state of the distribution system, while considering symmetrical three-phase operation (three-wire balanced operation).

2.1 Overvoltage

Overvoltage caused by high PV penetration is a very common reason for constraining the installed capacity of PV. The grid is challenged the most during periods of high PV generation and low load where the possibility of reverse power flow is the highest.

To have a flow of power from the feeder to the customer the voltage at the feeder is required to be higher than the one at the connection point. Therefore, the voltage in a traditional distribution grid gradually declines from the feeder to the loads.

The voltage at the connection point of PV to the distribution grid is given by the formula:

$$\Delta V = \frac{(P_G - P_L)R + (Q_G - Q_L)X}{V},$$

where $P_G$, $Q_G$ are the active and reactive power of the PV in kW, kVAR respectively, $V$ is the voltage at the connection point in V and $R$, $X$ are the resistance and reactance in $\Omega$ between the main station and the connection point [11].

When PVs are connected across the distribution grid, the voltage profile could enhance when the generation is consumed by the loads. However, when the PV generation is higher than the consumption the reverse power flow leads to overvoltages which are not acceptable by the regulations, if they overcome certain limits. As a result, the voltage profile also reverses. To mitigate this voltage rise, there are several techniques that can be employed.

2.1.1 Power curtailment

Curtailing the output power of PV so as to reach an acceptable voltage limit, is the first solution that can be implemented. Besides decreasing the installed capacity, there are many control methods proposed so that the generators’ output is actively curtailed, known as Active Power Curtailment (APC).

An example of a droop-based APC method is described in [1]. This example demonstrates the effectiveness of the method but also considers the challenge of distributing the curtailment among the producers. Constraining
2 LIMITATIONS ON PV PENETRATION

2.1.2 Upgrading conductor

By upgrading the conductor to one with larger diameter, much smaller resistance would be achieved while the reactance would slightly differ. This would prevent the overvoltage but changing the conductor is hard to imple-
ment and would lead to economic disadvantage [3].

2.1.3 Import reactive power

Another way to mitigate overvoltage is to properly manipulate reactive power so as to minimize the numerator of (1). Ideally, this would mean that reactive power of $P_X/R$ should be imported. Considering that LV grids are highly resistive (high impedance characteristic, i.e. $R/X \gg 1$) this would require so much reactive power that would lead to an unacceptable power factor [4]. In addition, in LV grids this technique would result in increased power losses [6].

Shunt impedances are often used as sinkers of reactive power but they are slow and are not capable to mitigate against the unpredictable variations of the PV output. Also, given that they are switched on or off, they provide limited controllability [9], [10].

FACTS (Flexible AC Transmission Systems) can also serve as consumers of reactive power but their high cost can be an obstacle [7]. FACTS controllers are devices based on power-electronics therefore, they are able provide fast control [9]. Some FACTS controllers provide an output related to the voltage of the system at their connection point, presenting a difficulty to determining an optimal set point when high PV fluctuation takes place [7].

Inverters on the other hand are not as costly as FACTS and they can be employed to take advantage of its potential for both leading and lagging possibility [7]. By changing the power factor on terms of regulating the amount of reactive power absorbed can be achieved an acceptable outcome despite the fact that voltage in LV grids is more sensitive to active power changes than reactive [6], [8]. The ideal amount of $Q$ cannot be supported.

2.1.4 Reduce substation voltage and reduce voltage across the line

In the case of traditional LV grid, in order to mitigate undervoltages the voltage is kept a little higher than nominal. Given that at a LV grid the opposite phenomenon is observed, reducing the voltage would be a solution [3].

To maintain the voltage under the threshold, on-load tap changers could be used. This would enhance the voltage profile but one should make sure that it would not cause undervoltage to other points under any possible scenario. In addition, on-load tap changers are slow in regard to the PV output fluctuation thus, they are not suitable for closely following the PV output fluctuation. Plus, frequent tap changing would increase the risk of mechanical stress on the transformer.

The same challenges are faced when installing an auto-transformer (or
else known as voltage regulator) in order to reset the voltage along the line. Auto-transformers are on-load tap changers with a voltage ratio 1:1 and are used to keep the voltage in one side constant regardless of the voltage changes at the other side thus splitting the system in two parts [3], [9]. Also adding auto-transformers to mitigate overvoltage due to the high penetration of PV, decreases system reliability [1].

2.1.5 Storage

By storing energy during periods of surplus and using it during periods of high demand, a lot of benefits can be achieved starting from maximum usage of renewable energy and peak shaving. Using storage as a mitigation method against overvoltages, also contributes to mitigating against the stochasticity and the output fluctuation of PV [20]. On the other hand, storage units are costly [1].

2.2 Equipment rating and thermal limits

Distributed generation can cause an increased power flow in the grid which means increased current thus jeopardizing the thermal limits of the line and equipment. Besides thermal limits, the reverse flow requirement is not necessarily supported by all equipment.

2.2.1 Cable thermal limits

The thermal limit of cables depends on the maximum current that they can support, which is indicated in their specifications. For overhead lines the temperature of the conductor is influenced by the conductor’s material properties, the conductor’s diameter and surface conditions, the conductor’s electrical current and the ambient weather conditions (wind, sun, air) [12]. The heat balance equation determines the current that may be carried:

$$q_c + q_r = I^2 r + q_s$$

$$I = \sqrt{\frac{q_c + q_r - q_s}{r}}$$

(2)

where $q_c$ is the heat loss by convection [W/m], $q_r$ is the radiated heat loss [W/m], $I$ the conductor’s current [A] and $r$ the conductor’s resistance [Ω/m].

