THE IMPACT OF DISTRIBUTED HYBRID PHOTOVOLTAIC BACKUP SYSTEMS ON SHARED RESIDENTIAL FEEDERS

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Abstract

Battery energy storage systems will increasingly be connected to shared low voltage (LV) feeders, as the uptake of electric vehicles (EVs), hybrid photovoltaic (PV) backup systems (i.e. grid-interactive PV systems with self-consumption and uninterruptable power supply functionalities) and other behind-the-meter storage technologies rises. While there are many benefits from the increase in these technologies they may also pose several issues.

This paper discusses the potential impacts of hybrid PV system installations on LV networks in various scenarios of net load capacity (the offset between generation and consumption), grid access regulations and the customer's battery-use behaviour. Using one of the scenarios, the paper demonstrates the potential impacts of increased hybrid PV system penetration on voltage levels, phase unbalance and thermal loading of the feeder, referenced against the relevant quality of supply standards. A stochastic-probabilistic approach is used to conduct the simulations; the Monte Carlo Simulation method is used to simulate the stochastic nature of the unknown hybrid PV system placement while the extended Herman Beta transform accounts for the uncertainty and variability in both the PV generation and loads. The results show that hybrid PV systems can cause the violation of voltage unbalance limits even if injection into the grid is not allowed. Further simulations demonstrate that the distribution of customers along the feeder affects the extent of the unbalance and thus the permissible penetration.

Keywords: hybrid PV systems; stochastic PV distribution, probabilistic load flow; LV network hosting capacity, PV grid impacts.

1. Introduction

The placement, size and usage patterns of battery energy storage systems (BESS) on shared LV feeders are not centrally planned, but rather decided by the end customer, informed by technology pricing and electricity pricing signals, amongst other factors. This is similar to the roll-out of embedded generation (EG) on shared feeders.

The technical impacts of the random and subsequently difficult-to-predict roll-out of BESSs will also be similar to that of EG: the introduction of current flows for which the LV feeder was not designed, impacting feeder voltage profiles, thermal loading and phase unbalance. Regulations like NRS097-2-3 [1] provide some guidelines on managing the impact of the roll-out of EGs but does not include BESS yet.

Currently in South Africa, the BESS with the highest uptake is likely to be hybrid PV backup systems, primarily due to frequent load shedding, favourable return on investment of PV and self-consumption requirements. This paper focuses on the impacts of these hybrid systems on shared LV feeders, further limited to residential applications to allow for a sufficient depth of analysis.

The primary objective of this paper is to gain a better understanding of the effects on voltage level, thermal loading and phase unbalance as the number of hybrid PV backup systems connected to a shared residential feeder increases. The research applies a stochastic-probabilistic methodology initially developed by Gaunt et al. [2] and recently extended for enhanced accuracy and further applications [3]. This methodology is explained and was used successfully in [4] for LV feeders with PV EGs without storage and with feedback limits of 50% of the customer's rated circuit breaker. In this paper, it is used to map the impacts of hybrid PV systems at different penetration levels, for a large number of placement scenarios that are randomly generated.

The difference with BESSs compared to EGs is however that many variations of charge-discharge schemes exist, defined by customer behaviour, pricing signals, regulations to name a few, compared to EGs based mainly on solar irradiation. The value of this work will be in understanding how these different charge-discharge schemes correlate to the technical impacts as a function of uptake.

The next section discusses the potential technical impacts of BESSs on the LV grid. It also illustrates how various system configuration constraints affect these technical impacts. Section 3 explains various power generating energy system configurations and how they affect the grid. In section 4, six hybrid PV system scenarios are explained, one of which is simulated to study the technical impacts of self-consumption hybrid PV systems without grid export. The simulation process and load flow analysis method are also described in section 4. This is followed by a discussion of the results and finally, conclusions are drawn and recommendations for possible further studies made.

2. Grid impacts

There are several impacts that increasing penetrations of hybrid PV systems will have on an LV feeder. In this paper, the various hybrid PV system configuration scenarios will be analysed based on the following technical impacts: feeder voltage level, phase unbalance and thermal loading. These technical impacts are defined below, followed by explanations on how different system scenarios contribute to these technical issues.

