3-PHASE LOW VOLTAGE NETWORK LOAD BALANCER : A COST EFFECTIVE SOLUTION TO LINE VOLTAGE VARIATIONS

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ABSTRACT

A low voltage network load balancer was designed and homologated for use on the French public grid in 2009. This paper analyses 5 years of operation of 60 devices installed between 2010 and 2014. In 95% of the cases voltage variations were reduced from an average 16% to the standard limits of +/-10%. The installation cost of the balancers represented a mere 6.4% of the planned reinforcement budget.

INTRODUCTION

The project started in 2005 in Burgundy and aimed at investigating voltage quality issues and cost effective alternatives to line reinforcements. Detailed monitoring in the dwellings connected along 45 long and impedant LV rural lines were carried out. For each of these, power and voltages were recorded at 1 minute interval during 2 weeks. This study showed that single phase loads causing LV network imbalance was by far the largest contributor to voltage variations.

Even when load balancing was relatively properly achieved in theory, the actual current balance in real time was limited due to the low dwelling count. Improving balancing by changing a few homes supply from single phase to 3 phases proved rather effective but quite intruding and expensive.

A fully passive LV network load balancer was then developed to achieve a higher degree of current balancing among the 3 phases and reduce neutral currents, in the attempt to mitigate voltage variations at low cost and with quick implementation possibilities.

LV NETWORK LOAD BALANCER

Single phase loads create 6 times more voltage variations than 3 phase balanced loads for the same transited power on 3-phase 4-wire networks. Firstly 3 times, since the power is split amongst 3 phase wires, and secondly 2 times since perfectly balanced currents do cancel out in the neutral cable while it does not for single phase loads. And this can even be worse in the widespread case where neutral wire impedance is higher than that of phase wires. Proper balancing of the lines requires every single large power appliance switching at the very same time on the 3 phases, which is far from the real life experience in low density areas.

Optimizing load balancing in the 3 phase supplied dwellings and of all dwellings on the network is effective because it limits the maximum currents drawn per phase. But in order to achieve the full capacity of the line, a step further needs to be taken, which can be achieved by parallel mounting a load balancer. The idea is not new, but as a well sized and cost effective unit was not readily available at that time, the project team decided to develop one.

How the network load balancer works

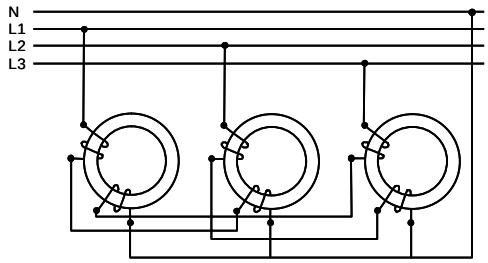


Fig. 1: 3 phase zigzag load balancer

3 zigzag coupled 1:1 transformers are connected to the 3 phase wires (L1, L2, L3) and create a neutral point connected directly to the relatively high impedance line neutral wire (N).

As the impedance of the transformers is lower than the line itself, it creates a low impedance zero sequence path that unloads the line neutral wire and improves phase current balancing.

Such devices are also known and sometimes used to mitigate 3rd harmonic based currents in neutral wires. In the present project, this was not of primary importance: monitoring data showed that the highest voltage variations occurred upon power consumption peaks, when mostly high power resistive loads were on (electric heaters, boilers, ovens...). But with the growing number of inverter fed heat pumps, induction cooking plates and other 3rd harmonic generators, the load balancer may well provide further advantage in the future.

As can be seen from the Fresnel diagram example (Fig. 2), the voltage variations are reduced by a factor 2.4. This only applies to the variations caused by the line induced voltage drops, but still makes it a potentially viable solution even against severe voltage quality alterations.

