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Studying unbalance and voltage conformity in residential distribution systems due to asymmetric photovoltaic connections

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Abstract. As, in Brazil, residential distribution systems present two nominal voltages of supply depending on the state you are (127 V or 220 V, phase-neutral), the solution for photovoltaic systems connection are different. In 127 V, majority of insertions make use of 220 V device, in a phase-to-phase connection. This action can lead to unbalanced distribution of power flow in many situations, with associated problems. This paper study the diversity of aleatory connections in a low voltage distribution system and its influence mainly in voltage and current unbalance but also voltage profile. By simulation, typical situations are explored and the main conclusion is that it is important for energy distributors to rearrange prosumers connections in order to achieve better voltage quality.

Key words. Distribution system, photovoltaic, unbalance, low voltage

1. Introduction

Existing residential distribution systems were mostly planned before the explosion of photovoltaic (PV) sources connection. The voltage profile, during project analysis, had considered a power flow from the Low Voltage (LV) side of a distribution transformer to houses.

With the commercial advent of photovoltaic generation for residences, in the beginning PVs were introduced in a random manner in time, and their effects were not observed immediately.

However, as long as the number of PV connections increase, this incorporation of a high number of connections can change a lot the power flow at low voltage distribution systems. This has a strong potential to cause overvoltage or voltage imbalance in the system due to reverse flux, promoting associated problems [1,2] and requiring actions to correct the unbalance [3,4,5].

Brazil has jumped from generating 806 kW on 01/01/2020 to 17.3 GW on 01/01/2025, only considering PV residential connections [6]. This big number of connections had changed a lot the power flow at low voltage distribution systems that incorporates a high number of PV, having a strong potential to cause voltage imbalance or overvoltage in the system due to reverse flux.

Brazil also presents a particular characteristic concerning rated voltages at secondary distribution systems, and it is that the nominal value is not the same in all states. Some states (13) have a supply line-to-line voltage (V_{LL}) of 380 V, while the others (15) use V_{LL} = 220 V. Due to economic reasons, therefore, majority of PV inverters employed in the 220 V grid are phase-to-phase connected using the single-phase inverters usually installed in a 380 V grid, in that the line to neutral voltage is V_{LN}=220V: both employ a two-terminal 220 V device. This phase-to-phase connection can promote different system behavior, seeing that many configurations are possible.

This paper realizes a simulation study exploring the voltage behavior along a seven-pole LV distribution system, in that PV sources are aleatory connected as time goes by. A 220 V three-phase grid is considered, what means that al PV inverters are single-phase units connected between line voltages.

2. System Description

In order to evaluate some aspects of power quality considering the atypical configuration of secondary distribution systems incorporating phase-to-phase PV sources, a general but realistic circuit is considered. Figure 1 is a stylized visualization of the distribution system.

There is a pole supporting a three-phase transformer, responsible to accommodate voltages of the primary distribution system to the secondary one. The transformer, besides to feed houses in its own pole, feeds six more poles in what several houses are connected.

Houses are aleatorily phase-to-phase connected, so that at each pole, no matter the type nor the number of connected houses, the total power load can be considered balanced.

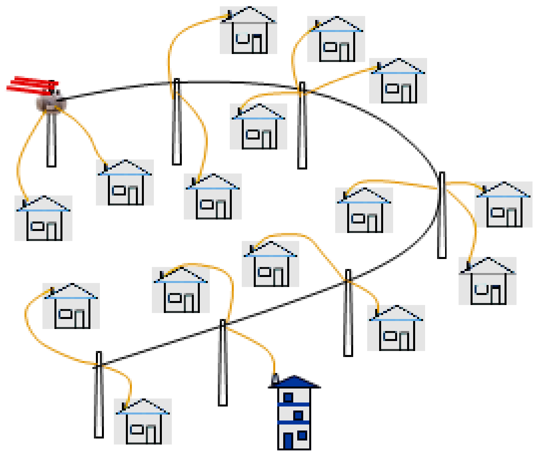


Fig. 1 – Stylized representation of the secondary distribution system to be considered.

In Figure 2 the electrical schematic of the configuration can be seen.

