# 3-PHASE LV NETWORK LOAD BALANCING: COMPARING PASSIVE AND ACTIVE SOLUTIONS

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## Abstract

The present paper is part of a joint experiment including installation of dozens of passive balancers and development of an active balancer prototype in 2024 and 2025 by Réséda and Ores, two major european regional DSOs. It compares active and passive solutions to mitigate voltage drops on low voltage three phase grids. Simulations and on site measurements are used to analyse power flows, voltage quality and line losses on 4 grids. While active balancers show several advantages in terms of balancing performance, low loss, ease of installation, they have yet to confirm that they can surpass passive units for long term reliability and TCO.

## 1. Introduction

Distributed energy generation and electric vehicle charging increase loads on low voltage networks and pose new challenges to maintain voltage quality along weak LV lines. Current balancing over the 3 phases is known to have a major effect to keep voltage in the range allowed by the standards in 3 phase 4 wire networks, where a single phase load creates 6 times more voltage drop than a balanced three phase one of identical total power. The paper compares passive and active load balancing using parallel mounted devices connected near the ends of the lines, where highest voltage fluctuations occur.

### *1.1 Grid unbalance and passive solution*

Passive balancers generally use a zig-zag transformers connected in parallel to the grid. The transformers create a low impedance zero sequence path that unloads the line neutral wire and improves current balancing. The unit is connected away from the feeder, and its sizing is determined by the maximum current that may flow through the transformer given the line and unit relative impedances. Voltage fluctuations caused by the line resistance for single phase consumption or generation are typically reduced by a factor between 2 and 3.

### *1.2 Active balancing*

Active balancing uses 3 phase inverters to transfer power from the unloaded phases to the loaded phases via a common DC bus. Most active filters on the market require the installation of current sensors to measure the 3 phase loads and set their reference currents accordingly, which makes them less suitable on LV grids where loads are distributed along the lines. A SiC (Silicium Carbide) based shunt filter was designed, using solely 3 phase voltage measurements at the connection point. The modulation of power switches to control the currents flow has been validated on a scale model, then on a 400V unit.

### *1.3 Unbalance Voltage definition*

Voltage unbalance in 3 phase LV grids mostly results from differential line voltage drops due to unbalanced currents [1]. Single phase loads and power generation are their main contributors. There are several voltage unbalance definitions leading to various results [4]. The IEC formulation uses the ratio of invert to direct sequence and is relevant for 3 phase motors. In residential areas, the voltage quality affecting the users is mostly influenced by the phase to neutral voltages. As a result, the IEEE definition of phase voltage unbalance rate (PVUR) seem more appropriate:

$$\%\,\mathrm{PVUR} = \frac{\text{max voltage deviation from the avg phase voltage}}{\text{avg phase voltage}}$$

*Fig. 1: Phase Voltage Unbalance Rate definition*

It should be noted that this choice is important when assessing zigzag transformers, as passive balancers only alter the zero sequence. As a result, they have negligible effect on the unbalance as calculated per IEC definition.

### *1.4 Modeling of grids and simulations.*

Four different grid cases were used in the present study. They all have aerial bundle lines with the following impedance: Aluminium (Al) cable: R=31.1 Ohm/km.mm² / X=0.08 Ohm/km. Almelec (Am) cable: R=34 Ohm/km.mm² / X=0.08 Ohm/km. HV feeding line is considered perfectly stiff and balanced. 3x400V transformers tap is +2.5%. The location of balancer has the following symbol:

Case 1: 800m 3Al70Am54 line connected to a 160kVA 20kV/3x400V+N transformer and with a single phase 5Ohm resistive load at the end of the line.

