Defining Reasonable PV Penetration Goals: Assessment of the Effect of High PV Capacity Levels on Low Voltage Networks

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Abstract:

We analyzed 33 million residential Smart Meter 15-minute period records for electricity consumption and photovoltaic electricity generation from low voltage (LV) feeders with various photovoltaic (PV) penetration levels. In turn we modeled a range of higher PV penetration scenarios and assessed the effect on the LV network. On the one hand, we showed how on-load tap changers (OLTCs), reactive power controlled inverters, or energy storage units can be introduced to handle the situation. On the other hand, we found that active power losses, while decreasing in modest PV penetration scenarios, increased markedly beyond the PV-free scenario at PV penetration levels that do not yet experience overvoltage problems and are in full compliance with stipulated grid code conditions. We thus argue that active power loss might be a significant aspect to be considered when PV penetration targets are formulated.

Keywords: renewable energy, photovoltaic (PV), grid integration, Malta, DIgSILENT

1 Introduction

The benefits of high renewable energy shares in terms of climate change mitigation and energy security are well documented and reflected in national energy plans around the world. Malta, a Mediterranean island nation, after entering the European Union devised a National Renewable Energy Action Plan (NREAP) to achieve a 10 percent renewable energy consumption share (up from zero percent in 2005) by 2020 (Table 1). However, after it was demonstrated that planned offshore wind energy was far more expensive compared to PV electricity in Maltese settings, and available rooftop space would be sufficient to cater for PV installations to substitute for planned offshore wind capacity, the NREAP has been re-written, though yet pending official publication (Weissenbacher, 2012, 2013). Based on grant schemes as well as generous feed-in tariffs (15.5 cents/kWh for 20 years in 2015 for systems below 40 kWp), Malta has indeed experienced radical growth in terms of installed PV capacity. By the end of 2010 745 kWp worth of PV capacity had been connected to the grid, while it was 53,538 kWp by the end of 2014 (with another 25,887kWp registered, but not yet connected). And although the share of large, roof-based PV installations in the total national PV capacity is rapidly growing (ground-based ones are not allowed in Malta), residential PV systems by the end of 2014 still accounted for over 63 percent of connected capacity and over 95 percent of connected PV installations. Notably, large installations require a grid integration study, with associated integration costs such as transformer upgrades being borne by the PV investor. Photovoltaic installations up to 16 Amps on any of the electrical A.C. phases (230/400V) on the other hand do not require an authorization or license in Malta. In such context, residential systems are more of an issue with regard to the management of a continuing expansion of PV capacity without jeopardizing grid stability and compliance with the network code. In this study we investigated the effect of rising PV capacity on low voltage networks and attempted to devise criteria that would allow the grid operator to decide how much residential PV capacity may be added to a LV feeder under a given demand scenario and PV output profile.

Renewable Energy Option	%	GWh/year
Offshore Wind	3.48	216
Biofuels	2.40	149
Energy from waste - Electricity	2.18	135
Solar PV	0.69	43
Onshore Wind	0.61	38
Solar Water Heating	0.52	32
Energy from Waste – Heat	0.32	20
TOTAL:	**10.20**	**634**

Table 1: The contribution of different renewable energy options to 2020 gross final energy consumption according to Malta's National Renewable Energy Action Plan submitted in June 2010 and resubmitted in May 2011 (MRRA, 2010, 2011). A new plan that eliminates the wind contribution in favor of solar PV capacity will eventually be published.

2 Methodology

We reviewed and processed 15-minute electricity consumption and PV electricity generation SMART meter data for consumers and producers on the central Mediterranean island of Gozo, with 67 km^2 and some 37,000 inhabitants the second largest island within Malta's territory. We focused on meters ultimately connected to four substations known to require seasonal substation transformer tapping adjustments in order to avoid overvoltage issues, and analyzed the data for the period 01/01/2013 to 30/06/2014. The total number of consumer meters associated with these four substations was 1,600, while the total number of PV meters was 157. Since many of the PV systems in these locations had been recently installed, we also used the data from 200 PV meters that were randomly selected from locations all over Gozo to create a generic PV output profile. Data from master meters installed in the substations was available as well.