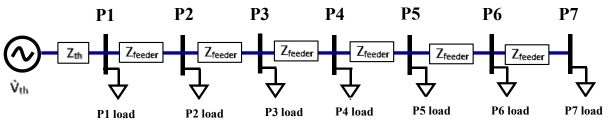


Fig. 2 - Electrical schematic of the configuration.

A PV system, without a Battery Energy Storage System (BESS), insert power into the grid only during the day, mainly between 9 am to 3 pm. In such interval, houses are typically consuming low power. In the equivalent circuit, the voltage V_{th} is the open-circuit voltage on the low voltage terminals of the transformer, and the impedance Z_{th} is the equivalent impedance of the system upstream the voltage V_{th}, but in the same low voltage terminals. The parameter values of the system, in the present analysis, are given in Table I.

Table I

V_{th} (phase to neutral)	127	V, rms
Z_{th}	0.005 + j0.002	ohms
Z_{feeder}	0.02 + j0.004	ohms
3Φ Load, P1 to P7	3	kW
	1	kvar

3. Contextualization

To illustrate the matter that is being considered, lets take a simple simulation comparing active and reactive power for each phase, absorbed from the grid, as well as respective power factors. Three situations are considered, and system data are those shown in Table I. In the first case, the low voltage distribution system feeds only the low demand loads. For the case two, a single 10 kW PV distributed generator is be connected at pole 4 between phase to neutral. It is the usual connection for a 220V line to neutral system in Brazil, but not for a 127V (rms) line to neutral. In this case, the last one, power source is phase to phase connected (220V rms), taking advantage of the same inverter used in three-phase 380V feeders.

Active and reactive powers for phases a, b, and c, delivered by the transformer, in each case, are exposed in Table II. And Fig. 3 displays the expected voltage and current waveforms, showing a balanced passive system with a power factor of 0.95 inductive, case 1.

Table II

Active and reactive power for different conditions

kW/kvar	Pa/Qa	Pb/Qb	Pc/Qc
Case 1	6.9/2.3	6.9/2.3	6.9/2.3
Case 2	-2.7/2.3	6.9/2.3	6.9/2.3
Case 3	1.9/5.1	1.9/-0.6	6.9/2.3
Case 4	-22/2.3	6.9/2.3	6.9/2.3
Case 5	-8/10.9	-8/-6.3	6.9/2.3
Case 6	-3/2.3	-3.1/2.3	-3/2.2

All cases will be explained along the text, but they are summarized in Table III.

Table III

Connections summary for the six cases

Case	PV connection and poles
Case 1	none
Case 2	v_a / pole 4
Case 3	v_{ab} / pole 4
Case 4	v_a / poles 2/4/7
Case 5	v_{ab} / poles 2/4/7
Case 6	v_{bc} (pole 2), v_{ab} (pole 4), / v_{ca} (pole 7)

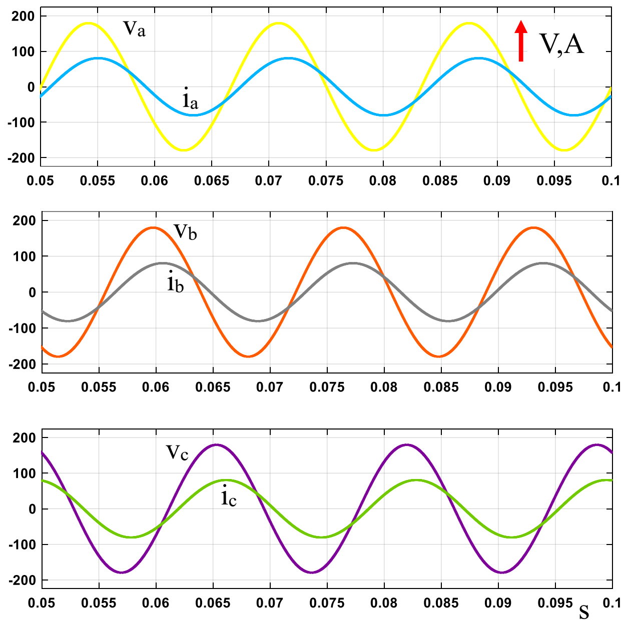


Fig. 3. Voltage and current waveforms entering P1 and feeding passive loads.