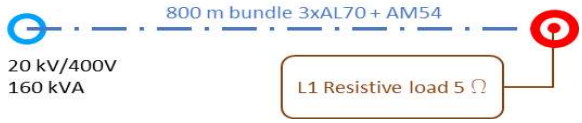
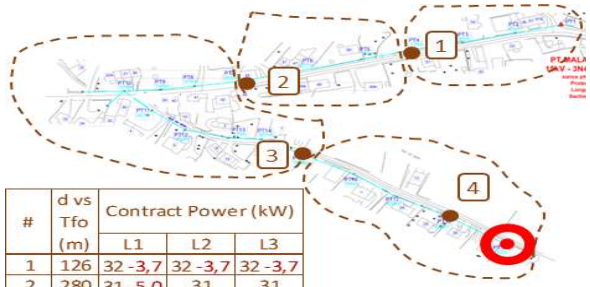



*Fig. 2: Grid Case 1 layout*

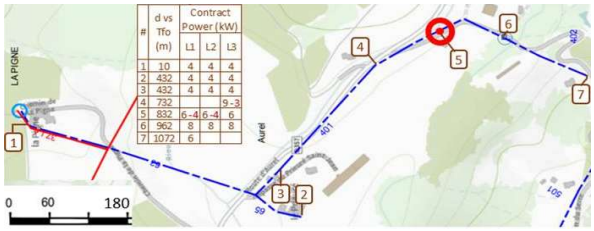
Case 2: Izier (BE). 742m 4Al70 bundled line connected to a 100kVA 15kV/3x400V+N transformer, with 40 residential customers along the line.




| # | d vs Tfo (m) | Contract Power (kW) L1 | L2 | L3 |
|---|---|---|---|---|
| 1 | 126 | 32 -3,7 | 32 -3,7 | 32 -3,7 |
| 2 | 280 | 31 -5,0 | 31 | 31 |
| 3 | 507 | 83 -4,3 | 83 -4,3 | 83 -4,3 |
| 4 | 690 | 22 -8,5 | 22 -8,5 | 22 -8,5 |
| | 742 | Equi8-Passive Balancer | | |

*Fig. 3: Grid Case 2 map*

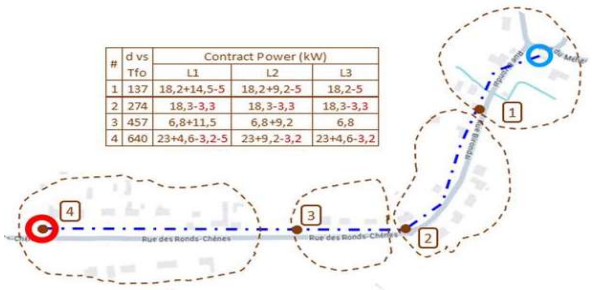
Case 3: Aurel (FR) 1072m 3Al70Am54 bundled line from a 100kVA 20kV/3x400V+N transformer, with 7 residential customers along the line.




| # | d vs Tfo (m) | Contract Power (kW) L1 | L2 | L3 |
|---|---|---|---|---|
| 1 | 10 | 4 | 4 | 4 |
| 2 | 432 | 4 | 4 | 4 |
| 3 | 432 | 4 | 4 | 4 |
| 4 | 732 | | | 9-3 |
| 5 | 832 | 6-4 | 6-4 | 6 |
| 6 | 962 | 8 | 8 | 8 |
| 7 | 1072 | 6 | | |

*Fig. 4: Grid Case 3 layout*

Case 4: Birondai (BE) 3Al95 bundled line connected to a 100kVA 15kV/3x230V transformer, with 13 residential customers on the first line section, and 15 on the last one.




| # | d vs Tfo | Contract Power (kW) L1 | L2 | L3 |
|---|---|---|---|---|
| 1 | 137 | 18,2+14,5-5 | 18,2+9,2-5 | 18,2-5 |
| 2 | 274 | 18,3-3,3 | 18,3-3,3 | 18,3-3,3 |
| 3 | 457 | 6,8+11,5 | 6,8+9,2 | 6,8 |
| 4 | 640 | 23+4,6-3,2-5 | 23+9,2-3,2 | 23+4,6-3,2 |

*Fig. 5: Grid Case 4 map*

### *1.5 Grounding*

As grounding impedance vary with time and climatic conditions and is hard to measure precisely [3], we assume that grounding at the feeder is achieved with X=2 Ohms resistance, 10 Ohms in the middle and at the end of the line. Carson-Clem formula was used to determine the share of return current flowing through the neutral wire vs within earth. The following table compares unbalance rate when with or without grid grounding for case 1 feeder:

Table 1: Case1 influence of grounding on unbalance:

| | Case 1 with grounding | Case 1 without grounding |
|---|---|---|
| PVUR (%) | 13.41 % | 13.77 % |
| Zero sequ. voltage | 25.0 V | 25.8 V |

The zero sequence voltage at the end of the line is referred to the line neutral voltage. Grounding hardly affects voltage unbalance even for weak grids and unusually good earthing of LV lines. This is in phase with other works and measurements [14]. Consequently, LV lines earthing will be neglected in this study. Grounding still affects the neutral wire potential in reference to earth and impacts safety.