Based on these data sets a Structured Query Language (SQL) model was developed as a first step. Data sets were subjected to filtering routines to exclude data or meters that showed unusual readings (Significant NULL records; PV electricity output during night-time; unrealistic daytime or significant zero PV output). Notably, the meters installed in households in Malta do not register reactive power. The 15-min data was converted into hourly periods for each type of consumer meter and then combined with the generic PV output profile model and compared to the substation master meter data sets to assess the model accuracy.

More precise models utilizing Geographic Information System (GIS) data and physical network information (transformer and cable characteristics such as impedance, distance, etc.) were designed for two of the four substations' networks using power systems software

DIgSILENT (short for “Digital Simulation of Electrical Networks") PowerFactory. For one of these substations an additional model was set up using exclusively original meter data. The entire Gozitan 11kV network with all substations (loads based on connected type and number of consumers) was included. These models were used for load flow studies. We explored different photovoltaic penetration scenarios to reveal their effects on the LV network and to test compliance with the required standard, European Standard EN 50160. We tested what kind of infrastructure upgrades would be necessary under the high PV penetration scenarios and attempted to derive general criteria for the maximum allowable PV penetration (in absence of any mitigation measures) for the case studies’ given electricity consumption and PV generation profiles.

3 Theoretical Framework

In the following a brief overview on PV penetration metrics and aspects of the European Standard EN 50160 on "voltage characteristics of electricity supplied by public distribution systems" is provided.

3.1 PV penetration metrics

Various renewable energy penetration metrics have been forwarded. (See, for instance, Kroposki, 2010, or Lilienthal, 2007). Penetration based on peak load is the ratio of the renewable power systems’ aggregate nameplate capacity to the peak load. Notably, this metric may not always be meaningful, for instance, when PV capacity is compared to a peak load that happens to occur in the evening. Penetration based on system capacity is the ratio of the renewable power systems’ aggregate nameplate capacity to the system’s total (non-renewable) installed capacity. This ratio is smaller in value compared to the metric based on peak load because utilities maintain reserve capacity in excess of the required peak load generation capacity. Instantaneous renewable penetration measures the ratio of renewable power to the system load at any given moment. It may vary continuously due to the intermittent nature of renewables and the variability of the load. The maximum instantaneous renewable penetration load may reflect the highest “stress” situation and thus highest numeric value of all penetration metrics in case a large renewable energy capacity provides high output during favorable environmental conditions while energy demand is low. Last not least, the penetration level may also be based on energy, by stating the ratio of the renewable system’s annual energy output to the total energy supplied. This metric typically results in the smallest penetration percentage out of all the metrics mentioned. To be sure, penetration may be expressed for various segments, from national or even continental levels down to the penetration on a single feeder, i.e. the cabling routing from a substation to final consumers.

3.2 Requirements according to European Standard EN 50160

European Standard EN 50160:2010 “*Voltage Characteristics of Public Distribution Systems”* defines the main voltage parameters and their permissible deviation ranges at the customer’s point of common coupling (PCC) in public low voltage (LV) and medium voltage (MV) distribution systems under normal operating conditions. Within this study overvoltage and voltage unbalance have been considered, as these parameters are taken into account by

DIgSILENT load flow steady-state analyses. Other parameters, such as Total Harmonic Distortion (THD), flicker, and voltage dip and swell are also regulated by EN 50160, but would only reflect in transient analyses.

Supply voltage variations may not exceed ±10% of the nominal voltage V_n according to EN 50160. For four-wire three phase systems V_n equals 400V between phases, while for single phase systems V_n equals 230V between phase and neutral. The standard specifically states that "… *during each period of one week 95% of the 10min mean Root Mean Square (RMS) values of the supply voltage shall be within the range of V_n ±10% and all 10 min mean RMS values shall be within the range of V_n +10% / -15%"*. With regard to voltage unbalance, which is a condition where the RMS value of the phase voltages or the phase angles between consecutive phases in a three-phase system are not equal, EN 50160 maintains that "*… under normal operating conditions, during each period of one week, 95% of the 10min mean RMS values of the negative phase sequence component (fundamental) of the supply voltage shall be within the range 0% to 2% of the positive phase sequence component (fundamental)".*

To be sure, the voltage along the length of a feeder is not uniform. Due to transmission lines' impedances the voltage drop increases the further away from the transformer (substation) a load is situated. With higher loads, a higher current is drawn, which results in a larger voltage drop. The voltage at furthest loads still needs to be at least 90% of the nominal voltage under maximum load conditions, while the voltage should never be above 110% of the nominal voltage anywhere along the feeder even under low load conditions. To handle the variations, transformers may be equipped with automatic on-load tap changers (OLTC) or with less expensive off-load manual tap changers.