Under operation without PV insertion, the electrical results are as usual: the pole voltages decrease as far as the poles are from the transformer; and voltages and currents are totally balanced. As obvious, all phase voltages present the same value at each pole, as can be seen in Figure 4.

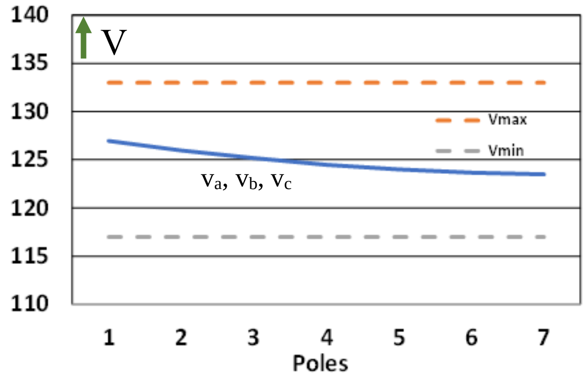
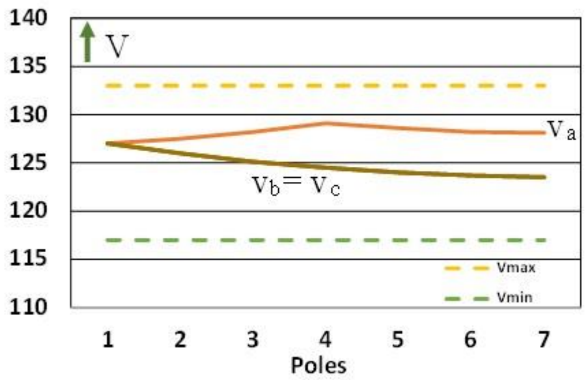


Figure 4 – Operation without PV: phase voltages are equal at each pole.

Next results consider a line to neutral connection of a 10kW PV at pole 4, only to phase a. As can be seen in table II, and as expected, a reverse active power flow occurs at phase a, and the other two phases follow equal. A different distribution of phase voltages on poles is obtained, as can be seen in Figure 5: 5.a - phase voltages, and 5.b - line voltages. As phase a voltage presents a better profile due to the PV inserted, line voltages ab and ca have its influence. Line voltage bc presents the worst result.



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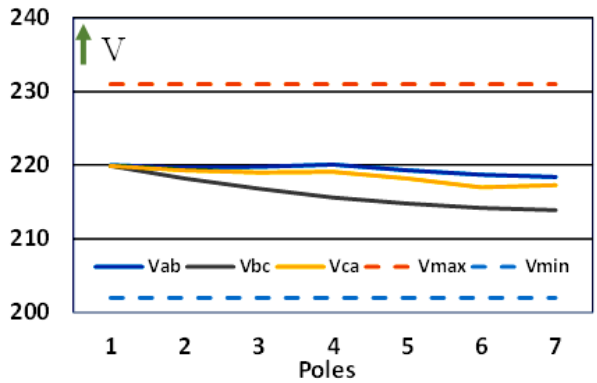


(b)

Figure 5 – Operation with a 10kW PV, phase a pole 4: a) Phase voltages (b and c are equal but phase a is different); b) Line voltages (v_{bc} does not have influence of phase a).

Figure 6 shows the three phases' voltages and currents. The phase a power factor is -0.76 while for phases b and c remains 0.95. It is clear that, connecting the PV to line-neutral, the unbalance occurs only due the phase containing the power insertion.

