Applicability of True Voltage Unbalance Approximation Formula for Unbalance Monitoring in LV Networks with Single-phase Distributed Generation

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Abstract: In the hierarchy of power transmission and distribution systems, the three-phase LV distribution networks are most susceptible to voltage unbalance (VU). The main causes are large presence of randomly distributed single-phase loads and, following the latest trends, the increasing presence of single-phase distributed generators. Most widely accepted VU calculation is based on percentile ratio of negative and positive sequence voltage (voltage unbalance factor, VUF). Obtaining sequence voltages is a complex domain calculation and requires simultaneous sampling of three-phase voltages and angles. This is why the existing VU monitoring and mitigation solutions are dominantly three-phase. Without an additional three-phase aggregation device, there is an inherent gap in VU monitoring for single-phase loads and generators. In this paper, the data concentrators for a growing PV micro-inverter niche are identified as an infrastructure that could be exploited to somewhat close this gap. Due to potential technical limitations of PV data concentrators, a non-complex VUF approximation formula is tested as a "light" calculation alternative, by comparing it against conventional VUF. The comparison results are obtained from Monte Carlo load flow simulation for an unbalanced LV network.

1 INTRODUCTION

1.1 PV Penetration and Voltage Unbalance Mitigation Problem

The voltages in a 3-phase distribution network are considered unbalanced if differences in magnitudes and/or angles between phases exist beyond specified limits (Driesen and Craenenbroeck, 2002). At high (HV) and medium voltage (MV) level loads are mostly three-phase and balanced, but at low voltage (LV) level many single-phase loads are encountered and randomness of load profiles is greater. Despite the best practices of LV network planning , some increased unbalance is always experienced compared to MV and HV level. The trends of increasing single-phase distributed generation can further promote the increase of unbalance at LV levels. In most cases those are single-phase photovoltaic (PV) systems, therefore studies were performed on their impact on unbalance (Vegunta et al. 2013; Shahnia et al. 2011a). The VU can cause a decrease in the induction motor efficiency, sub-optimal operation of power electronics and reduced capacity in transformers, lines and cables, therefore it is important to have mitigation solutions at disposal.

Most basic and most limited solution is to improve the planning practices. Further solutions that can come from distribution operator side is the application of specialized transformers and fast-acting power electronics devices (Driesen and Craenenbroeck, 2002). In (Shahnia et al. 2011b) VU mitigation by distribution static compensators and dynamic voltage restorers was analyzed. There are also proposals for an active involvement of distributed generation. In (Chua et al. 2012) a PV with storage is used to mitigate unbalance. The new control designs for PV inverters are integrating the unbalance mitigation (Caldon et al. 2012; Wang et al. 2008; Weckx et al. 2014).

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1.2 Voltage Unbalance Quantification and Monitoring

Before reviewing the inverter-based solutions, the calculation and quantification of VU needs to be understood, because it impacts the technical implementation of monitoring and control, especially for single-phase devices. Whether only magnitudes or both magnitudes and angles are considered, the VU calculation depends on the adopted VU definition (Pillay and Manyage, 2001). Most widely accepted is the true voltage unbalance definition that takes both magnitudes and angles into account. Quantitatively it is expressed in percentages as the voltage unbalance factor (VUF):

$$VUF(\%) = \frac{V^-}{V^+} \quad (1)$$

where V^- and V^+ represent the magnitudes of negative and positive sequence voltages. By applying the method of symmetrical components, positive and negative sequence voltages are obtained:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} V^0 \\ V^+ \\ V^- \end{bmatrix} \quad (2)$$

These are complex domain calculations where complex operator a is function of phase angle: $a=e(j2\pi/3)$. In order to calculate sequence voltages, the instantaneous three-phase voltages and angles must be obtained simultaneously (ed. Zobaa, 2013). Technical implementation of monitoring therefore requires a device directly connected to a 3-phase supply. This is an inherently insurmountable problem for single-phase devices unless an external device acting as their coordinator is used.