## 2. Methodology

The following devices were used to model and measure the performance of balancing and calculate the losses of passive and active solutions.

### *2.1 Equi8 passive balancer*

The Equi8 consists in 3 single phase transformers coupled in zig-zag and directly connected with 4 wires to the end of the weak line where voltage variations are the greatest. Safety features include fuse protection and thermal disconnection with automatic re-coupling. The nominal current handled by each phase of the unit is 15amps and 20amps up to 3 hours. Several units can be parallel mounted to increase handled currents.

### *2.2 Active balancer prototype*

A four wire active shunt filter, also sometimes referred to as D-Statcom, was designed using 3 phase SiC modules (IM828 Infineon Tech.), split capacitors and dedicated control (STM32F4xx STMicroelectronics). 30-50kHz switching frequency is used to reduce filter inductor requirements to less than 0.5mH and improve dynamics. The operation is based solely on line 3 phase voltage measurements.

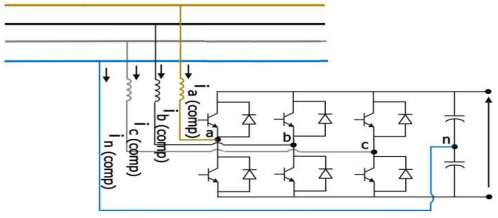



*Fig. 6: Active balancer schematic*

In contrast with most available D-Statcoms, grid voltage control is achieved by transferring active power form one phase to another rather than affecting reactive power flows. The switching patterns were optimised to reduce losses, leading to 97% efficiency above 30% loading. The maximum current is limited to 20Amps per phase and 40Amps in neutral wire, allowing up to 4600W of active power transfer between phases. Such balancing could be achieved using existing hardware such as three phase grid tie inverters, but there are currently several technical and non technical hints, along with no incentive for manufacturer to include this function.

*2.3 Roseau Load Flow*

Roseau Load Flow is a multi-phase load flow solver for unbalanced power flow analysis that offers four-wire multi-phase modelling with no Kron reduction, no transformation, no assumption on the network topology and no implicit earthing, but support for flexible, voltage-dependent, loads directly in the Newton algorithm for better convergence. Roseau Load Flow was used for all simulations in this paper.

*2.4 Onsite validation*

Measurements using customers smart meters and power analyzers (PQ box 50 – A. Eberle and MV2-Adecwatts) were made on grid cases 2 and 3 to confirm the performance of active and passive balancer in real conditions of use.

## 3 Results

*3.1 Simulation Case 1:*

3 simulations were computed for grid Case 1. The results show a reduction by a factor 3 of PVUR. Both active and passive balancing manage to make the phase voltages conform with EN50160.

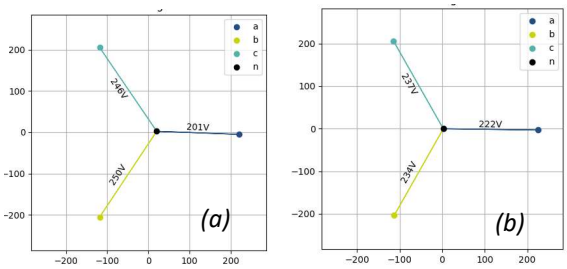



*Fig. 7: (a) Case1, Initial (b) active balancer phasor*

*Table 2: Case 1 results*

| Case 1 | Initial | Passive Equi8 | Active 4600W |
|---|---|---|---|
| PVUR | 13.8 % | 4,12% | 4,7 % |
| Unbalance IEC | 2.3 % | 2.6 % | 0.8 % |
| Va (V) | 201,2 | 221,8 | 221,3 |
| Vb (V) | 249,6 | 233,5 | 237,1 |
| Vc (V) | 245,5 | 237,0 | 235,6 |
| Line losses (W) | 1415 | 505 | 360 |
| Balancer losses | N/A | 141 | 138 |

Line losses are divided by 3 using Equi8 and by 4 with the active balancer of 4600W rating. Near perfecting balancing would require 7000W of redistributed power (i.e. 2/3 of the single phase consumed power).