2.1 Feeder Voltage

The feeder voltage level can be affected mainly by two factors namely the amount of current being drawn along a feeder (the load current) and phase unbalance.

2.1.1 Load

Quality of supply (QoS) standards define margins in which certain parameters, like feeder voltage level, need to operate within. For South Africa, the voltage received on a residential LV distribution network level is 230 V within a 10% tolerance band [5].

The flow of current from the distribution transformer to connected customers (electric load points) results in voltage drop due to the impedance characteristic of the distribution cables. The larger the load current the larger the voltage drop. Accordingly, a large enough voltage drop could cause the voltage level received by the consumer to fall below the limit stipulated in the QoS standards.

The inverse is also true. EGs can also independently affect the feeder voltage level if injection of power into the grid is allowed. If a resident is allowed to inject stored battery power or excess power generated from a PV system into the grid, this could cause a voltage rise that could violate the QoS standards if the feeder voltage becomes too high. When injection is not allowed, the reduction in the net load is anticipated to limit voltage drop. However, where this occurs unequally between the phases, voltage rise due to unbalance may also result. This is discussed in detail in the subsequent section.

2.1.2 Unbalance

Electricity is generated and transported in three phases and each household along an LV feeder is typically connected to only one of the three phases. If the three phases are not evenly loaded this could result in voltage unbalance. QoS standards stipulate that the voltage unbalance allowed is up to 2% [5]. This voltage unbalance, although possibly small, can in three-phase motors result in large negative-sequence currents which causes poor efficiency, excess heat generation causing increasing operating temperature affecting equipment lifespan and even permanent damage or failure [6], [7].

Apart from possible damage to equipment, voltage unbalance affects the voltage level of the feeder itself. If one phase is more heavily loaded than the other two, because the phase voltages are dependent on each other, this will affect the voltage level of the other two phases. However, the variation may not be significant enough to violate the QoS standards.

A cause for these unbalanced residential loads is the stochastic uptake of EG, PV and hybrid PV systems as well as BESS. However, this is something the utility has limited control over. Standards that regulate this uptake may however aid in reducing the impact on load and phase unbalances.

2.2 Thermal Limits

The thermal limits referred to here are in relation to the current carrying cables and the transformer windings. As previously mentioned in Section 2.1.1, the cables can be modelled having an impedance comprising of a resistance and inductance, this being a physical property of the cable. If a current passes through the cable, the cable will heat up due to this resistance. A large enough current will cause the cable to heat up significantly. This can not only cause fires and irreparable damage but will also decrease the efficiency of the cables and windings. Larger loads than accommodated in the network design could cause the thermal limits of the cables to be exceeded. Knowledge of the expected loads is therefore imperative when doing distribution network design to ensure that these cables and transformers are chosen appropriately and will be able to handle the expected currents.

Table 1 summarises the effects of grid charging and injection on the technical impacts discussed in this section.

3. Power generating energy system configuration scenarios

Different system configurations or the same system under different constraints will have varying impacts on the network. PV systems and BESS that are not allowed to inject excess generated power into the grid might have a smaller impact on the network compared to PV systems in

Condition	**Voltage Conditions**		**Thermal Limits**
	Level	**Unbalance**	
Grid charging	Mass simultaneous charging will increase the magnitude of load currents, therefore significant voltage drops.	Charging of single-phase systems results in unequal phase load currents which leads to voltage unbalance.	High/continuous load current from simultaneous charging can cause thermal overloading.
Injection	High enough injection levels can cause reverse power flow and therefore voltage increase.	Unbalanced injection will cause phase unbalance.	High enough reverse power flow current can cause thermal overloading.

Table 1: Grid charging and injection effects on technical grid impacts

which injection into the grid is allowed. Similarly, PV systems that have batteries to store excess power generated for self-consumption at a later stage will affect the network differently to PV systems with batteries that can inject into the grid during peak tariff periods. Whether injection into the grid is allowed and whether charging of batteries take place via excess PV power generated versus grid power will play a role in the penetration percentage a network can accommodate while meeting QoS standards.