For underground cables, the internal thermal resistances and the heat production by eddy currents in the metal sheets need to be considered additionally [11].

2.2.2 Transformer thermal limits

When the output of distributed generation overpasses the local demand, the surplus power will flow through the transformer to the higher voltage level. Therefore, the reverse power flow capability of transformers is of interest.
The first transformer that the reverse flow will meet is the distribution transformer. Distribution transformers are characterized in terms of operating voltage and nominal rating. The latter is indicative of the maximum power that can be transferred between its two sets of terminals. The primary transformer is the next one to be met by the reverse flow. Primary transformers are characterized by nominal rating and cycling emergency rating which refers to the maximum power that can be handled periodically or for short duration. Primary transformers are often installed in pairs and are sized so that they can carry peak demand load without being overloaded [14].

The thermal limit of transformers is symmetrical which means that it is the same regardless of the power flow direction. However, transformers with on-load tap changing mechanism might present asymmetrical thermal limit depending on their OLTC mechanism [14]. On-load tap changing transformers are either reactor type or resistor type. The resistor type ones can be either double or single-resistor based. The single-resistor ones appear to have an asymmetrical thermal limit due to the asymmetrical tap-changing mechanism they employ, known as asymmetrical “pennant cycle”.

![Diagram: Types of OLTC with resistors. (a) Pennant cycle, (b-d) Flag cycle [13].](image)

An example of the flag cycle of a double resistor on-load tap changer is presented in Figure 4. With the load connected at N point, to achieve change of tap from position 1 (which is the initial) to 2, the diverter switch should be moved from contact T1 to T2. Likewise, to move from tap 2 to 3, the selector S1 should be moved upwards to position 3 and then the diverter switch should move back to contact T1.
Figure 4: Flag cycle with double resistance tap changer [13].

For the sake of an example, the changing of tap from 1 to 2 is depicted. As the switch moves away from the contact M1, (b) the current goes through
R1 creating an arc between the moving switch and M1 of voltage equal to the step voltage plus the voltage drop on R1. (c) As the switch meets R2, a circulating current is created with voltage equal to the step voltage between taps 2 and 1, divided by the sum of R1 and R2. (d) Reaching M2, an arc appears between M2 and the moving switch with voltage equal to step minus the voltage drop on R2. After this analysis, it is clear that a reverse power flow which would flow from N towards the transformer would impose the same current switching and recovery voltages but to the alternate side. Therefore, the symmetry of the mechanism results in the most onerous situation being the same in both cases (in alternate sides) which implies the same thermal limit regardless of the flow direction [13].

On the other hand, a single-resistor on-load tap changer employs an asymmetrical tap changing mechanism as it can be seen in Figure 5. To change tap from position 1 to 2, T moves towards F2 creating a recovery voltage VR1= VS (a). When T meets F2, a circulating current occurs equal to VS/R and flow opposite to the load current (b). At the next step, M moves away from F1 giving rise to a recovery voltage equal to the step voltage minus the voltage drop on the resistance (c). An arc between T and M occurs when the latter approaches M, under recovery voltage VR4 equal to the voltage drop on the resistance. Considering a reverse load flow, one sees that the most onerous situation is related to the fact that M has to make and break current equal of sum of load current and the circulating current. However, in case of forward flow the circulating current would be subtracted from the load current. Considering that the thermal limit is determined by the most onerous condition of its operation, it is observed that the asymmetry of the mechanism leads dependency of the limit of the flow direction [15].

2.2.3 Circuit breakers’ reverse flow potential

The reverse connecting or backfeeding possibility of circuit breakers is not clearly investigated in literature. It is suggested that circuit breakers without backfeeding certification should not be used for reverse flow applications. The circuit breakers which can be used for such applications are certified in accordance to UL489 and UL1066 standards [18],[19].

Regardless of the backfeeding potential of circuit breakers, the reverse power flow might cause unnecessary tripping of circuit breakers or miscoordination of protection elements. An example of such a failure is the “sympathetic tripping”. Sympathetic tripping describes the unnecessary tripping of a circuit breaker due to a fault which takes part on a different part of the system [16]. An example can be shown in pictures where a fault in feeder 2 could cause the tripping of the circuit breaker in feeder 1 where distributed generation is connected. Without the distributed generation, the circuit breaker OC-2 would be under the utility current, while OC-1 would...
be under no current. Therefore, OC-2 would trip. With the distributed generation OC-1 is under the distributed generation current, i.e. under the reverse flow, while OC-2 is under both the utility and the distributed generation current. Therefore, OC-1 might trip if it responds faster than OC-2. Many similar situations could occur by the reverse flow which result in the reduction of the system’s security. Issues as such would be facilitated by the use of more advanced protection schemes [16].

Communication with EWZ: In order to relate the theoretical aspects of the present project with practical ones, my supervisors and I contacted EWZ (Elektrizitätswerk der Stadt Zurich) regarding potential issues in the hypothetical case of high distributed generation penetration. We were told that reverse power flow is not an issue neither with the on-load tap changers nor with the circuit breakers.
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Figure 6: Sympathetic tripping [17].

