EFFECTS OF ASYMMETRICALLY CONNECTED PV AND BATTERY SYSTEMS ON THE NODE VOLTAGES AND PEN-CONDUCTOR CURRENTS IN LOW VOLTAGE GRIDS

Marco WAGLER
Professorship for Power Transmission Systems
Technical University of Munich (TUM) - Germany
marco.wagler@tum.de

Rolf WITZMANN
Professorship for Power Transmission Systems
Technical University of Munich (TUM) – Germany
rolf.witzmann@tum.de

ABSTRACT

In this work an exemplarily grid is investigated and analysed concerning the effects of unsymmetrical behaviour of PV and battery systems. The voltage values as well as line and neutral conductor currents were evaluated for different unbalance limits per phase. Furthermore, this scheme was applied to a variety of PV distributions within the grid in order to produce generalised conclusions. The overall goal of this work is to investigate whether the prevailing unbalance limit of 4,6kVA in Germany is still acceptable or if it has to be (and to which amount) adapted.

INTRODUCTION

Approximately 70% of all installed PV systems in Germany are connected to the low voltage grid and simultaneously exhibit a nominal power below 13.8kVA [1]. According to [2], a maximum unbalance of 4,6kVA per phase is permitted leading to the circumstance that only devices with a nominal power higher than 13.8kVA must exchange power with the grid in a symmetrical way. Combining these two statements, this in turn means that about 70% of all PV systems in Germany are allowed to feed in unsymmetrically. Detailed investigations in [3] show that in some example low voltage grids the majority of all connected PV systems lower than 5kW are connected exclusively at L1. Furthermore most of the 5-10kW PV systems have a L12 connection. For areas with a high penetration of PV, this can lead to distinctly higher voltages within the stressed phases in comparison to a symmetrical connection. In addition to this, unsymmetrically exchanged power leads to a current flow over the neutral conductor. It must be ensured that all node voltages do not exceed the allowed limits and that undesired current flows do not surpass the thermal capacity of the neutral and line conductors.

Recent publications [4] considering this topic show that with conventional symmetric planning methods it is not possible to satisfy the mandatory voltage band. Due to the expected addition of storage systems following the expiration of the mandatory PV-tariffs, the risk of a further worsening of the grid state especially regarding the neutral conductor current flow and the node voltages exists. This paper investigates the effect of an unsymmetrical connection of PV and storage systems on the node voltages and neutral conductor currents. Different limits for the allowed unsymmetrical power per phase are analyzed in order to deliver a foundation for new planning methods regarding unbalance.

INVESTIGATED AREA

All investigations were performed for a real Bavarian low voltage grid which exhibits both suburban and rural features and has 533 nodes. It is connected via two 630kVA transformers (T1 and T2) to the medium voltage grid and features a meshed topology. Both transformers have a DYn5 interconnection. All buildings and facilities were integrated in a TN-C-S earthing system, which is common in Germany. Regarding the load, the area is dominated by households and occasional business enterprises. A considerable high amount of night storage heating systems (nearly every tenth household is equipped with such a heating system) should be mentioned. Furthermore a total amount of 960kW PV is installed within the investigated area. Figure 1 gives an overview of the grid topology.