When conducting distribution network design, specifically referring to LV feeders in this case, knowledge of the expected loads is important. After Diversity Maximum Demand (ADMD) is used and based on the type and number of customers connected to the feeder, the network is designed accordingly. However, the ADMD assumptions without modification become invalid as soon as EG and batteries are introduced; as the capacity and characteristics of the loads change significantly. For instance, with grid charging of batteries, the loads will be more continuous opposed to traditional loads like geysers, ovens and refrigerators controlled by thermostats causing varying loads due to the on-off switching.

Table 2 illustrates the potential technical impacts of various PV and battery system configurations with injection of power into the grid prohibited and allowed. Although the extent to which the technical impact is affected is not noted, this could be determined through simulations.

The very first row shows a system than consists of only PV with no battery for storage and regulated such that no excess generated power may be injected into the grid. This scenario, when applied to single phase systems, may significantly affect phase unbalance as some customer loads are reduced while others completely offset by the PV generated power causing them to appear off-grid. This may cause uneven loading of the three phases, resulting in voltage unbalance. This scenario will not have an impact on thermal loading as the load current will decrease and no reverse power flow is allowed due to the injection restriction.

The batteries mentioned in the table above could refer to batteries of EV's. When no export is allowed, the battery is only charged with the grid power and injection into the grid is not allowed. In the scenario in which injection is allowed, this may be during periods in which the vehicle is not being used. Reverse power flow is possible and feeder voltage increase is likely.

Without explaining each scenario as extensively as the first, it is evident that the diverse states of configuration will lead to different constraints on the network indicating the complexity of planning as a result of new technologies. References to papers investigating the technical impacts associated with the other scenarios of Tables 2 include [8], [9], [10], [11].

4. Simulation Process

The following section will introduce six operating scenarios specific to hybrid PV systems. The scenario most relevant to typical South African shared LV feeders will then be simulated to demonstrate how the stochastic-probabilistic load flow method can be used to study the impacts of hybrid-PV systems on LV feeders.

Scenario	**Technical Grid Impacts**		
	Voltage Conditions		Thermal Limits
	Level	Unbalance	
PV only (no export)		✓	
PV only (export allowed)	✓	✓	✓
Battery only (grid charging, no export)	✓	✓	✓
Battery only (grid charging, export allowed)	✓	✓	✓

Table 2: Effects of scenarios on technical grid impacts

4.1. Background

4.1.1 Possible Scenarios

Systems consisting of a PV and wind combination or PV and other forms of EGs are often also referred to as hybrid PV systems [12], [13], [14]. However, in this paper, the term “hybrid PV” refers to PV systems with an additional component being a battery. This allows for charging of the battery when the PV generation is higher than the load and self-consumption of battery power at a later stage when the PV generation might be low or unavailable. This could be particularly beneficial during load shedding periods or even for energy arbitrage.

When simulating the impact of hybrid PV systems, a range of scenarios are possible. Four scenarios are visually represented in figure 1 in which the restriction on grid charging of the batteries and injection of battery or generated power is toggled.

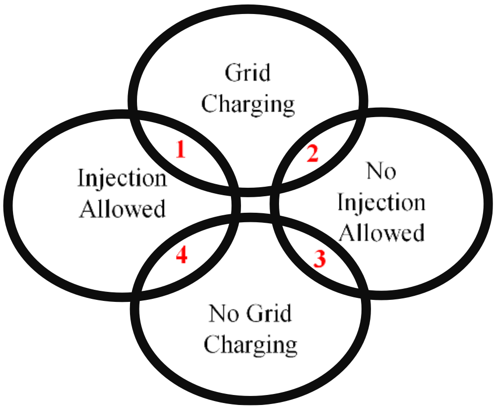

Fig. 1. Scenarios for Hybrid-PV System Operation Restrictions

For the scenarios in which grid charging is allowed, time of use (ToU) tariffs may introduce an additional two scenarios; with ToU and without ToU tariffs. Grid charging without ToU tariffs would be purely for UPS functionalities when load shedding events take place, while ToU tariffs makes energy arbitrage a possibility.