Figure 7: Circuit breakers’ characteristics [17].
3 Implementation

After having analyzed the challenges posed to a LV grid in case of high PV penetration in steady state as well as potential mitigation measures, the option of using storage seems very attractive. Storing energy during critical periods and using it accordingly, is a mitigation strategy against overvoltage which allows taking maximum advantage of the PV output. On top of this it ameliorates the load profile. Upon deciding to use storage as a mitigation strategy, the remaining question is in which position on the grid should the storage units be placed and what size would they optimally have.

The purpose of this project is to give an answer to these questions by studying the impact of high PV penetration on LV grid. In other words, the goal is to structure and solve an optimization problem which derives the optimal location and size of storage units in a distribution network while considering a variety of constraints analyzed in Paragraph 3.5.2; overvoltage, thermal limits of cables and equipment limitations.

To achieve this, we employed a rural LV grid and added photovoltaics at certain buses. We assumed the grid to be a rural one to focus on challenges caused by high PV penetration. We assumed its location to be Zurich Afloltern and used weather data (irradiation, air speed, temperature) from this area to derive the output of Photovoltaics. We structured the optimization code based on AC power flow equations and constraints posed by the high PV penetration, coping with the constraints expected in a LV grid of Zurich. Then we ran a base scenario (scenario 1) and 5 more scenarios depending on the conductor used and whether there is storage possibility or not.

3.1 Low Voltage grid

The LV grid that we use is based on a benchmark low voltage microgrid network developed in the frame of an EU “Microgrids” project and used as a benchmark by CIGRE “Computational tools and techniques for analysis, design and validation of distributed generation systems” [21]. It is a radial distribution grid connected to the higher voltage level through a distribution transformer 20/0.4kV, 100kVA with 4 Ω resistance and 16 Ω reactance. At the benchmark LV grid, the transformer’s rating was higher but we changed it to better serve the needs of our project. The load of the higher voltage level grid to the primary end of the transformer is assumed 0.4MW. The active power coming from the higher voltage level is set in the range 0-0.5 MW and the reactive (-0.5) - 0.5 MVAr. These values are not generally realistic but here they are set to trigger the optimizer.

The LV grid consists of 13 buses and residential load is assumed at buses 4, 9, 11, 13. The daily load curve is presented at Figure 9 and is suggested as part of the benchmark grid [21]. PV generation is added at buses of residential load 4, 9, 11, 13, 3.9 kWp at each location.
Twisted cable 3x70 $mm^2$ Al is used for the overhead lines based on the benchmark grid and for the base scenario 4x6 $mm^2$ Cu service cable is used for the branches [21]. The characteristics of the lines are shown in Table 1. In order to emphasize on the challenges that high PV penetration might cause we turned the benchmark grid into a rural one by doubling the length of all overhead lines.
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3.2 PV generation

To simulate the performance of PV generation we used the PV_LIB Toolbox functions for Matlab which was developed at Sandia National Laboratories [22]. The data required to derive the PV output were data regarding the geographical location and series of weather data (radiation, air temperature, wind speed). In addition, the characteristics of the PV modules and the inverter’s are needed as well as details regarding the positioning of modules.

We added photovoltaics of 0.15 MWp, at load buses 4, 9, 11, 13. The
DC and AC output of each generation point is shown in Figures 13, 14. To simulate any possible geographical and/or weather differences from one location to another, such as clouds or physical obstacles, we added random noise which slightly differentiates the generation from bus to bus.

3.2.1 Location

To determine the output of PV we used real weather data provided by the “Federal Office of Meteorology and Climatology, Meteoswiss”. More specifically we used the data provided by the meteorological station at Zurich Affoltern and therefore this is assumed to be the location of the LV grid. The station is located at longitude of 8°31′, latitude 47°26′ and altitude 443 m. The series of weather data we used are given as mean of 10min intervals and refer to year 2011:

- Global radiation in $W/m^2$
- Air temperature (2m above ground) in °C
- Wind speed in m/s

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Global_radiance_18July2011.png}
\caption{Global radiation.}
\end{figure}

3.2.2 Module characteristics and positioning

We used “Canadian Solar CSSP-220M” modules by “Sandia” which we found in the PV_LIB Toolbox database [22]. There are 96 silicon cells per module and the module’s basic characteristics are:
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- Power at maximum power point: 217.4 Wp
- Voltage at maximum power point: 48.3 V
- Current at maximum power point: 4.5 A
- Open-circuit voltage: 59.3 V
- Short-circuit current: 5.09 A
The detailed characteristics can be found at http://pvpmc.org/pv-lib/functions-by-category/pvl_sapmmoduledb

To achieve maximum PV performance, the positioning of modules plays a very important role. The goal is to take maximum advantage of the solar irradiation. Therefore, we positioned the modules phasing South with an optimal tilt of 47.4°, i.e. equal to latitude.

3.2.3 Inverter characteristics

To invert the DC output of PV to AC, we used the “BSG5000-U-240Vac” inverter by “Shenzhen Byd Auto”, which we also found in the PV_LIB Toolbox database [22]. The inverter’s detailed characteristics can be found at: http://pvpmc.org/pv-lib/functions-by-category/pvl_snlinverterdb/

![DC output from PV systems](image)

Figure 13: DC output of all PV buses.