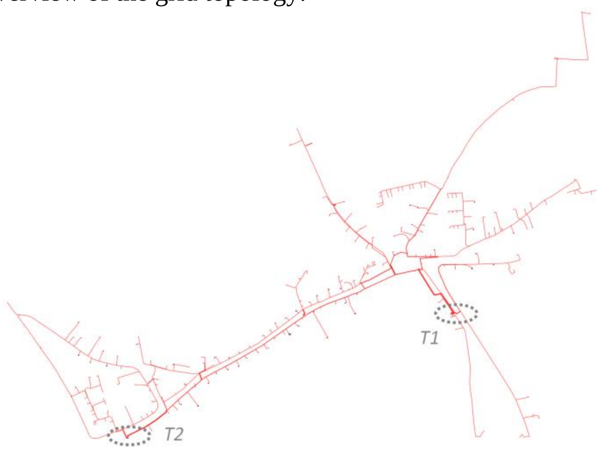

Figure 1: Topology of the investigated low voltage grid

APPROACH AND DATA BASIS

The goal of this work is to analyse the impact of unsymmetrically connected PV and corresponding battery storage systems. In order to produce a general statement, different PV distributions within the grid must be simulated. Therefore all previous PV installations were discarded. An algorithm was used to install new PV systems at existing households until either the 3% voltage limit according to [2] is reached or a thermal overloading occurs. A grid simulation without loads and feed-in serves as benchmark. The size of the PV system is chosen randomly dependent on existing PV installations in German low voltage grids according to [1]. In the same step also battery storage systems are connected in case the PV DC power is below 10kW. The reason for this constraint is based on the German renewable energy law (EEG), imposing costs for self-supplied energy for PV systems with a power higher than 10kW [5]. Based on realistic values regarding self-supply operational strategies and the c-rate provided in [6], the capacity of the batteries was chosen to be half of the installed DC-power with a c-rate of 1. The phase connection was performed according to table 1. The current unbalance limit in Germany is 4,6kVA according to [2]. Within this work, different limits should be investigated in order to analyse the specific effects on the voltage level and the line as well as the neutral conductor currents.

Condition:	*Phase connection:*
$PV_{DC} \leq$ unbalance limit	L1
$PV_{DC} >$ unbalance limit & $PV_{DC} \leq 2\cdot$unbalance limit	L12
$PV_{DC} > 2\cdot$unbalance limit	L123
Storage capacity $\leq$ unbalance limit	L3
Storage capacity $>$ unbalance limit	L123

Table 1: Phase connection scheme for PV and battery systems

Referring to PV systems, this phase connection scheme seems to be a worst case scenario due to the fact that all single phase inverters are connected to the same phase L1 and the two-phase inverters are exclusively connected to L12. However according to [3], investigations in real low voltage grids show similar conditions. The single line connection at L3 for all storage systems with a nominal power ≤ the unbalance limit represents a worst case scenario for the grid. Considering the space conditions within a building's wiring, this connection scheme is also not unrealistic. According to [7], a two-phase connection scheme for battery systems is not common so that all bigger battery systems are connected symmetrically. The number of different investigated distributions amounts to 100.

All distributions are simulated with the help of symmetrical components over a time period of one week with a 15-min resolution. The considered week exhibits a high PV irradiation. The applied load profiles for household loads were individually generated with a load profile generator according to [8]. Standard load profiles for business enterprises and night storage heating systems were applied.

THEORETICAL BACKGROUND

An unsymmetrical power exchange with the grid leads to the following results:

- Higher power flow over the connected line in comparison to the symmetric connection.
- The neutral conductor is current-carrying in comparison to a symmetric connection where the sum of all three phases is equal to zero.
- The current across the neutral conductor leads to a shifting of the neutral point resulting in higher or lower line-neutral voltages (this voltage is the input voltage for all PV systems, household devices, etc. and is in the following shortly denoted as voltage).

Figure 2 briefly explains the effects of an unsymmetrical power exchange with the help of a vector diagram.

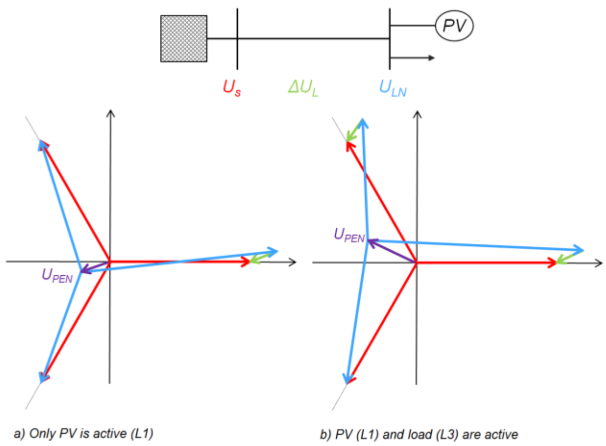

Figure 2: Vector diagram of a simple grid topology (R/X=2,5) with an exclusively PV feed in at L1 (a) and a PV feed in at L1 coupled with an equal load at L3 (b).

A single phase PV feed in at L1 (figure 2a) results in a distinct (nearly six times higher compared to a symmetric connection) higher line-neutral voltage U_{LN} at L1. Both other phases experience a voltage decrease due to the shift of the neutral point voltage U_{PEN} displayed in violet. The green arrows indicate the voltage drop over the line. The red arrows represent the source voltage U_s. For a battery storage system with a self-supply operational strategy the physical coherence leads to an additional worsening as it can be seen in figure 2b. While energy is fed in at L1 the battery consumes energy at L3. This behaviour leads to an additional increase as well as a shift of U_{PEN} due to the varied current across the neutral in figure 2b. Based on that the line-neutral voltage U_{LN} at L1 reaches even higher values compared to figure 2a. In addition to that the voltage U_{LN} at L3 exhibits even lower values compared to figure 2a.