1.3. Lack of Solutions for Single-phase Inverters

In (Caldon et al. 2012) an external controller at substation level coordinates single-phase and three-phase inverters in order to mitigate unbalance. Three-phase inverter control designs are proposed in (Wang et al. 2008) and (Weckx et al. 2014). In (Tangsunantham and Pirak, 2013) a three-phase smart meter is used to monitor VU with high accuracy and low cost. What is common for all these referenced solutions is that they all use VUF to assess VU. This is why these solutions are dominantly three-phase. It is evident that without an additional three-phase device, there is an inherent gap in VUF monitoring and control for single-phase inverters. Additional device also incurs additional cost to the PV system, therefore it would be worthwhile looking into single-phase devices whose existing ICT infrastructure could be software-retrofitted for purpose of enabling VUF monitoring and control in LV networks.

In this paper, data concentrators used in PV micro-inverters are addressed for their retrofit potential in VU monitoring application. Due to potential hardware limitations, a non-complex approximation formula for VUF calculation (AVUF) is tested as a light alternative to conventional VUF. Modelling of VUF and AVUF is carried out in Matlab/Simulink and presented in Section 2. To account for randomness of PV generation a Monte Carlo load flow is performed for an unbalanced 3-phase 4-wire network model. Both Monte Carlo scenario setup and network modelling are described in Section 3. Comparison between VUF and AVUF on the basis of Monte Carlo simulation results is given in Section 4. The implication of results are discussed in Section 5.

2 PROPOSED SOLUTION

2.1 Data Concentrators in LV Networks

Data concentrators are the key components for Advanced Metering Infrastructure (AMI). They aggregate instantaneous data from numerous smart meters and transmit it to the utility server. Without their use as a mediator, the direct meter-to-server communication would face many technical difficulties. Other than application in AMI, the data aggregation technology for PV generation is also increasing its presence. It has become standard part of the package for PV plants based on micro-inverter and DC optimizer technology. The implementation of power electronic converters at module-level expanded the opportunity for monitoring operational parameters from a single point to each module/micro-inverter in the PV plant. This generates a lot of data. In high PV penetration areas there can be hundreds of panels and their data needs to be aggregated and presented to the application or the end-user in a meaningful way. Most of the micro-inverters available on the market today are sold in package with data concentrator devices, more often called "gateways". They communicate to micro-inverters via mesh radio or power line communication while remote communication with an application is done via internet (Enphase, 2015;

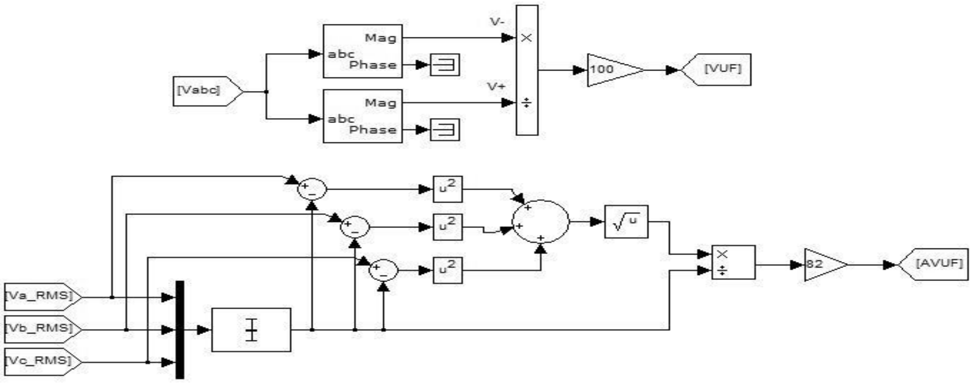

Figure 1: Simulink models of VUF (top) and AVUF (bottom).

ABB, 2014). One gateway can cover from several tens to several hundreds of micro-inverters. PV owners use them for monitoring and easy troubleshooting, manufacturers for more complicated troubleshooting and firmware updates. In (Gagrica et al. 2015a; Gagrica et al. 2015b) it was discussed how a gateway infrastructure could be exploited by DSO for wide area feed-in management of PV generation, only by software retrofit without addition of external hardware. However, trying software retrofit for the purpose of obtaining VUF would likely face implementation difficulties on the gateway hardware side. The symmetrical components sequence analyzer requires phase detection circuits and complex digital filtering (ed. Zobaa, 2013). Such features are found in power quality analyzers which are considerably more expensive devices. The proposed alternative is to try approximating the VUF with a less computationally and technically demanding method.