4.1.2 Load Flow Analysis Methods

Placement and Capacity of Connected Systems:

Because the uptake of power generating energy systems (in this case hybrid PV systems) is dependent on factors like the interest of the resident and pricing of the technology, the uptake subsequently lies outside the control of the utility. This means that it is very difficult for the utility to predict the capacity and location of these installations making network planning with PV uptake a challenge.

To simulate the randomness in capacity and location of the hybrid PV system installations in the load flow analysis, a stochastic approach can be taken to account for the unknown placement of hybrid PV system installations along a feeder. The Monte-Carlo Simulation (MCS) is one such method. Gaunt et al. [4] applied the MCS approach for random capacity and placement allocation of PV in a study to determine the hosting capacity to only PV (no battery) on an LV network. Several other authors [15], [16], [17] and [18] identified the need to use this approach to account for the stochastic placement of loads (EVs) during impact assessments on LV feeders. Valsera-Naranjo et al [19], used both a deterministic and probabilistic approach to account for the placement of EVs in an impact assessment to determine the effects of EV on a network. It was noted that although a deterministic method accounted for various worst-case scenarios; the stochastic method was deemed more appropriate as it is more consistent with the nature of EV uptake.

Solving the Load Flow:

When it comes to the load flow calculation, once again either a deterministic or probabilistic approach can be taken. Deterministic load flow analysis uses fixed, predetermined values for the loads and generations. Using this method, a single scenario in a spectrum of thousands of possible operating scenarios is analysed. This approach does not however take into account the likelihood of such scenarios. Without the knowledge of the full spectrum of feeder performance, a planner cannot tell the risk associated with a particular design, which, may impact network performance and total investment.

On the other hand, probabilistic load flow (PLF) methods take the uncertain and varying characteristics of both the loads and generators into account. Extreme cases can still be analysed but the likelihood of such cases is known. The result is that the planner has full awareness of the operating states of the network, which enables informed decisions.

Several PLF approaches of different speed, complexity, and accuracy exist. The MCS, when used with adequate samples, is regarded the most accurate. However, it is very slow due to the iterative approach. With the requirement of an MCS to solve the random allocation problem, speed is a critical characteristic in the selection of the PLF approach. The Herman-Beta Extended (HBE) is a single-pass statistical method used for PLF analysis [20]. When the HBE is compared to the MCS, the computational speed of the HBE is significantly faster without loss of accuracy [21], [22]. Accordingly, the HBE is appropriate for use in the combined stochastic-probabilistic approach and is used in the simulations in this paper.

4.2. Conditions and Assumptions of Simulated Scenario

Now that different placement and capacity methods, load flow solving methods and potential technical grid impacts have been discussed, in addition to six system operation scenarios, one of these scenarios will be simulated.

Scenario 3 in figure 1, in which grid charging and injection is prohibited is simulated. This scenario is chosen specifically because it is practically relevant currently in South Africa. Most utilities encourage self-consumption of generated power and although injection is not prohibited, it is discouraged through tariff instrumentation. For instance, in Cape Town, the current electricity rate for a home user is 201.78 c/kWh (incl. VAT), while residential small scale embedded generation (SSEG) can inject into the grid at 84.95 c/kWh [23]. This may be seen as a way in which the City of Cape Town encourages users to self-consume and deter injection into the grid. A question which arises is that should the customers comply with the suggested regulations (by fully self-consuming without export), what is the associated technical performance of the network? To study this, Scenario 3 from figure 1 will be simulated. The following baseline conditions and assumptions are applied:

- To increase the service life of the battery, the battery will never be discharged past a certain point. Therefore, only a certain minimum percentage referred to as depth-of-discharge (DoD) will be used.
- A portion of the battery capacity will always be assigned for UPS functionality in the case of load shedding.
- The battery can be used for self-consumption up until a minimum point equal to the percentage retained for protection plus that retained for load shedding.
- When the PV generation is less than the load, the battery will be used to match the load. If the battery has reached the minimum point, grid power will be used to match the load.
- When the PV generation is more than the load, the battery is charged.
- Injection into the grid is not allowed.
- If the battery is full, excess PV generation will be curtailed.
- The battery will never be charged with grid power.