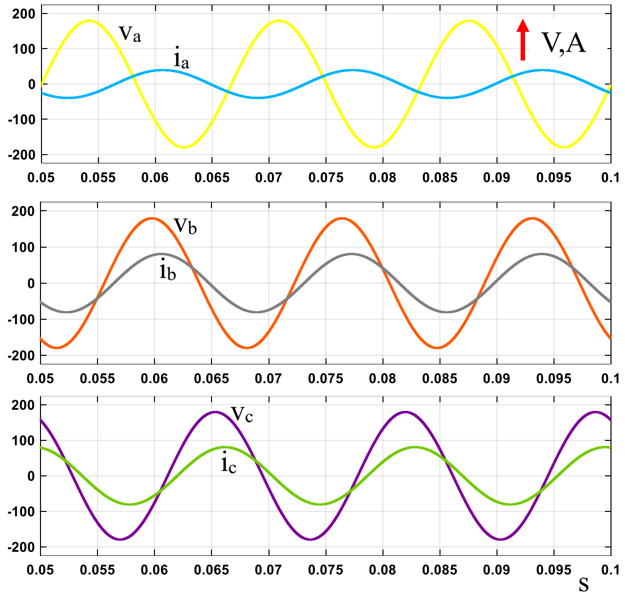


Figure 6 -Three phases' voltages and currents, connecting a 10 kW PV at pole 4, phase a.

The voltage unbalance at each pole is registered in Table IV. The unbalance was calculated using definition given by IEC 61000-4-30, as well as IEEE 1159. So, the unbalance VU is given by the percentage ratio between the negative sequence voltage, V^-, and the positive one, V^+, of the three-phase system at each pole.

Table IV
Voltage unbalance:

Pole (case)	1	2	3	4	5	6	7
% VU (2,3)	0.0	0.4	0.9	1.3	1.3	1.3	1.3
% VU (4)	0.1	1.3	2.1	2.9	3.3	3.7	4.0
% VU (5)	0.1	1.3	2.1	3.0	3.4	3.8	4.2
% VU (6)	0.0	0.0	0.4	0.8	1.1	1.4	1.8

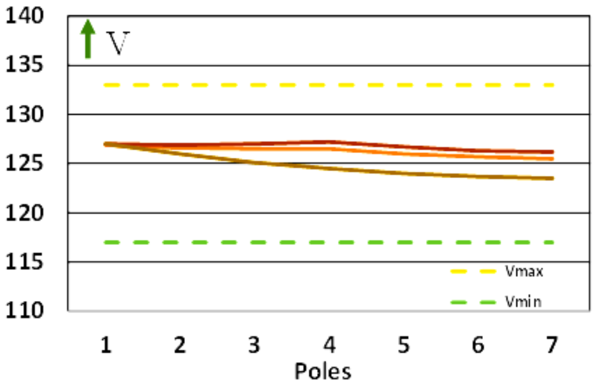
The current unbalance (IU) at the output of the secondary distribution transformer for all cases are presented in Table V.

Table V
Current unbalance

Case	IU (%)
Case 1	0
Case 2	73.8
Case 3	77.8
Case 4	270
Case 5	260
Case 6	1.5

To conclude the problem presentation, let's consider a phase-to-phase connection of the 10 kW PV system in pole 4, between phases a and b. For Rooftop solar panels installation companies and considering single-phase inverters connected line to line, it is not relevant the sequence of phases.

From values on Table II, and comparing to the anterior case, both a and b phases power flow from grid are reduced. It is expected a better phase voltage profile for both phases, whereas no changes in phase c. Rms phase voltage values are shown in Figure 7 (a), corroborating previous analysis. Line to line voltages are shown in Figure 7 (b). Waveforms of voltages and currents are presented in Figure 8.



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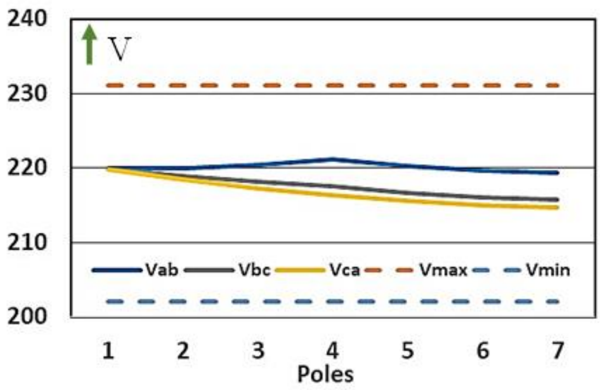


(b)

Figure 7 – Operation with a 10kW PV, phases ab pole 4: a) Phase voltages (a and b are very near values, and but phase c is different); b) Line voltages (v_{ab} is almost constant).