2.2 VUF Approximation Formula and Its Application

In (Pillay and Manyage, 2001) an overview of three VU definitions and their respective calculations was given: NEMA, IEEE, true definition (VUF). More importantly a new formula was proposed. This is a non-complex calculation formula that doesn't use phase angles but nevertheless approximates VUF by using only voltage magnitudes:

$$AVUF = \frac{82\sqrt{V_{ae}^2 + V_{be}^2 + V_{ce}^2}}{avg\ phase\ voltage} \quad (3)$$

where V_{ae}, V_{be} and V_{ce} are differences between phase (a, b, c) voltages and the average phase voltage. In (Pillay and Manyage, 2001) it was provided in its final form without derivation steps. The authors claimed that it can approximate to VUF better than other definitions even under highly unbalanced conditions, so it was selected as is for this study. The modelling is performed in Simulink for both VUF and AVUF. Models are presented in Figure 1. For modelling VUF the default Simulink three-phase sequence analyzer blocks are used, one for positive and one for negative voltage sequence at 50Hz. Unlike VUF that uses instantaneous voltage at input the voltages for AVUF had to be averaged to RMS at fundamental frequency otherwise the output will be sinusoidal and unsuitable for comparison with VUF.

2.3 Application Limitations

The technical application would be to aggregate micro-inverter output RMS voltages and execute AVUF calculation by the existing gateway microprocessor. Two limitations are currently foreseen. The data concentrators often use wireless communication (mesh radio) to aggregate data. Compared to micro-inverters their sampling rate is limited. For example in (ABB, 2014) the sampling rate is limited to 1 minute. Providing AVUF in 1 min interval might be sufficient for a LV monitoring application, but protection/control applications (like fault clearing or dynamic unbalance control) would be more demanding.

Secondly, the AVUF is only applicable in scenarios where all three single-phase PV plants connect to the same 3-phase supply point like in Figure 2 (left). In reality PV plants will more likely be scattered (Figure 2, right) due to randomness of process of consumers becoming prosumers. If the supply point where only Va is available is the AVUF acquisition point, the other two phase voltages are missing. The only available voltages are from the neighbouring systems on different phases and supply points (Vb' and Vc").

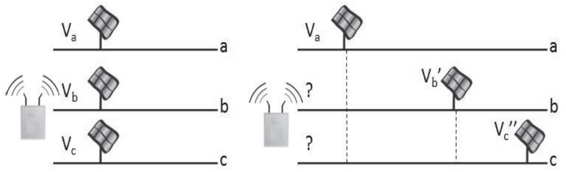

Figure 2: The limitations of aggregating voltages from a single supply point due to scattered single-phase PV.

In this case AVUF would have to be assisted with some kind of state estimation method, which is out of scope of this paper. Also the technical complexity of acquiring voltages Vb' and Vc'' would increase as they might be out of range of the data concentrator.

3 DISTRIBUTION NETWORK MODELING AND SIMULATION

3.1 Distribution Network Model

A 3-phase 4-wire residential feeder is built in Simulink (Figure 3). The feeder has 14 supply buses extending radially from a 400kVA delta-star transformer (400/230V, X/R ratio=3.2). The transformer tap is set to 1.05pu to compensate for voltage drop along the feeder. Each bus provides a three-phase supply where each phase connects one household. Total feeder length is 490m. There is a common neutral going through each bus with star grounding at transformer. The grounding, neutral and lines are modelled as RL branches. One PV and three load profiles with hourly resolution were created based on profiles in (Shahnia et al. 2011a). Peak values of three loads are 1, 1.8 and 4.6kW. They are randomly distributed along the feeder. The PV is modelled as a single-phase AC current with a phase-locked loop.

The PV rating is in the 1-4kW range and varies in accordance with Monte Carlo setup. Together, load and generation form the net power flow subsystems as shown in Figure 3 (Net flow 1, 2,...,14).