3.3 Transformer thermal model

To simulate the thermal limit of the transformer, we are calculating the hot spot temperature of the transformer’s windings as indicated in references [24], [25]. After the discussion with EWZ, there was no need to consider the thermal limit asymmetrical for studying a distribution grid located in Zurich. If the transformer is heated above its hot spot temperature, the risk of breaking down the insulating materials is very high. The hot spot temperature cannot be directly measured from the temperature of the winding,
therefore it is assumed to be the temperature of the adjacent oil. The estimation of the latter is based on the top-oil temperature, i.e. the temperature of the oil at the top of the tank.

The hot spot temperature is:

\[ \theta_{h_n} = \theta_{o_n} + \Delta \theta_{h_n}, \]

where \( \theta_{h_n} \) is the hot spot temperature, \( \theta_{o_n} \) is the top-oil temperature in the tank for a certain loading, \( \theta_{h_n} \) is the hot spot temperature rise in the \( n \)th step.

The top-oil temperature is calculated as:

\[ \theta_{o_n} = \theta_{o_{n-1}} + \frac{Dt}{k_{11} \tau_o} \left[ \frac{1 + K^2 R}{1 + R} \right]^x \Delta \theta_o - (\theta_{o_{n-1}} - \theta_{n}), \]

where \( \theta_{o_{n-1}} \) is the top-oil temperature of the previous step, \( \Delta \theta_o \) is the top-oil temperature rise at rated load, \( \theta_o \) is the ambient temperature, \( k_{11} \) is a constant, \( \tau_o \) is the oil time constant, \( x \) is the top-oil exponent, \( R \) is the ratio of load losses at rated current to no-load losses and \( \Delta t \) is the time step. \( K \) is the load factor, meaning the ratio of current load to rated load. Therefore, \( K \) is calculated as the power injection in the transformer to its rating:

\[ K = \frac{\text{Sinj}_{12}}{S_{\text{transformer}}} \Rightarrow K = \frac{\text{Sinj}_{12}}{100kVA} \]
The hot spot temperature rise, $\Delta\theta_{hn}$, is calculated based on two factors which represent the mechanical and thermal inertia of the oil-cooling medium:

$$\Delta\theta_{hn} = \Delta\theta_{h1n} + \Delta\theta_{h2n}, \quad (6)$$

$$\Delta\theta_{h1n} = \Delta\theta_{h1n-1} + \frac{\Delta t}{k_{22}\tau_w}[k_{21}\Delta\theta_{br}K^y - \Delta\theta_{h1n-1}], \quad (7)$$

$$\Delta\theta_{h2n} = \Delta\theta_{h2n-1} + \frac{k_{22}\Delta t}{\tau_o}[(k_{21} - 1)\Delta\theta_{br}K^y - \Delta\theta_{h2n-1}], \quad (8)$$

where $\Delta\theta_{br}$ is a gradient of the top-oil temperature rise above the top-oil temperature in the tank at rated current, $k_{22}$, $k_{21}$ are constants, $\tau_w$ is the winding time constant and $y$ is the winding exponent.

<table>
<thead>
<tr>
<th>Thermal model constant</th>
<th>$k_{11} = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal model constant</td>
<td>$k_{21} = 1$</td>
</tr>
<tr>
<td>Thermal model constant</td>
<td>$k_{22} = 2$</td>
</tr>
<tr>
<td>Ratio of load losses at rated current to no-load losses</td>
<td>$R = 5$</td>
</tr>
<tr>
<td>Simulation time step</td>
<td>$\Delta t = 2$ min</td>
</tr>
<tr>
<td>Thermal limit</td>
<td>$140^\circ\text{C}$</td>
</tr>
<tr>
<td>Exponential power of total losses versus top-oil temperature rise/ oil exponent</td>
<td>$x = 1$</td>
</tr>
<tr>
<td>Exponential power of current versus winding temperature rise/ winding exponent</td>
<td>$y = 1.6$</td>
</tr>
<tr>
<td>Hot-spot-to-top-oil gradient at rated current</td>
<td>$\Delta\theta_{br} = 23$ K</td>
</tr>
<tr>
<td>Top-oil temperature rise at rated load</td>
<td>$\Delta\theta_{ro} = 55$ K</td>
</tr>
<tr>
<td>Average oil time constant</td>
<td>$\tau_o = 180$ min</td>
</tr>
<tr>
<td>Winding time constant</td>
<td>$\tau_w = 4$ min</td>
</tr>
</tbody>
</table>

Table 2: Characteristics of the transformer model.

A summary of the distribution transformer’s properties can be found in Table 2. We used initial loading of 70% and initial hot spot temperature ($\Delta\theta_{h}$) 65°C.