After obtain the voltage unbalance for case 2 and case 3 (case 1 is naturally balanced), it can be noticed that, although phase voltages and line voltages be different for both cases, same unbalance result is obtained, as detailed in Table IV.

4. Expanding PV Insertion - Results

Several combinations of PV insertion were simulated in order to observe unbalance and voltage profile behavior. The basic topology is the one presented in section 2. A few cases are considered, since a large set of possibilities is present.

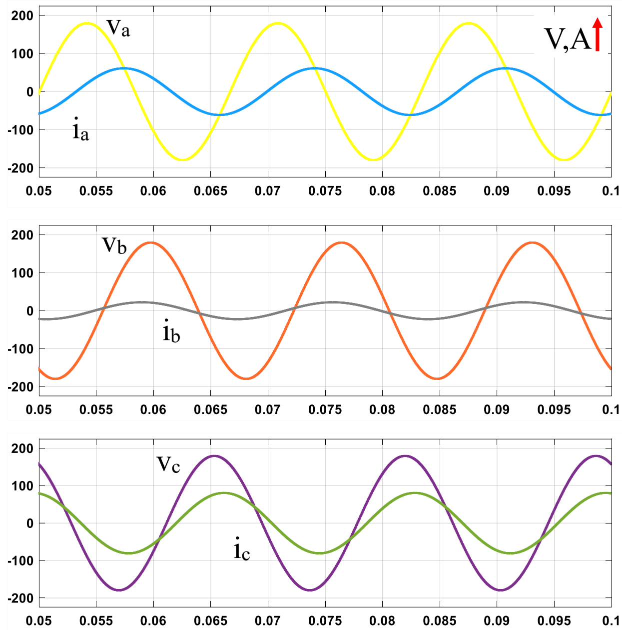
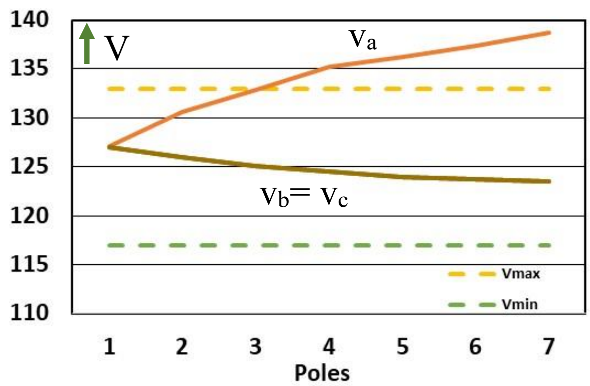


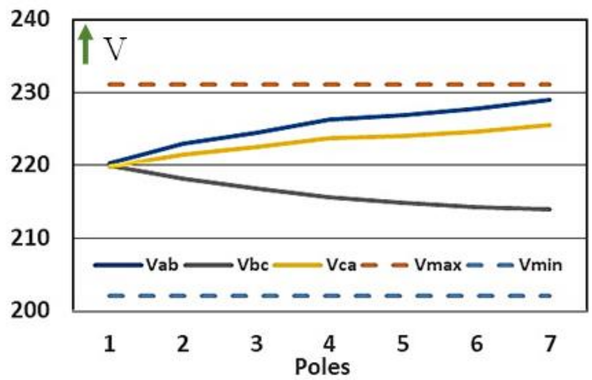
Figure 8 -Three phases' voltages and currents, connecting a 10 kW PV at pole 4, phase ab – case 3.

To restrict the study, let's consider the insertion of the typically used residential 10 kW PV source in poles 2, 4 and 7. The first analysis considers all PV connected between phase a and ground – case 4.

The voltage unbalance is inserted in Table IV, whereas phase voltages (rms) are presented in Figure 9.



(a)



(b)

Figure 9 – Operation with a 10kW PV, phase a, poles 2,4,7: a) Phase voltages; b) Line voltages.

Waveforms of voltages and currents, case 4, are presented in Figure 10.