With the conditions and assumptions clear, the load flow analysis method used will be explained below.

This paper makes use of a simulation approach combining the MCS method and the HBE. The MCS deals with the random placement of hybrid PV systems along the feeder while the HBE is used for the probabilistic load flow analysis.

When using the HBE, the loads and PV models are characterised as Beta probability density functions (PDFs) of currents. The simulation was conducted for a very extreme case period of the day in which PV production would be high while consumption is low. In South Africa, this usually occurs around midday during summer. Only the effects on the grid during that interval were simulated. The charging of the battery with excess PV power for later use does not have affect the grid in the worst-case interval. The battery is assumed to be at its minimum due to consumption the previous evening, so the load was not supplemented with the battery when PV generation was less that the load.

4.2.1 Description of Test System

A simple, three-phase four-wire, 11-bus, radial feeder supplied by a 11/0.4 kV transformer is used. Each bus (apart from the source bus) supplies three residential customers and is separated from the subsequent bus by a 45-metre conductor branch.

4.2.2 Input modelling: Load and PV

For the selected simulation scenario, to simulate the condition of no injection into the grid, the net load conditions at each node must be zero or bigger. This presents a huge computational challenge: since the loads and PV are characterised by different statistical models, they are treated separately in the HBE; PV nodes are separated from load nodes by a dummy, ‘negligible voltage-drop’, branch. This means it is difficult to control the net load capacity without reformulating the algorithm, which is beyond the scope of this work. However, two approaches, based on the modification of inputs, are possible.

The one involves redefining the load model to include the effects of PV generation. This would result in net load probabilistic models for various levels of PV generation. With net load models and no allocation to PV nodes, the HBE can be used to simulate the stochastic reduction of the load as a result of PV generation. However, the definition of probabilistic models for the net load has not been done and thus requires separate attention.

Another approach, which is relatively easier has two components; the allocation of PV installations matching the load capacity, and the modification of the statistical parameters of the input beta PDFs to ensure the stochastic sum of the two does not result in significant negative currents. This can be achieved by reducing the variance of the load while maintaining its after-diversity-maximum-demand (ADMD) and modelling the PV generation under optimal conditions in which the output from each customer is mostly high.

The reduction in variance is achieved by setting the alpha and beta parameters for the loads and PV models very high, resulting in high-pitched, tall distributions. This ensures that in majority of the scenarios PV generation would either be less than or equal the load. In cases where this is not so, the negative currents are negligible as a result of the reduced variance. It should be noted that by reducing the stochasticity of the loads and PV, the hosting capacity determined by the simulation will be affected. As shown in [4], when the loads are modelled with little variance, the impacts of PV installations were reduced by almost 100% compared with the result achieved using a full stochastic load. The reduced penetration observed with the full stochastic load is due to increased diversity in the load which in turn increases unbalance. Therefore, the results shown in the following section may in actual fact be conservative.

4.2.3 Simulation Investigations

The technical impacts of hybrid PV system without grid injection were simulated using two investigations with a total of five case studies.

The first investigation looks at the influence of load magnitude on the technical impacts of hybrid-PV systems. The customer distribution was balanced having one customer connected to each phase at each node along the feeder. PV installations were assigned at random in 1 kW increments. This implies that for a house with a 4 kW load to be completely offset by PV generation and appear off-grid, that specific house needed to be chosen four times at random. Two test cases are conducted; Case 1 loads have a 2 kW afternoon customer load while in Case 2 higher customer loads of 4 kW are used. The 4 kW loads are those of customers that most likely have air-conditioners installed and pool pumps that may be running during the summer midday period. In each case, the maximum PV capacity is matched to the load.

The second investigation focusses on the impact of different customer distributions on the gravity of technical issues. Three case studies are used; Customers were assigned in both a cosine (3-0-0) and cyclic (2-1-0) pattern and compared to that of a balanced (1-1-1) distribution.

5. Results

The results from the first investigation are shown in Table 3. The penetration percentages at which violations to voltage unbalance, minimum feeder voltage and transformer maximum loading are shown.