Alongside the described voltage-related problems, the current across the neutral conductor is also increasing due to the geometrical addition of feed-in and consumer current. For this reason, the probability of thermal overloading of the neutral conductors also increases and therefore should be investigated.

SIMULATION RESULTS

Figure 3 shows the overall active power for both transformers over the simulated time period of one week for an exemplarily distribution. The unsymmetrical behaviour of the PV systems can clearly be seen due to the highest reverse flow of PV power at L1. Furthermore the self-supply operational strategy of the batteries can be discerned. In contrast to L1 and L2 (where a reverse power flow from the early morning to the afternoon occurs) the Phase L3 temporarily increases the power consumption (because of the self-supply strategy of the households) in the morning. After most of the batteries are fully charged also at L3 a reverse power flow is visible. This point is typically reached before the peak of PV power penetrates the grid. After sunset a balancing of the power flow can be seen within the three phases.

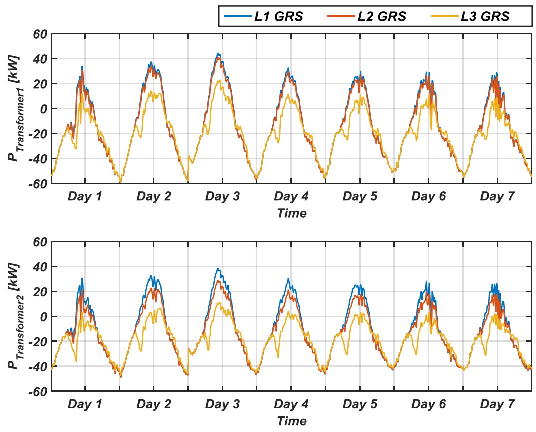

Figure 3: Transformer Power (GRS = generator reference arrow system) of an exemplarily distribution within the simulated time period

In Figure 4 the maximum voltage rise within the grid during the investigated week for all 100 distributions in comparison to the benchmark scenario is displayed. Furthermore the effects of varying the unbalance limits (ub) can be gathered. In order to check the plausibility of the results, different battery capacity factors (fb) are also analyzed for the 4,6kVA unbalance limit (only the capacity is varied, not the maximum power of the batteries defined by the initial size).

For an unbalance limit of 4,6kVA (magenta line in figure 4), a maximum voltage rise of about 7% can be determined within the 100 distributions. However, the symmetrical grid planning process tries to restrict the maximum voltage rise at a level of 3%. The simulation without batteries (fb=0) exhibits nearly similar results whereby the maximum voltage rise shows slightly smaller values. This is justified by the missing voltage rise effect of battery power consumption at L3. A twentyfold battery capacity would increase the maximum voltage rise within all distributions up to 10%. This theoretical phenomenon can be explained by the fact that these large batteries still exchange power with the grid during high PV irradiation times when the normal capacity is already depleted.

According to [9], a voltage band allocation of 1% is reserved for unsymmetrical behavior in the low voltage grid. In addition to the symmetrical 3% an overall voltage rise of 4% is conceivable. If this voltage increase of 4% should be satisfied with a quantile of 100% (in every distribution the voltage rise should not exceed 4%) an unbalance limit between 2 and 3kVA must be specified.

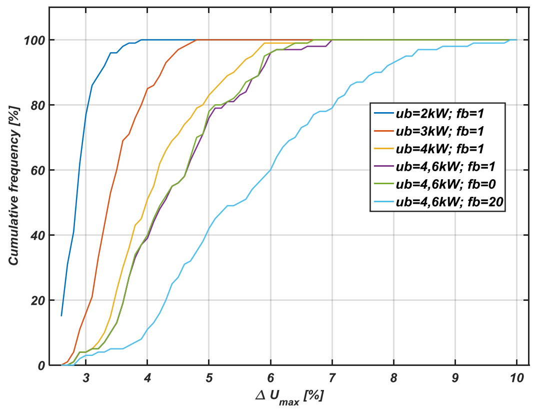

Figure 4: Cumulative frequency of the maximum voltage rise within the grid and the investigated week (referring to the benchmark scenario) for different unbalance limits and battery factors.