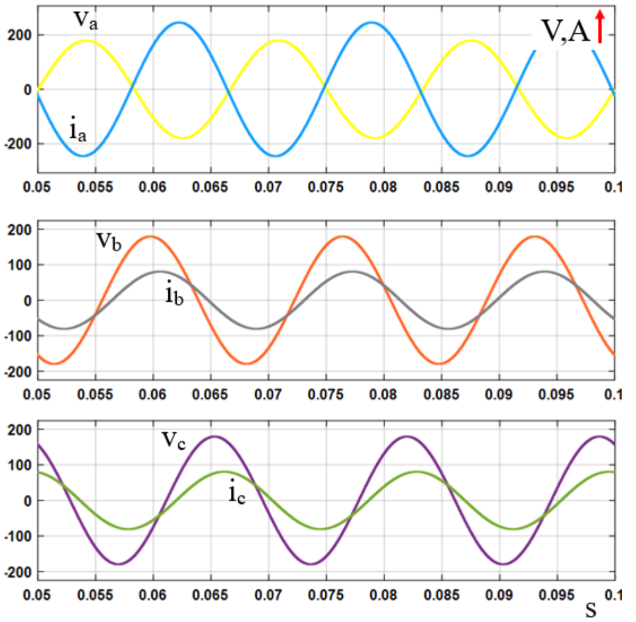
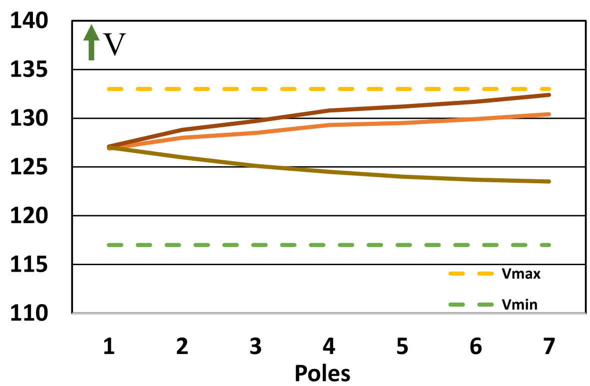
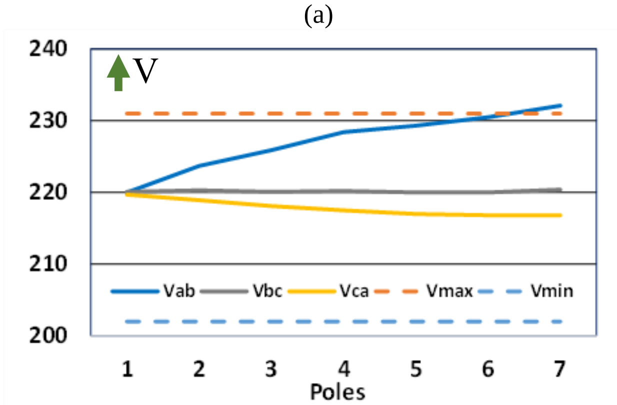


Figure 10 -Three phases' voltages and currents, connecting a 10kW PV at poles 2,4,7 phase a.

The case 5 is the line-to-line connection of PV sources to v_{ab}, poles 2, 4 and 7. Figure 11 contains the phase voltage values (11.a), and line voltage values (11.b). The voltage unbalance is included in Table IV.



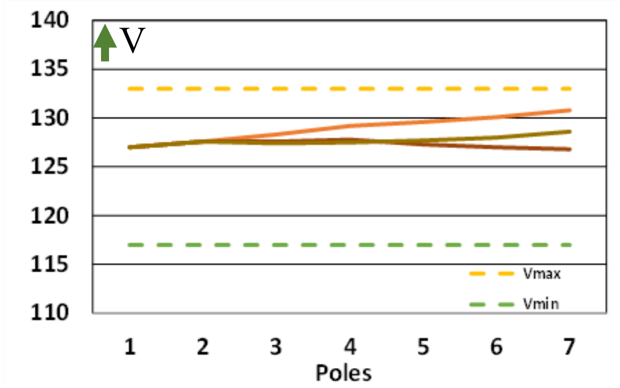
(a)