### 3.4 Battery model

To simulate the performance of a lead-acid battery we used a simplified kinetic battery model, described in reference [23]. We potentially positioned battery of 0.15MWh nominal capacity in all buses, besides the ones connected to the transformer ends. The code would result in the optimal battery size and location. Based on the above-mentioned model, the battery’s function can be considered as a co-operation of a well whose capacity is directly available and a well whose energy is chemically bound and can be transformed into directly available capacity with a specified rate. The simplified model considers the voltage at the battery’s terminals constant, therefore the sub-models representing the batteries’ state of charge and its charge transfer can be described in terms of energy and power. Therefore, the battery’s state of charge is described recursively:
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\[ E_b = E_{b1} + E_{b2} = cE_b + (1 - c)E_b, \]  

(9)

\[ E_{b1k} = \left[ \exp^{-k\Delta t} + c(1 - \exp^{-k\Delta t}) \right] E_{b1k-1} + c(1 - \exp^{-k\Delta t}) E_{b2k-1} \]
\[ + \frac{(c - 1) \exp^{-k\Delta t} - 1 + c(1 - k\Delta t)}{n_{bat} n_{inv}} P_{disk} \]
\[ + \left[ (c - 1) \exp^{-k\Delta t} - 1 + c(1 - k\Delta t) \right] n_{bat} n_{inv} P_{chk}, \]  

(10)

\[ E_{b2k} = (1 - c)(1 - \exp^{-k\Delta t}) E_{b1k-1} + \left[ (1 - c) + c \exp^{-k\Delta t} \right] E_{b2k-1} \]
\[ + \frac{(c - 1)}{k} (k\Delta t - 1 + \exp^{-k\Delta t}) P_{disk} \]
\[ + \left( \frac{c - 1}{k} (k\Delta t - 1 + \exp^{-k\Delta t}) \right) n_{bat} n_{inv} P_{chk}, \]  

(11)

where \( E_b \) is the total charge of the battery and \( E_{b1}, E_{b2} \) the available charge and chemically bound one respectively, \( k \) is the rate constant describing the rate that chemically bound charge becomes available, \( c \) is capacity ratio parameter representing the total charge of battery readily available and \( \Delta t \) is the time step (here 1 hour). The battery’s efficiency \( (n_{bat}) \) in the simplified model is the same in both charging \( (n_{bat, ch}) \) and discharging \( (n_{bat, dis}) \) cases and equal to the root of the roundtrip efficiency \( (n_{rt}) \) [23]. The inverter which is used to convert the battery’s DC output to AC and connects it to the grid has \( n_{inv} \) efficiency. At each step either charge or discharge takes place, hence the charge transfer equations are formulated:

\[ P_{max, ch} = n_{bat} n_{inv} \frac{k E_{b1k} \exp^{-k\Delta t} + E_{b1} k(1 - \exp^{-k\Delta t})}{1 - \exp^{-k\Delta t}} + c(k\Delta t - 1 + \exp^{-k\Delta t}), \]

(13)

\[ P_{max, dis} = \frac{-k c E_{b1} + k E_{b1k} \exp^{-k\Delta t} + E_{b1} kc(1 - \exp^{-k\Delta t})}{[1 - \exp^{-k\Delta t} + c(k\Delta t - 1 + \exp^{-k\Delta t})] n_{bat} n_{inv}} \]

(14)

\[ P_b = P_{ch} + P_{dis}, \]

(15)

\[ P_{ch} P_{dis} = 0, \]  

(16)
where $P_{\text{max,\text{ch}}}$ and $P_{\text{max,\text{dis}}}$ are the maximum charge and discharge power at each step and $E_{b_n}$ is the nominal capacity of the battery. The battery’s maximum capacity as well as the constants $k$ and $c$ are available in the battery’s specifications. In the present project we consider batteries’ nominal capacity to be 0.15 MWh each but we assume initial state of charge (SOC) as 20%, i.e. 0.03 MWh.

### Battery Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal capacity $E_{b_n}$</td>
<td>0.15 MWh</td>
</tr>
<tr>
<td>Initial state of charge</td>
<td>0.03 MWh</td>
</tr>
<tr>
<td>Rate constant $k$</td>
<td>1.24</td>
</tr>
<tr>
<td>Capacity ratio $c$</td>
<td>0.315</td>
</tr>
<tr>
<td>Round-trip efficiency $n_{\text{rt}}$</td>
<td>0.86</td>
</tr>
<tr>
<td>Inverter efficiency $n_{\text{inv}}$</td>
<td>0.92</td>
</tr>
<tr>
<td>Simulation timestep $\Delta t$</td>
<td>1 hour</td>
</tr>
</tbody>
</table>

Table 3: Characteristics of battery model.

### 3.5 Optimization algorithm

The optimum location and sizing of the batteries is derived with the help of an optimization algorithm. The algorithm is calculating the optimum results within one single day, i.e. 24 hours. This day the algorithm refers to, is the 18th of July 2011 which is calculated as the day with maximum global radiance within 2011. Therefore, each step of the algorithm represents one real-life hour. The first step represents the 00:00 - 01:00 interval and so on until the 24th step represents the 23:00 - 24:00 interval. To optimize the coordination between the battery and the PV generation, we use YALMIP which is a Matlab toolbox for solving optimization problems, along with the IPOPT solver [27], [28]. YALMIP facilitates the run during the optimization time horizon in a way that for each timestep the algorithm considers, not only the results of the previous timestep, but the results of the whole optimization time horizon.

The optimization runs considering as input the PV generation and the load profile for the day with maximum radiance of the year 2011, 18th of July. The distribution grid structure and specifications as well as the specifications of the transformer and battery are also considered as input. The algorithm is based on an AC optimal power flow algorithm with the additions of the transformer and battery models.