PV systems in residential areas may cause local overvoltage issues, especially when high midday output meets low demand. PV systems also contribute to voltage unbalance, similar to the uneven distribution of single-phase loads on a three-phase system. Residential PV systems generate power on only one phase and, unlike the phase-assignment for loads, tend to be integrated to the grid without control to which phase they are connected. What is more, PV inverters operate at unity power without any reactive control.

4 Malta's Electricity Distribution Network

Based on standard EN 50160 Enemalta, Malta's designated distribution system operator, has formulated a network code. Directive 2009/72/EC grants Malta a derogation from the requirement to have separated transmission and distribution system operators, and the entire electricity network is formally considered one distribution system with no transmission system. The tolerated steady-state operating voltage ranges are shown in Table 2, and it can be seen that Malta's electrical distribution network operates on four voltage levels (Enemalta, 2014). The power stations are located at the southern tip of the main island (Malta), at Delimara. The annual electricity demand is around 2.1 TWh, and the nominal local electricity generation capacity currently totals 490 MW, all based on heavy fuel oil, while the record peak system demand was registered at 438 MW in July 2015, only slightly up from the previous record of 434 MW in July 2007.

Network Level	Nominal Voltage (3-φ)	Steady-state	Voltage Range
LV	400V	± 10%	360V – 440V (3-φ)
			208V – 254V (1-φ)
MV	11kV	± 5%	10.45kV – 11.55kV (3-φ)
MV	33kV	+ 5% , -10%	29.70kV – 34.65kV (3-φ)
HV	132kV	± 6%	124.08kV – 139.92kV (3-φ)

Table 2: Malta's voltage levels with ranges (Enemalta, 2013).

What is more, scheduled imports of electricity through a new 200 MW (220 kV) HVAC interconnector to Sicily started in April 2015, and an independent power producer is currently constructing a 215 MW CCGT plant, also located at Delimara, to be supplied through a new LNG infrastructure that includes a floating storage unit (FSU) and regasification facility. The 132kV HV circuit, laid in tunnels or buried underground, leads from the Delimara power plants to distribution centers at central locations (Marsa, Mosta, Kappara), where the voltage is stepped down from 132kV to 33kV or 11kV, and continues to the more northern Maghtab Terminal Station, where the interconnector arrives (220kV to 132kV). The 33kV circuit connects to 18 strategically located distribution centres that step down the voltage from 33kV to 11kV. (Most of the 33kV and 11kV circuits are underground, while some are overhead lines.) The 11kV circuit connects the circa 1,200 sub-stations (140 of which are located in Gozo) that step down the voltage from 11kV to 400V/230V for final consumers, though a few large consumers are connected directly to the 11kV network. Gozo, where no power stations are located, is supplied via three 33kV submarine cables connected to a single 33kV Distribution Centre (Qala Gozo).

The mentioned 18 distribution centres (33kV/11kV) are equipped with OLTC power transformers and a supervisory control and data acquisition (SCADA) system. This allows for automated and remotely monitored operation, while the ca. 1,200 11kV/400V transformers make use of manual tap changers consisting of five tap settings on their primary windings. Tap three is the default position (nominal secondary voltage), while taps one and two step the secondary voltage up 2.5% each (maximum of +5%), and taps 4 and 5 step the secondary voltage down the same way (minimum of -5%). Typically, the tap changer positions of these transformers are set once and never changed again, except when the networks are extended or modified.

5 Results and Conclusions

The SQL model achieved a close correlation between the sum of individual meters and the associated substation master meters. This model showed instances of reverse power flow during the period April to June around 11:00 to 15:00 at the current PV penetration level for all four modeled substations. The DIgSILENT models for two substations were initially built with monthly average hour records (consumer and PV output profiles from the SQL model), but subsequently for one of the substations actual hourly SMART meter consumption data was used: the results remained largely the same. In the ensuing load flow analysis it was ensured that the maximum cable current loadings were never exceeded. In the Base Case/“No PV” scenario as well as the Present Situation Scenario (meters @ 31/12/2014) all feeders operated within the ±10% voltage range. In a “Plus 1kWp PV” scenario (a 1kWp PV system was added to those households that had no PV systems installed), existing substation transformers coupled with phase balancing were still able to bring all node voltages within EN50160 limits. In a “Plus 2kWp PV” scenario, transformers had to be replaced to allow for greater tapping flexibility. For one of the substations an OLTC 11kV:400V 9-step tap change transformer was required since two tap changes had to happen during the same day to keep all feeders within limits. For the other substation it was possible to handle the situation by switching the inverters to reactive power Q(V) control, or else to invest into a new manual tap changing transformer (from 11kV:433V to 11kV:400V). (Solutions with energy storage are not included in this presentation.) In short, we concluded what is generally reflected in the literature: technical barriers to high PV penetration can be overcome, but at the cost of infrastructure upgrades.