3.2 Monte Carlo Simulation

Monte Carlo is a convenient method for simulating stochastic nature of PV generation. In particular it was used in the unbalanced network analysis (Shahnia et al. 2011a). Similarly, in this study Monte Carlo is used to vary the PV ratings on all three phases. The limitation of having PV present on all three-phases simultaneously is taken into account. The PV in 1-4kW range is varied following a (0,1) uniform distribution. In Monte Carlo applications in power system studies the coefficient of variance is often used as a convergence criterion or a stopping rule (Wenyuan, 2005). In this study coefficient of variance $\eta(\overline{VUF})$ is used:

$$\eta(\overline{VUF}) = \sqrt{Var(\overline{VUF})}/\overline{VUF} \quad (4)$$

where Var(VUF)stands for variance. Simulink load flow is carried out for each iteration until $\eta(\overline{VUF})$) reaches an acceptable convergence.

4 SIMULATION RESULTS

The AVUF and VUF results are retrieved for the entire Monte Carlo set (1000 trials). Figure 4 shows the outcome of applying two different calculation methods. It can be seen that AVUF results are much more dispersed with a higher density of extreme values compared to VUF.

This is attributed to AVUF relying on voltage magnitudes only. Also it can be observed that AVUF almost always resolves in the same fashion being the

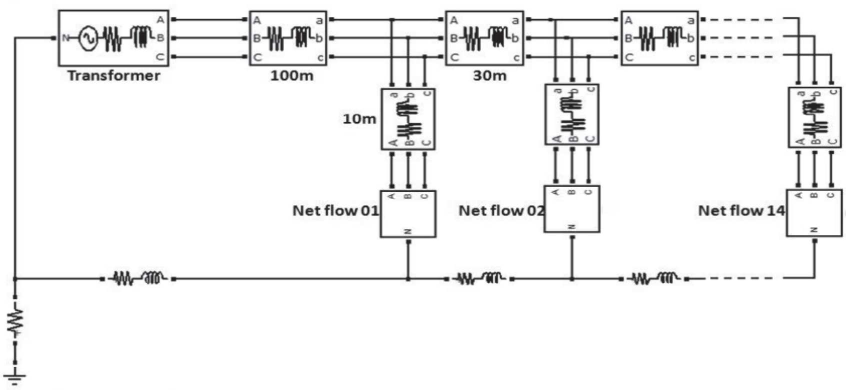

Figure 3: Simulink model of three-phase four-wire distribution network.