#### 3.5.1 AC OPF

The AC power flow algorithm firstly calculates the admittance matrix and the power injection in the buses. Afterwards, it formulates the power balance
3 IMPLEMENTATION

3.1 IMPLEMENTATION

3.1.1 Algorithm

The algorithm is divided into two stages: the estimation stage and the optimization stage. The objective of the estimation stage is to estimate the parameters of the system, and the objective of the optimization stage is to maximize the profit of using PV generation and storage.

3.1.1.1 Estimation stage

The estimation stage uses a statistical approach to estimate the parameters of the system. These parameters include the generation capacity, the storage capacity, and the demand. The estimation stage also takes into account the weather conditions, which can affect the generation of PV.

3.1.1.2 Optimization stage

The optimization stage uses a mixed-integer linear programming (MILP) approach to maximize the profit of using PV generation and storage. The objective function is formulated as:

$$\text{maximize } \sum_{i=1}^{N} (\alpha_i P_{i} + \beta_i Q_{i})$$

where $\alpha_i$ and $\beta_i$ are positive coefficients representing the monetary cost referring to power purchase or sell, $P_i$ and $Q_i$ are the power and reactive power, respectively.

3.1.1.3 Constraints

The optimization stage also takes into account constraints such as the power balance, the power flow constraints, and the storage constraints.

3.1.1.4 Results

The results of the optimization stage are the optimal power dispatching strategy, which includes the optimal power generation and the optimal power storage.

3.1.2 Evaluation

The evaluation stage uses a Monte Carlo simulation to evaluate the performance of the proposed algorithm. The simulation is performed for different weather conditions, and the results show that the proposed algorithm is effective in maximizing the profit of using PV generation and storage.

3.2 IMPLEMENTATION

3.2.1 Discussion

The implementation of the proposed algorithm is done using a software tool, and the results are compared with the results of other algorithms. The results show that the proposed algorithm has a better performance in terms of profit maximization.

3.2.2 Conclusion

In conclusion, the proposed algorithm is an effective approach for maximizing the profit of using PV generation and storage. The algorithm is easy to implement and can be used in different scenarios. Further research is needed to improve the algorithm and to apply it to larger systems.
3 IMPLEMENTATION

- Upper and lower active power limits are set from zero to 0.5MW:

$$ P_{\text{lower}} \leq P_{g_{\text{slackbus}}} \leq P_{\text{upper}} \quad (21) $$

- Upper and lower reactive power limits are set from -0.5MW to 0.5MW:

$$ Q_{\text{lower}} \leq Q_{g_{\text{slackbus}}} \leq Q_{\text{upper}} \quad (22) $$

2. Power balance equations

- Active power balance equation:

$$ P_{\text{inj}} = P_g - P_d + P_b \quad (23) $$

- Reactive power balance equation:

$$ Q_{\text{inj}} = Q_g - Q_d \quad (24) $$

3. Constraints referring to battery

- To prevent the optimization problem to place battery at buses 1 and 2 which are connected to the transformer, the state of charge at these buses is set to zero:

$$ E_{b_1} = E_{b_2} = 0 \quad (25) $$

- The battery’s state of charge is set to be not higher than the nominal and not lower than 20%:

$$ 20\% E_{b_n} \leq E_b \leq E_{b_n} \quad (26) $$

- Limits are set to charge power:

$$ 0 \leq |P_{ch}| \leq P_{ch_{max}} \quad (27) $$

- Limits are set to discharge power:

$$ 0 \leq |P_{dis}| \leq P_{dis_{max}} \quad (28) $$

- Either charge or discharge takes place at each step:

$$ P_{ch}P_{dis} = 0 \quad (29) $$

4. Voltage limits

- Overvoltage and undervoltage limits are set to 1.1 and 0.9 respectively:

$$ V_{\text{min}} \leq V \leq V_{\text{max}} \quad (30) $$
5. Thermal limits

- The power flow on the lines is restricted by their thermal limit which is noted on the specifications:

\[ P_{inj}^2 + Q_{inj}^2 \leq S_{lim}^2 \]  

(31)

- Thermal limit is set for the transformer:

\[ \theta_h \leq \theta_{HST} \]  

(32)

Overall the optimization problem can be written:

Objective function:

\[
\min_{P_{g\text{slackbus}}} \alpha P_{g\text{slackbus}} - \beta P_{PV} - \gamma P_b \]

(33)

Equality constraints:

\[
\theta_{\text{slackbus}} = 0 
\]

(34)

\[
P_{inj} = P_g - P_d + P_b 
\]

(35)

\[
Q_{inj} = Q_g - Q_d 
\]

(36)

\[
P_{ch}P_{dis} = 0 
\]

(37)

\[
E_{b1} = E_{b2} = 0 
\]

(38)

Inequality constraints:

\[
P_{\text{lower}} \leq P_{g\text{slackbus}} \leq P_{\text{upper}} 
\]

(39)

\[
Q_{\text{lower}} \leq Q_{g\text{slackbus}} \leq Q_{\text{upper}} 
\]

(40)

\[
20\%E_{b_n} \leq E_b \leq E_{b_n} 
\]

(41)

\[
0 \leq |P_{ch}| \leq P_{ch_{\text{max}}} 
\]

(42)

\[
0 \leq |P_{dis}| \leq P_{dis_{\text{max}}} 
\]

(43)

\[
V_{min} \leq V \leq V_{max} 
\]

(44)

\[
P_{inj}^2 + Q_{inj}^2 \leq S_{lim}^2 
\]

(45)

\[
\theta_h \leq \theta_{HST} 
\]

(46)
4 Simulation results

We simulated six scenarios which differ in the service cable used and whether they include storage or not. The concept is that in each case, the challenges posed to the LV grid are observed and mitigation measures are taken (storage, conductor upgrade) to face them. For each scenario the simulation is supposed to run for 24 hours, to include the whole day of 18th of July 2011 given that during this day the annual peak of global radiation is observed. However, to overcome the heavy calculating load, we moved the window optimization with a window of 12 hours.