*Table 3: Case 1 – 7000W active balancer*

| Case 1 | Initial | Active 7000W |
|---|---|---|
| PVUR | 13.8 % | 0.95 % |
| Line losses (W) | 1415 | 268 |
| Balancer losses (W) | N/A | 210 |

*3.2 Onsite validation Case 2:*

15 min Smart-meters data were used to compare PVUR (max and average per day) before and after installing the passive balancer. The network loading is represented in the upper curve as the average voltage drop between feeder and line end. Two comparable periods of 65 days with and without balancer allowed calculation of average PVUR and losses in both cases.

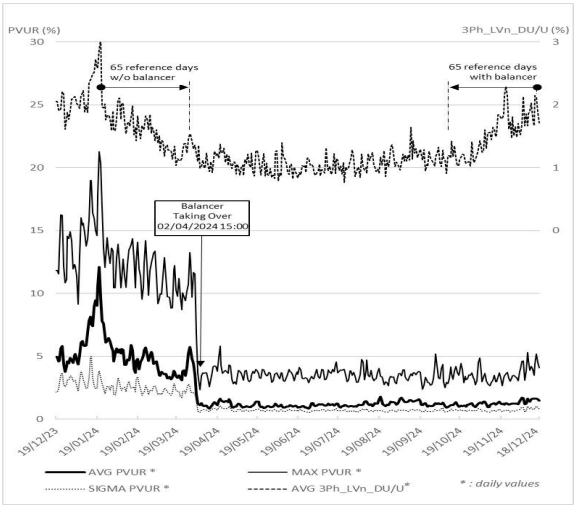



*Fig. 8: Case 2: Voltage variation and unbalance w/o and w. the passive balancer.*

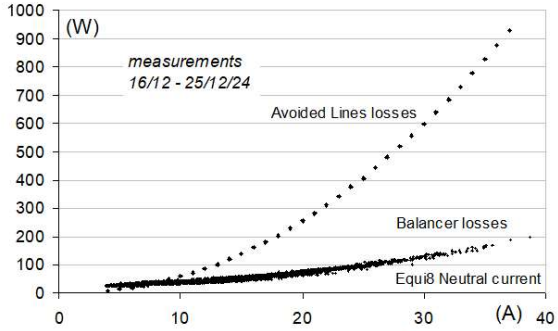



*Fig. 9: balancer losses and avoided line losses vs balancer neutral current*

In order to compare the effect of the passive balancer with the network initial state, the study focused on periods with highest loads. As shown on figure 8, the highest PVURs occur in winters for this case. The load of the network was assessed by calculating the voltage variation between the transformer and the end of the LV line for the average of the 3 phases:

$$\%\,3Ph_LVn_dU/U = \frac{\sum_{Ph=1}^{3}\left|\left(U_{end_i} - U_{transfo_i}\right)\right|}{3 * avg\left(U_{transfo_{1\ to\ 3}}\right)}$$

*Fig. 10: Network load estimator definition*

Data before January 24th show higher PVURs due to a 10 days long cold temperatures (-3°c in average) and was discarded. The two 65 day long reference periods without and then with passive balancer have similar network loads (3Ph_LVn_dU/U=1.6%). Table 3 show that average and max. PVUR is divided by factor 2.7 to 3.2 with the passive balancer. Hence the max. PVUR (22%) that occurred on January 21st would have been mitigated to approx 8% with the passive balancer.

Table 4: Case 2 Voltage variation and unbalance

| Case 2 | Initial | Equi8 | Improvement |
|---|---|---|---|
| PVUR(%) avg | 11.52 % | 3.58 % | Divided by 3.2 |
| PVUR(%) max | 16.48 % | 6.02 % | Divided by 2.7 |

The measurements confirm that PVUR is 3 times lower with passive balancing in similar grid load conditions. Total lines losses for this feeder were reconstructed using the Smart-meters 15 minutes time step data and show that the Equi8 yields approx. 0.5MWh savings per year (LV line and transformer losses reduced from 1.2% to 1%), including demand resolution correction factor as per [11]. Accurate evaluation of lines and transformer losses mitigation in the general case by balancers is a non trivial task that would require further work.