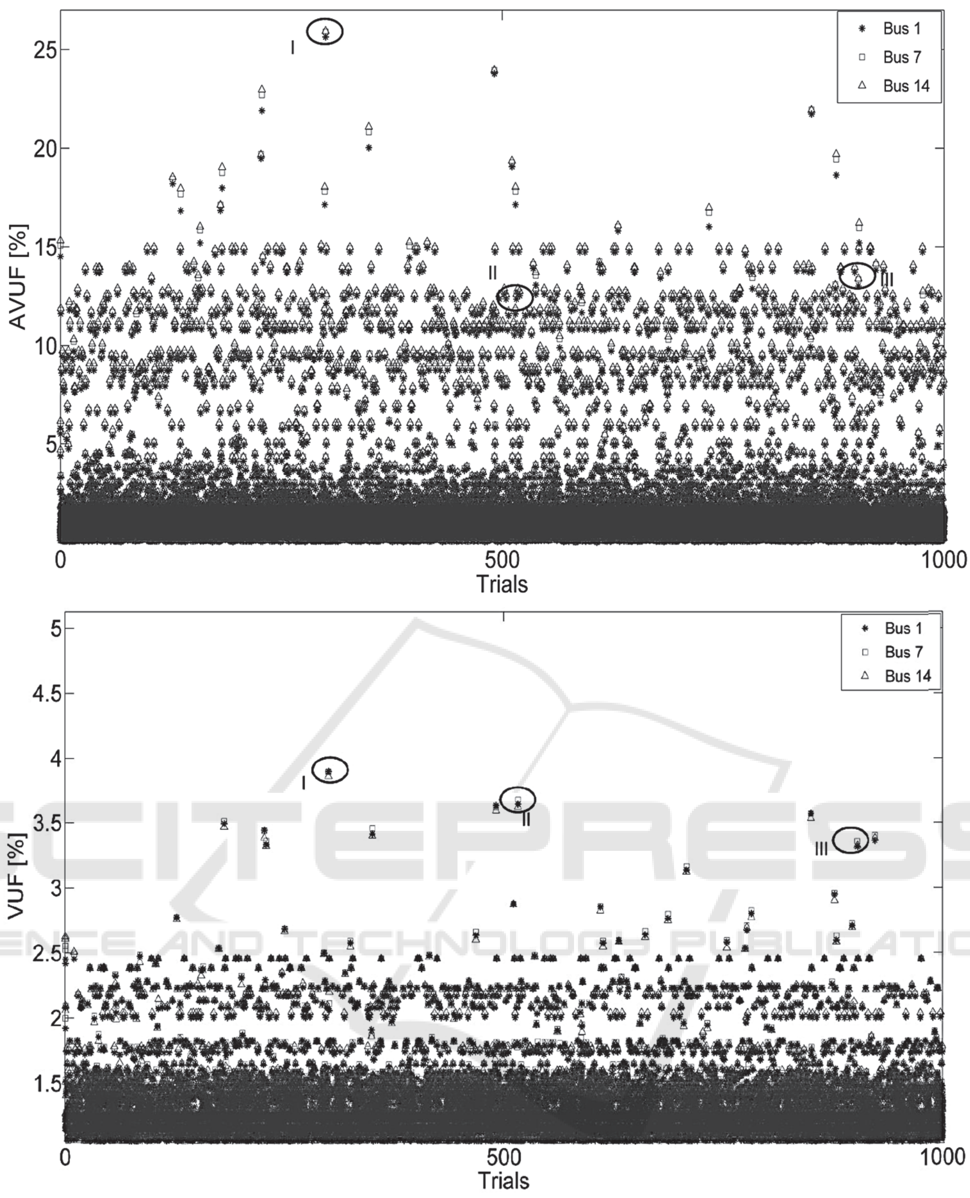

Figure 4: AVUF and VUF calculated in 1000 Monte Carlo trials.

highest at bus 14 and lowest at bus 1. Given how the load and generation is distributed this should not always be the case. The VUF at bus 7 will often have a slightly higher unbalance than bus 14 especially during the more extreme unbalance cases (over 2.5%), but around 2% the bus 14 will have a higher VUF. Therefore in addition to inflated magnitudes the AVUF will tend to give a voltage magnitude-biased result when the whole feeder is analyzed.

Three extreme VUF peaks and their corresponding AVUF peaks are circled in Figure 4 at different simulation times (I,II,III). To better understand when AVUF makes a good approximation and when it diverges into extreme peaks, the peaks are zoomed into and compared against three-phase voltage snapshot at the corresponding time (Figure 5). Daily three-phase voltage profiles are taken from bus 1 for each of the selected trials. It can be seen that the high AVUF peaks correspond to situations when the load flow resolves into simultaneous two-phase overvoltage. VUF will also experience peaks at this time, but AVUF, relying only on voltage magnitudes, is much more sensitive to overvoltage than VUF.