Besides the absolute value of the voltage, the relationship between all three phases must also meet specific requirements. According to [10], the ratio between the negative sequence voltage and the positive sequence voltage (called voltage unbalance) must be kept below 2% for every node of the grid.

Figure 5 displays the cumulative frequency of the voltage unbalance for all 100 distributions depending on different unbalance limits and battery factors. Regarding the 4,6kVA unbalance limit, there is a significant difference between the investigated battery limits. With a battery factor of 0 it is possible to fulfill the legal requirements at any distribution. However with a factor of 1 voltage unbalances up to 2,5% are ascertainable. For a twentyfold capacity the 100% quantile even reaches values up to 3%. If the compulsory limit of 2% should be kept, an unbalance limit between 3 and 4kVA must be introduced.

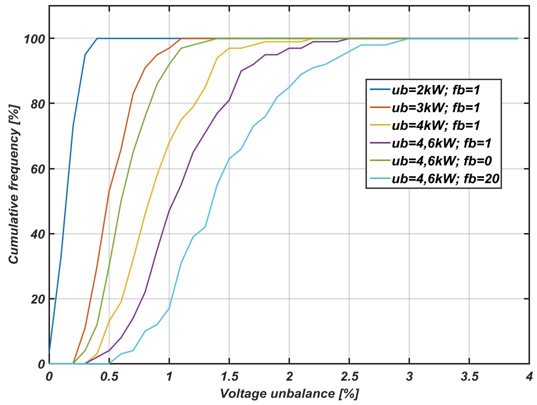

Figure 5: Cumulative frequency of the voltage unbalance within the grid and the investigated week for different unbalance limits and battery factors.

Figure 6 displays the results for the line currents as well the currents across the neutral conductor. It was assumed that the sum of all phases equals the current across the neutral conductor. This means that the small amount of current flows across earth is treated like neutral conductor current.

Considering symmetrical planning conditions, the 3% voltage criteria is nearly always met before line overloading is achieved in the investigated grid. Referring to the above part of figure 6, unsymmetrical conditions lead to a tightening of the unbalance limit because every line current loading distribution exhibits line currents over 100%. Even for an unbalance limit of 2kVA only 95% of all distributions show a maximum line current below 100%. However a maximum loading of about 130% is not exceeded in any distribution for any unbalance limit and battery factor.

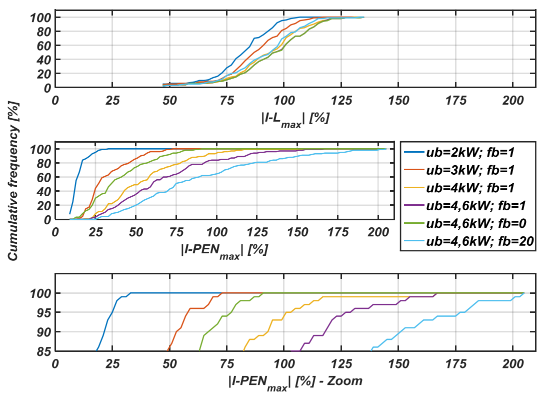

Figure 6: Cumulative frequency of the maximum line current and neutral conductor current loading within the grid and the investigated week for different unbalance limits and battery factors.

Indeed the neutral conductor presents even higher loading values. For the prevailing unbalance limit of 4,6kVA maximum values of around 160% occur. Over 50% of all distributions exhibt maximum neutral conductor currents exceeding a loading of 60%. Considering the fact that some cables in low voltage grids have a reduced cross section (60% is an applied value), this circmstance may lead to a destruction of the neutral conductor. If such a limit of 60% is applied, an unbalance limit between 2 and 3kVA must be satisfied. Furthermore the neutral conductor current is not only caused by unsymmetric loads and infeeds. Harmonics of the third order also penetrate the neutral conductor. For both current sources in combination it has to be assured that no overloading of the neutral conductor occurs. Again there is a distinct difference between the investigated batteryfactors. On the basis of this result, the exact connection of future unsymmetric loads (for example household e-car charging systems) will have a strong impact on the neutral conductor current. A modified loading in both directions is possible depending on the applied unbalanced limit.