*3.3 Simulation Case 3:*

Loads on that network were modelled as pure resistances and estimated so as to obtain similar end line voltages as the ones measured during peak load with highest unbalance.

*Table 5: Case 3 results*

| Case 1 | Initial | Passive balancer | Active (4600VA) |
|---|---|---|---|
| PVUR (%) | 12.4 % | 4,74 % | 4.12 % |
| Va (V) | 199.0 | 214.6 | 218.0 |
| Vb (V) | 241.3 | 227.9 | 226.7 |
| Vc (V) | 234.4 | 229.1 | 228.0 |
| Line losses (W) | 1798 | 1287 | 1139 |
| Balancer losses | N/A | 100 | 138 |

*3.4 Measurements Case 3:*

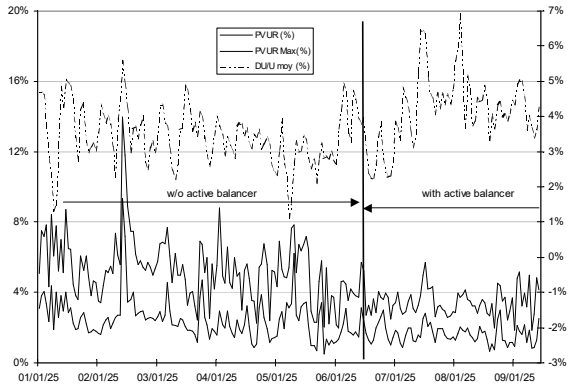



*Fig. 11: Case 3: PVUR at #7 before and after installation of the active balancer location #5*

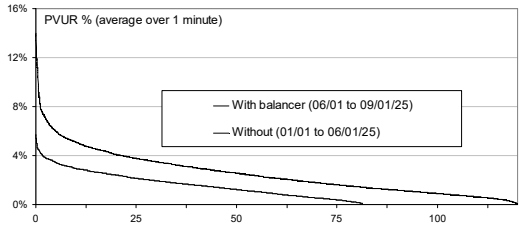



*Fig. 12: PVUR improvement on case 3*

The active balancer could only be installed on location #5, and could have performed better if connected near the line end. It nevertheless manages to improve voltage quality by a factor of more than 2 in the peak cases of PVUR. This is comparable to a grid reinforcement of doubling conductors sections, (including neutral wire which is rarely the case as many bundled wire have a smaller neutral conductor).

*3.5 Simulation Case 4:*

3x230V grids have their loads connected between 2 phases, so passive balancers action on zero sequence has no impact, and active balancing requires more current and leads to less significant improvements:

*Table 6: Case 4 results*

| Case 1 | Initial | Active 4600W | Active 7000W |
|---|---|---|---|
| PVUR (%) | 5.39 % | 2.21 % | 0.63 % |
| Va (V) | 199.8 | 206.3 | 209.3 |
| Vb (V) | 216.1 | 213.4 | 211.9 |
| Vc (V) | 217.8 | 213.1 | 210.7 |
| Line losses (W) | 7032 | 6671 | 6680 |
| Balancer losses | N/A | 138 | 210 |

A dedicated version of active balancer is required for 3x230V grids as voltages are lower and currents needs to be higher to transfer the same amount of power, namely 35Amps instead of 20Amps per phase leg for

the 4600W version of active filter. Nevertheless, higher power (7000 Watts) active balancing can divide max PVUR by 9 and achieves EN50160 compliance as indicated in table 6.

## 4 Conclusion

Passive and active balancing solutions are compared in 4 cases of LV networks with long lines and unbalance conditions up to 16% as per IEEE definition. Both solutions could solve all cases regarding EN60160 phase-neutral voltages. Active balancer outperforms Equi8 passive solution when its transfer power capacity from one phase to the other exceeds 5kW. Higher power rating could solve cases with still more unbalance and is required for 3 phase grids without neutral wire. The active balancer prototype is still at development stage and has yet to confirm its long term reliability on public grids, but seem an attractive solution to increase voltage quality without major investment, and remains the only solution for lines without neutral. Furthermore, grid lines losses experience non marginal reductions using balancers, that may partially finance their installation.

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