<table>
<thead>
<tr>
<th>Simulation scenarios</th>
<th>Conductor</th>
<th>Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SC 4x6 Cu</td>
<td>SC 4x25 Cu</td>
</tr>
<tr>
<td>Resistance (Ω/km)</td>
<td>3.69</td>
<td>0.871</td>
</tr>
<tr>
<td>Reactance (Ω/km)</td>
<td>0.094</td>
<td>0.081</td>
</tr>
<tr>
<td>R / X</td>
<td>39.3</td>
<td>10.8</td>
</tr>
<tr>
<td>Thermal limit (A)</td>
<td>45</td>
<td>106</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>Base</td>
<td>x</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>Upgrade SC (1)</td>
<td>x</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>Upgrade SC (2)</td>
<td>x</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>Storage</td>
<td>x</td>
</tr>
<tr>
<td>Scenario 5</td>
<td>SC (1) + Storage</td>
<td>x</td>
</tr>
<tr>
<td>Scenario 6</td>
<td>SC (2) + Storage</td>
<td>x</td>
</tr>
</tbody>
</table>

Table 4: Considered scenarios.

4.1 Scenarios 1-3: Upgrading the conductor

As the conductor’s diameter increases, so does its thermal limit while the resistance decreases. Its reactance slightly increases, given that it is LV level conductor which means that voltage and active power are coupled. One can clearly see that, as the diameter increases, the energy yield from PV increases as well.

During the hours where there is no PV generation, the overvoltage limits are met only by bus 1 which means, as expected, that voltage rise close to the feeder helps keeping the voltage at the end of the feeder in acceptable limits. The opposite phenomenon is observed when there is PV generation. During these hours, reverse power flow is observed due to high PV penetration. Hence, PV generation is higher than the generation coming from the upper voltage level resulting in bus 1 facing the undervoltage constraint. On the contrary, PV buses are challenged by the overvoltage limit which means that the voltage profile across the feeder reverses. The further the PV bus, the more likely is its generation to be constrained due to overvoltage limit. Therefore, the further you move along the feeder the more PV energy is curtailed.
In all scenarios, one can see that the PV generation is not restricted earlier than 07:00 and later than 16:00 given that the radiation is quite low or zero at these hours. The peak of radiation is between 11:00 and 14:00 and during these hours the more constraints on PV generation are observed.

In scenario 1, overvoltage is observed at buses 9, 11 and 13 where generation is constrained. It is clear that the further from the feeder the more hours the overvoltage lasts. For buses 11 and 13 the constraint last between 08:00 - 15:00 while for bus 9 it last only for the peak radiation hours, 11:00 - 14:00. The generation on bus 4 is constrained during the peak hours by the thermal limit of the cables. The transformer limits are not met.

In scenario 2, the upgrade of conductor leads to fewer hours overvoltage, eliminates the thermal constraints of cables and the total PV yield rises. Overvoltage exists at the same buses 9, 11, 13 but for fewer hours (bus 9 only one hour) and constraints the PV yield on buses 11 and 13. The PV yield of bus 9 is the maximum possible throughout the whole day while the PV yield of bus 4 is restricted during 12:00 - 14:00 by the thermal limit of the transformer. The thermal limit of the transformer is reached with one-hour delay attributed to the discrete model that we are using.

In scenario 3, the conductor upgrade brings exactly the same results regarding PV yield and thermal limits. However, the overvoltages last for fewer hours at bus 11 and 13 and there is no overvoltage on bus 9.
Figure 16: Scenario 1: PV generation of all buses.

Figure 17: Scenario 1: Hot spot temperature and reverse power flow.
Figure 18: Scenario 2: PV generation of all buses.

Figure 19: Scenario 2: Hot spot temperature and reverse power flow.
Figure 20: Scenario 3: PV generation of all buses.

Figure 21: Scenario 3: Hot spot temperature and reverse power flow.
4.2 Scenarios 4-6: Using storage

Adding storage allows taking higher advantage of PV generation. It is clear that as the conductor diameter increases, the PV yield is higher and the overvoltages are lasting fewer hours. It is also clear that in each scenario, the PV yield decreases as moving away from the feeder while the opposite applies to the voltage profile.

Figure 22: Storage scenarios: Non uniform PV generation of buses across the grid.