In turn we decided to focus on active power losses, as it was noticed that losses on the feeders increase markedly in PV penetration situations that are still in full compliance with the grid code. Also, in the Maltese distribution network a total of 4.1% of sent out electricity is registered as technical losses, over half of which is associated with the LV network. Table 3 shows the model results for one feeder based on actual consumption data (15-minute records combined into one hour entries), with associated PV penetration metrics and active power losses (transformer and feeder). We are introducing a new, and in our opinion a more meaningful PV penetration metric based on daytime peak load, but the traditional metric based on overall peak load is also shown. Similarly, we are showing the traditional penetration based on energy next to a newly introduced metric based on self-consumed energy, i.e. the ratio of the renewable energy that is produced and actually consumed on this feeder to the total energy consumed on this feeder. This reflects how much PV electricity needs to be exported in scenarios of higher PV capacity, because generation and consumption profiles do not match. The “plus 1kW” scenario for this feeder required a one-time, permanent tap change at the transformer, but no infrastructure upgrade. The “plus 2kW” scenario required a transformer change, from 11kV:433V to 11kV:400V, but still of the non-OLTC type, in addition to phase balancing. Notably, the initial losses, 1.0% in the “no PV” scenario, were quite low at this particular feeder. (Another feeder on the same substation showed active power losses of 2.9% in the “no PV” scenario.) Losses always decrease in scenarios of modest PV penetration, as PV electricity is consumed directly at the feeder, but increase when higher penetration with more backflow through the substation is reached. To some extent, the situation can be improved by adjusting the distribution of PV systems’ panel tilt and orientation angles to reach a better match between PV output and consumption profiles (Weissenbacher and Attard, 2014). However, in this model we used the current real-world PV output profile for all additionally introduced PV capacity. At the feeder shown in Table 3, losses decrease from the “no PV” to the “current” scenario, but have risen beyond the “no PV” scenario in the “+1kW” situation. It can thus be optimized for minimal losses to recommend a PV penetration level. On the other hand, high renewable energy shares are also desirable, and it may be argued, for instance, that active power losses of the same order as in the “no PV” scenario might be acceptable, especially when such scenarios to do not require any infrastructure investments. The presented feeder shows instances of instantaneous penetration ratios of above 500% in every month, i.e. throughout the year (up to 737%), and yet no OLTC equipment is necessary to maintain required grid conditions on the LV network.

Scenario	No PV	Current	+1kW	+2kW
Substation 11kV/433V transformer rating (kVA)	500	500	500	500
Energy consumption, metered (kWh/year)	106,219	106,219	106,219	106,219
Peak load, evening (kW)[1]	41	41	41	41
Peak load, daytime: 11:00-15:00 (kW)[2]	25	25	25	25
Total PV capacity (kWp)	-	26.72	44.72	62.72
Total PV output (kWh/year)[3]	-	41,812	70,771	101,286
Penetration based on (evening) peak load[1]	-	65%	108%	152%
Penetration based on (daytime) peak load[2]	-	107%	179%	251%
Maximum Instantaneous Penetration[4]	-	304%	518%	737%
Penetration based on System Capacity[5]	-	5.3%	8.9%	12.5%
Penetration based on Energy	-	39%	67%	95%
Penetration based on self-consumed Energy	-	31%	36%	40%
Losses, absolute (kWh/year)	1063	982	1258	2040
Losses, relative (percent)	1.00%	0.92%	1.18%	1.92%

1: December evening peak; 2: Daytime peak load occurs in November on this feeder, though May is more typical; 3: PV output per unit of installed capacity varied because actual PV output was used for those installations that had SMART meter data available; 4: Occurs in June in all scenarios; 5: Substation transformer rating used as “system” capacity for this feeder.