In Figure 6 are presented the *mean absolute*

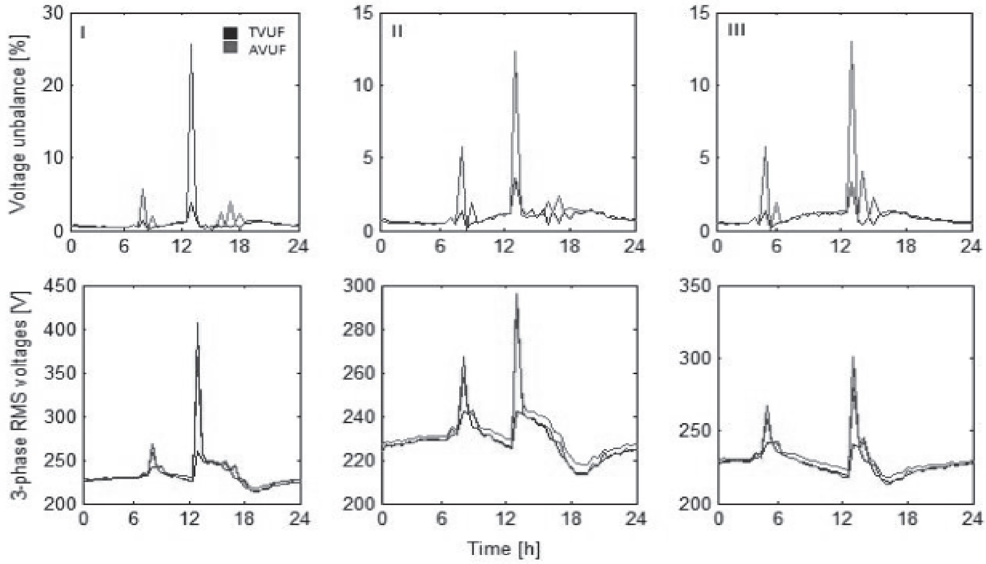

Figure 5: Zoomed-in extreme VU cases I, II, III with voltage profiles.

error (MAE) and *mean percentage error* (MPE) for buses 1-7-14 throughout the whole simulation. Also the converging process of Monte Carlo is presented in the bottom plot. While mean absolute error (MAE) does not exceed 0.4% the mean percentage error is much more sensitive to large peaks being included in the error averaging process. From the aspect of entire feeder both MAE and MPE increase with impedance. The $\eta(\overline{VUF})$ converges between 0.46-0.48. after 500 trials. So 500 trials could have been considered sufficient, although simulation was run for 1000 trials.

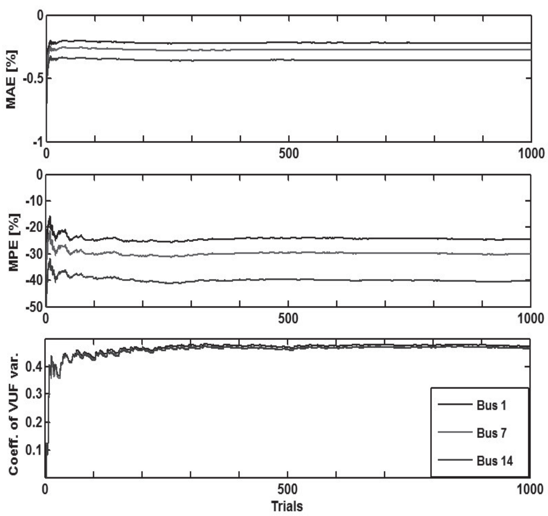

Figure 6: MAE, MPE and η(VUF) at buses 1, 7 and 14.

5 DISCUSSION AND CONCLUSION

The daily overvoltage occurrences due to excess PV generation under unbalanced conditions have caused at least two out of 24-hourly AVUF samples to give false readings compared to VUF. That makes about 8.3% of recorded AVUF profile. In a power quality analysis it would be possible to filter-out the false AVUF peaks by using their corresponding overvoltage events like it was presented in Figure 5, however it is likely that such large peaks would not have the chance to manifest in the first place. The tips of the analyzed voltage peaks reach almost 400V. If it is a steady-state voltage change (the subject of this study), its rise would be interrupted much sooner due to inverter overvoltage protection (at 253V) or even at a lower level if the inverter has voltage control capability (curtailment, reactive power). The AVUF preceding the trip or the curtailment event would then be smaller. Overvoltage could also occur in as a fast transient due to a fault (i.e. floating neutral might cause phase voltage to approach line voltage value), but again the inverter protection would act. It was shown that MAE and MPE increase with feeder impedance. This suggests that, if AVUF is to be applied, a calibration constant dependant on impedance would have to be determined and the calibration itself would have to be performed independently at each point of connection by using a suitable standard instrument (i.e. power analyzer).

Based on this study alone it is difficult to say with certainty that AVUF formula can reliably approximate VUF. But given the limitations that distribution operators face at LV level: lack of power quality monitoring capability, higher potential for VU and big presence of single-phase loads, it might be a worthwhile, intermediary monitoring solution that can add more value to the already deployed distributed generation. The proposed concept does not have to be contained only within the distributed generation context. Also home energy management systems consisting of data concentrators and smart single-phase appliances/meters could be considered for the same application.

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