Figure 7 gives an overwiew at which point of time maximum and also minimum voltage values occur. As expectet all maximum voltage values occur around the peak of the PV irradiation. A bigger size of the battery factor leads to a slight shift towards midday. For the minimum voltage value of the grid within the investigated time period, hours around midnight were expected to be the point of time with the lowest voltage of the week. This assumption is based on the high amont of night storage heating systems which exhibit there maximum consumption around midnight. Figure 3 underlines that the maximum power consumption takes place at this time. For an unbalance limit of 2kVA this assumpiton was confirmed, as 90% of all distributions have the minmal voltage directly between midnight and 1am. However, for a higher unbalance limit, minimum voltage values are observed during high PV irradiation. At this time also the maximum voltage levels appear. Further investigations show, that sometimes one node exhibits the highest voltage value of the week at L1 and at the same time the lowest voltage value of the week at L3 occurs.

For symmetrical conditions an adjustable stationary transformer is a comon answer to high voltage values during midday and low voltage values during the night. Most of these transformer stations control their switching procedure on the basis of the power flow. In case of a high reverse power flow, all three phases are switched so that the voltage at the low voltage side of the transfomer decreases. Such an operating strategy would even worsen the minimum voltage which occurs at the same time due to unsymmetric conditions.

An interesting observation can be gathered observing the different battery factors. Even withount a battery (fb=0), the lowest voltage values occur at highest PV irradiation periods just because of the shift of the neutral point.

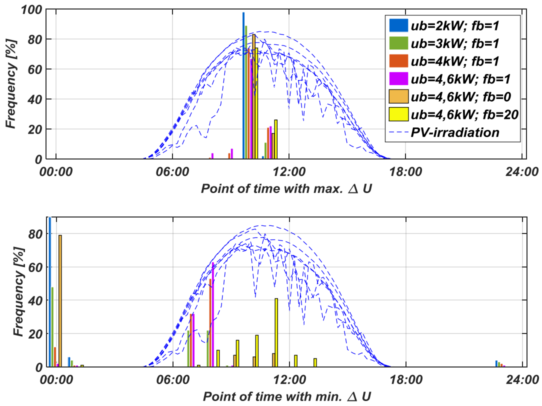

Figure 7: Transformer Power within the simulated time period

SUMMARY AND OUTLOOK

In this work the prevailing unbalance limit of 4,6kVA in Germany was reexamined. A variety of different PV distributions were evaluated within an exemplarily low voltage grid concerning the voltage band, voltage unbalance, line current and neutral conductor current. A phase connection scheme was applied so that PV systems fed in power either in L1, L12 or L123. Battery home storage systems exchanged power with the grid depending on their capacity either on L3 or on L123.

Referring to the voltage values, a reduced unbalance limit of 2-3kVA is suggested in order to satisfy a 4% (3% symmetrical + 1% reserve for unsymmetrical behaviour) voltage rise in comparison to the benchmark scenario without loads and PV feed-in. Regarding voltage unbalance, a value of 2% should not be exceeded. Therefore a reduction of the unbalance limit towards 3-4kVA is needed. Beyond that, a reduction below 2% is necessary if all line current overloadings should be kept below 100%. For the neutral conductor, overloadings up to 160% were determined for the prevailing unbalance limit of 4,6kVA. With a current limit of 60% (this cable type is still utilized in the grid), the unbalance limit has to be reduced to 2-3kVA. To sum it up it can be stated that all investigated parameters exhibit boundary value violations with an unbalance limit of 4,6kVA. Therefore a reduction of this value, especially considering the integration of new load types like battery home storage systems or e-car charging systems, is of the upmost importance to guarantee the compliance of all limits.

In addition it should be mentioned that a chronological difference between highest and lowest voltage value is not self-evident any more. Until now it was common sense that the highest voltage values occur during high PV feed-in around midday whereas low voltage values occur for example in the evening during a high consumption or in bad weather holidays during lunch time. A simultaneous occurrence of both scenarios has not been reported. However the results of this work show that the highest and lowest voltage values may occur at the same time and even at the same node on different phases. The reason for this phenomenon lies in the shifting of the neural point, provoked by a high in-feed for example at L1 and a high consumption at L3. The efficiency of adjustable stationary transformers (ront), which are an established method to counteract high voltage values during PV feed-in by lowering all three phases at the same time, must be scrutinized under unsymmetrical grid conditions.

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