Because injection of excess power generated into the grid is not permitted, violations to the upper limit of the feeder voltage are not expected and only the lower limit (minimum) feeder voltage level is shown.

Customers consuming 2 kW during the midday summer period did not appear to have any violations even when all customers were assigned the maximum PV load. However, when the noon load was increased in Case 2, the voltage unbalance limit was exceeded at 20 % penetration. The results demonstrate that for a class of customers with high noon demand, the impacts of unbalance are likely to be significant.

Table 4 shows the results from the second investigation on the impacts of customer allocation. The results show that when the customer distribution is balanced, violation of unbalance occurs at a higher penetration percentage than both the cyclic and cosine configuration. On further analysis, looking at unbalance at passive conditions (with no DG), the cyclic customer allocation had the highest unbalance while the cosine configuration was not much lower and the balance configuration nearly no unbalance. It can be deduced that the initial unbalance on a feeder, usually as a result of customer distribution along a feeder, will constrain the uptake of non-injecting PV systems as unbalance is easily aggravated beyond the permissible limits.

Simulation	**Customer Load [kW]**	**Maximum PV Load [kW]**	**Penetration percentage at which violations occur**		
			Unbalance	**Minimum Voltage Level**	**Transformer Maximum Loading**
1	2	2	No violation	No violation	No violation
2	4	4	20 %	No violation	No violation

Table 3: Simulation results for 2 kW and 4 kW customers with balanced distribution

Case	**Customer Distribution**	**Penetration at which violations occur**		
		Unbalance	**Voltage-drop**	**Transformer Loading**
1	Balanced (1-1-1)	20 %	No violation	No violation
2	Cosine (3-0-0)	16 %	No violation	No violation
3	Cyclic (2-1-0)	15 %	No violation	No violation

Table 4: Simulation results for 4 kW customers with different distributions

The results also illustrate that when injection into the grid is prohibited, the effects on unbalance are a lot more significant than the effects on feeder voltage level and thermal loading. In fact, as PV penetration increases (without export), thermal loading decreases as the customer consumes less and less from the grid. While the maximum recorded voltages on the feeder may in some cases increase due to the effect of unbalance, the magnitude of voltage rise is very small (less than 2% in the simulated case). Accordingly, violations of thermal loading and voltage level are much more unlikely compared to voltage unbalance violations.

From the results it is evident that the basis for the encouragement of self-consumption and deterrence of injection based on the premise that this will not have an effect on the grid, is flawed. Distribution networks are designed to accommodate a specified load capacity, with little allowance of load changes with time. Self-consumption, which leads to load reduction and ultimately causing customers to appear off grid, appears to have significant effects on unbalance.

6. Conclusions

This paper discussed three technical impacts that power generating energy systems have on the grid namely: voltage unbalance, voltage level and thermal loading. Then the power generation energy systems and the effects that increasing penetrations of these systems have on the three technical impacts were discussed.

The paper has identified four major operation configurations which are crucial when considering hybrid PV systems and their effects. These can be expanded to six if ToU tariffs are introduced to regulate grid charging and injection. The discussion also covers the simulation requirements for these applications. The work shows the complexity associated with the design of future networks, even the assessment of the adequacy of existing networks to host the new technology.

To demonstrate the potential impacts of hybrid PV systems, and the manner in which the simulations can be conducted, one of the many possible scenarios was simulated. The scenario involves cases in which grid charging and injection into the grid is not allowed. Simulation results demonstrated that the penetration of hybrid PV systems for self-consumption is likely to cause significant issues of voltage unbalance. Severity studies show the severity of the unbalance is higher on feeders with high demand in summer noon, due to air conditioners and pool pumps for instance, and feeders with high unbalance under passive conditions.

It is worthwhile noting that the simplified inputs models used in this paper were only sufficient to demonstrate the potential technical impacts of hybrid PV systems for one operating scenario. The accurate statistical modelling and probabilistic simulation of the full scope of technical parameters and operation scenarios, including the randomness of parameters such as the system location, PV and storage capacity, and operation mode, remains a research gap that encourages future work.

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