Table 3: Scenarios for one single feeder (Srug, F1), with associated PV penetrations metrics and active power losses (transformer and feeder).

On the other hand, losses increase sharply at high instantaneous PV penetration ratios (Figure 1). When we correlated active power losses at the substation/feeder level with increasing instantaneous PV penetration, losses expectedly decreased at first, with a minimum being reached at the 100% level that is defined as feeder PV output exactly matching the feeder load. Such instances might be regarded the ideal PV penetration level, but losses do not increase beyond the “no PV” scenario until a 200% instantaneous PV penetration is reached. We interpret that the first 100% of PV electricity are consumed locally on the feeder, while the second 100% are experiencing roughly the same cable and transformer losses (backflow through the 11kV/400V substation) that are observed when the load is solely met through grid electricity arriving through the substation in the “no PV” scenario. Despite the continuing compliance with the grid code, instantaneous PV penetration levels above 200% are not desirable to avoid undue losses situations. Depending on the particular substation or feeder, instantaneous PV penetration ratios of 350%, for instance, have been found to be associated with over five times the losses seen at the 200% penetration level (and in the “no PV” situation). We thus argue that actual PV penetration recommendations as well as models investigating the grid integration of large renewable energy shares should take the aspect of active power losses into account. Yet we find losses on an annual basis acceptable compared to the gain in renewable energy share in scenarios where single substations (with all their feeders) are carrying very high PV capacities. For the feeder shown in Table 3, for instance, an increase in penetration based on energy from 39% to 95% is associated with more than a doubling of the losses in kWh terms. However, relative to the total consumption on the feeder, losses increase by no more than 1% (from 0.92% to 1.92%).

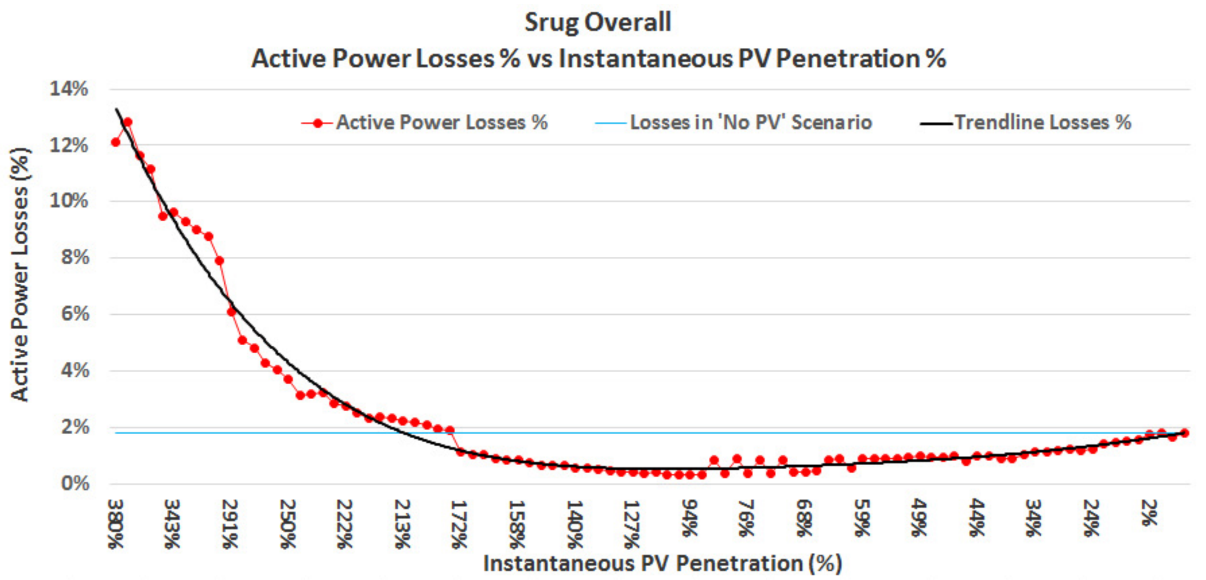

Figure 1: Active power losses decrease below the “No PV” scenario at low instantaneous PV penetration levels, but increase markedly when instantaneous PV penetration ratios above 200% are reached. The losses considered here include losses in the 11kV/400V transformer station and along the feeder all the way to consumer meters.

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