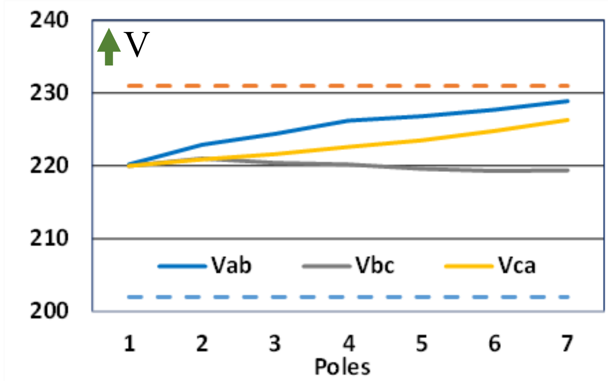
(b)

Figure 11 – Operation with a 10kW PV, line-to-line connection ab, poles 2,4,7: a) Phase voltages; b) Line voltages.

The next case, case 6, the pole 2 PV source is v_{bc} connected, the PV source at pole 4 is v_{ab} connected, while the pole 7 PV source is v_{ca} connected. RMS values of phase and line voltages are displayed in Figure 12, and waveforms of voltages and currents are presented in Figure 13.



(a)



(b)

Figure 12 – Operation with a 10kW PV, line-to-line connection bc (pole 2), ab (pole 4), and ca (pole 7): a) Phase voltages; b) Line voltages.

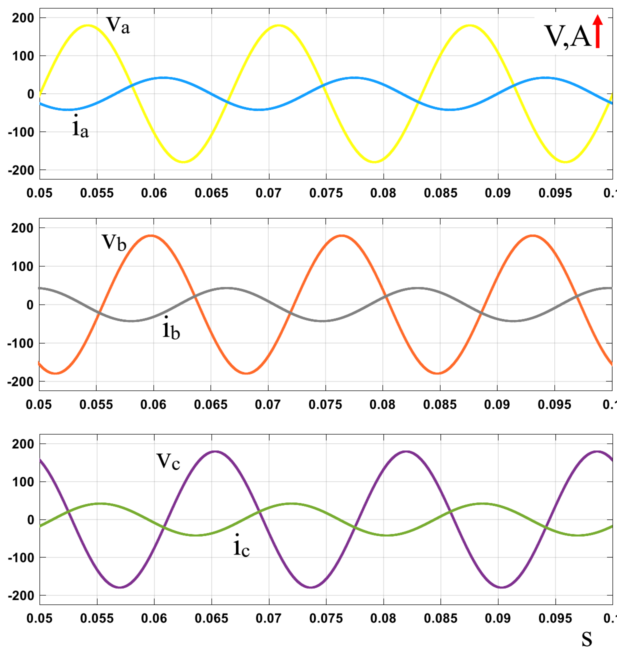


Figure 13 -Three phases' voltages and currents, connecting a 10kW PV to v_{bc} (pole 2), v_{ab} (pole 4), and v_{ca} (pole 7).

Active and reactive power for cases 4, 5 and 6 were inserted in Table II.

5. Comments and Conclusion

The power flow for each phase and cases is exposed in Table II. There is no novelty: as much as the PV sources are connected to the same phase or line, more reverse flux flows over the connected phase or line. What is relevant is that the reactive power varies significantly.

Analysing the voltage unbalance available I table IV, it can be observed that how many power sources are connected to the same phase, more voltage unbalance will occur – and this is expected. This also is reflected, and stronger, in the current unbalance, as can be saw in Table V. As the connection of PVs in a residential distribution system is not equilibrated, phase currents result unbalanced, with the possibility of bring consequences for the available voltage as well as bad equipment operation

Finally, studying the rms phase and line voltages for each case incorporating PV, it is noticeable that in some situations, in that reverse flux is present, phase voltages are well inside legal range of standards – but line voltages are outside the regulation. Or vice-versa. This indicates that both voltages need to be measured.

Concluding, comparing results it is clear that energy distributors need to put attention to rearrange prosumers connections in order to achieve better voltage quality. The option to connect phase-to-phase PV inverters in a Brazilian 220 V three-phase grid is not a problem if from the connection results balanced currents.

Acknowledgement

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