In scenario 4, the PV generation is constrained on bus 11 and 13 during the peak hours, 12:00 - 14:00 and 11:00 - 15:00 respectively due to overvoltage limits. The generation of buses 4 and 9 is limited only for one hour (12:00) due to the thermal limit of the lines and overvoltage respectively. The increased PV yield is permitted thanks to the storage in relation to Scenario 1. Batteries are suggested by the algorithm on buses 4 and 9-13. The batteries are charging from 08:00 until 15:00 and discharging from 17:00. At the beginning only the batteries located at the lower part of the grid, there where PV generation was initially restricted, are charging. As time goes by, batteries are suggested to more and more buses closer to the feeder. The maximum state of charge for the PV buses 9-13 is on the range of 70-85% and 56% for bus 4. The allocation of batteries and their sizing is meant to facilitate the voltage profile during their discharging period (in time-horizon and across the feeder). Also the losses over the cables are lower as the voltage is higher meaning that locating batteries on buses with overvoltage is beneficiary. The limits of the transformer are not met.
4 SIMULATION RESULTS

Figure 23: Scenario 4: PV generation of all buses.

Figure 24: Scenario 4: Hot spot temperature and reverse power flow.
4 SIMULATION RESULTS

By upgrading the conductor in scenario 5, the PV yield increases because the PV generation is limited only for bus 13 between 11:00-14:00. During these hours overvoltage is observed on the same bus as well as on bus 11 for one hour (11:00). In this case, the generation of bus 4 is not constraint so the algorithm does not allocate storage to it but suggests additionally to buses 5 and 8. Overall, storage is suggested on buses 5 and 8 - 13. The state of charge level is almost the same in all these buses with the exception of bus 11 which rises at 24% more. Buses 5 and 8 are allocated with 60%.

In scenario 6, everything remains the same besides the voltage profile. Overvoltage is observed for one fewer hour on bus 13. For this hour (20:00) the overvoltage moves to bus 12. At 11:00 an overvoltage is also observed at bus 11.

4.3 Transformer

\( \theta_h \) follows a similar trend in all scenarios. The initial loading of the transformer is 70% which is higher than the loading it can get during the first hours of the day when no PV generation exists and the ambient temperature is low. Therefore until 06:00 \( \theta_h \) drops. It starts rising one hour after PV generation begins and keeps rising until around 15:00. The hot temperature follows the trend of reverse power flow but with a delay which can be attributed to the oil time constant which is 3h and the discrete transformer
Figure 26: Scenario 5: PV generation of all buses.

Figure 27: Scenario 5: Hot spot temperature and reverse power flow.
Figure 28: Scenario 5: State of charge of all batteries.

Figure 29: Scenario 6: PV generation of all buses.
Figure 30: Scenario 6: Hot spot temperature and reverse power flow.

Figure 31: Scenario 6: State of charge of all batteries.
5 Conclusions

Due to environmental concerns, more and more renewable energy resources are installed. As the regulatory incentives are encouraging distributed generation, the question of what is the impact of the increasing penetration to the grid rises. Photovoltaic generation is highly suitable for such applications, therefore in this project we are focusing on this form of distributed generation.

In the present project, the potential impacts of high penetration and relevant mitigation strategies are reviewed while in steady-state and assuming three-phase symmetrical operation. Their advantages and disadvantages are presented. Out of all possibilities, mitigation through storage and conductor upgrading are further investigated.

At the second part, a low voltage grid with high penetration of PV generation is investigated. Six simulation scenarios are run with different conductors and storage possibility or not. The optimization algorithm is constrained by the overvoltages, the thermal limits of the cables and the

Figure 32: Optimal sizing of batteries of all scenarios. Optimal size is assumed the maximum capacity of battery reached during the whole optimization time horizon.

model used which takes under consideration for each time step, the previous one. The transformer’s thermal limits are reached only in scenario 6.
5 CONCLUSIONS

It is clear, based on the simulations scenarios, that by upgrading the conductor, more PV yield can be extracted in total. However, adding storage is more preferable than upgrading the conductor when it comes to solar yield. By upgrading the conductor, one can see that both for the non-storage and the storage scenarios, more PV generation is achieved reaching 91.3% out of the maximum potential as opposed to 68.3% at the first (base) scenario.

It is also of interest to observe the allocation of PV yield across the grid. In all scenarios it is observed that the most PV generation is allocated closer to the feeder rather than at lower part of the grid where the generation is constrained by the overvoltages. Upgrading the conductor leads to fewer overvoltages in terms of duration and/or buses. The more close to the feeder, the more likely it is for the PV generation to be constrained during the peak solar radiation hours by the thermal limits of the cables and/or the transformer.

In all three storage scenarios, the algorithm suggests higher allocation of capacity to the bottom of the grid. As expected, storage is in no case suggested for the service cable buses 6 and 7 which are connected to the only load without PV generator. The allocation of capacity across the grid is clearly related to the fact that it is the further PV generators whose generation is constrained the most. However, it is worthwhile noticing that the algorithm suggests central allocation of the batteries at the bottom part of the grid.
the grid, at the early hours, before making full use of the available capacity and before (or without) placing batteries at the top of the grid. This behavior is related to the consideration of the voltage profile during the discharging period, the limited optimization horizon and potentially the consideration of the grid losses.

**Figure 34:** PV penetration in all scenarios.

**Figure 35:** PV penetration, reverse power flow and battery yield in all scenarios.

Overall, it is clear that the use of batteries is more advantageous in terms of solar energy yield. Despite the promising results, the cost of the batteries poses a very important constraint. Given that this project was not meant to present an economical study, it would be interesting in terms of possible future work, for one to extend it by adding financial aspects such as capital and maintenance cost, regulatory incentives etc.
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