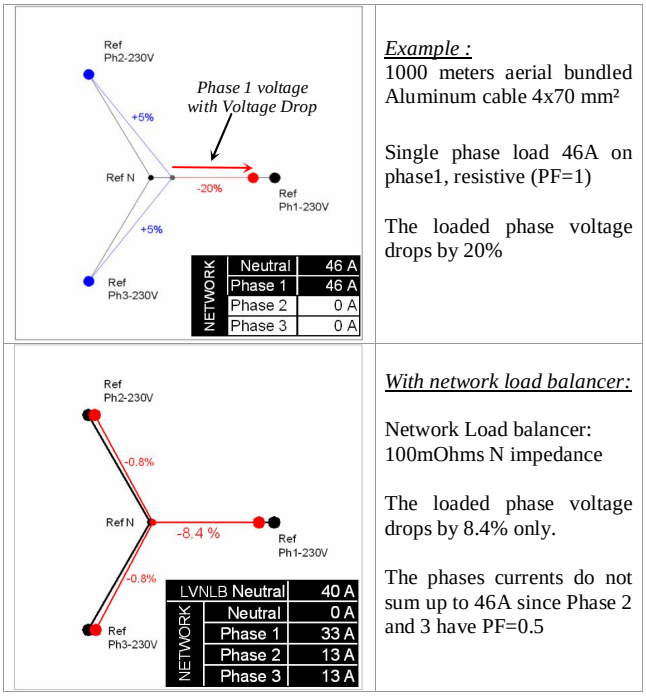


Fig. 2: Fresnel diagram : effect on voltage of a distributed load

The improvement factor does not change much, as long as the unit neutral output impedance remains low compared to the line neutral wire. This factor ranges from around 2 to 3, higher values occur when the neutral wire impedance is higher than that of the phases.

The impact of the balancer is guarantied as long as its neutral current is kept below the zigzag transformers nominal capacities.

Installation

The load balancer is connected in parallel with the network, at a point where voltage variations are greatest, away from the LV feeder. Several units can be installed at the very same point or possibly at different locations when the line splits to supply remote dwellings.

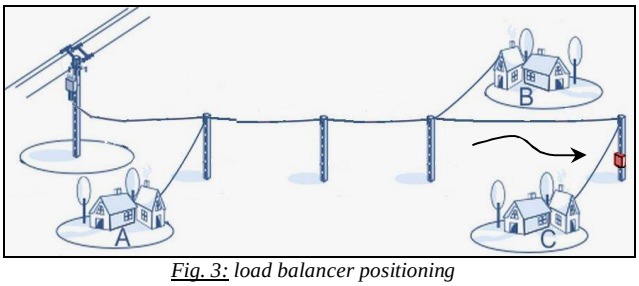


Fig. 3: load balancer positioning

Load balancer implementation

A unit with 45A nominal neutral current was designed and then manufactured by CME Transformateurs. Low loss toroidal transformers were used to reduce iron and copper losses and ensure that the avoided Joule losses in the lines outperform the balancer losses. The net energy balance of the unit is always positive.

Fig 4: internal view - 3 toroidal transformers and thermal switch (left) and pole mounted (right)

The size and enclosure allow manual installation without lifting device. Pole mounts have been designed to fit most cases. The load balancer sustains 45A for continuous use in 30°C external temperature. Peak currents up to 5In can be handled during limited times.

The unit has no electronic on board and components were oversized in order to provide a long term solution in phase with feeder and lines lifetimes. A mechanical thermal switch controls the internal enclosure temperatures, and temporarily disconnects the unit from the grid in case it overrides a safe operating zone.

As the device is connected in parallel with the public LV network, it had to fulfill the norms as determined by ERDF procedures. The homologation tests and examination were passed in 2008-2009.

PRELIMINARY LINE STUDIES

The load balancer requires a careful analysis before implementation. Situations where voltage disturbances are not caused by the line impedance and imbalance need to be rejected. Contrary to voltage converters the network balancer has little effect downstream when all 3 lines are equally loaded or when the initial voltage at the feeder is already beyond limits, but it cannot degrade voltage quality upstream as some converters do.

At first glance, the 45A capacity of the unit neutral current may seem low and usual generous sizing methods would tend to require several units in parallel to make sure the max currents can be handled at all times. The main goal of the project was to find the most cost effective solutions to mitigate the voltage drops. As a result, a more accurate sizing method was chosen: detailed monitoring data and lines parameters were used to simulate the real network under the worst case conditions observed.

Detailed monitoring

The monitoring periods were planned during the coldest climate periods due to the high impact of electrical heating in voltage variations in France, except for some power injection cases. 1 minute measurement interval appeared to be a convenient compromise between the accurate profiling of the currents circulation patterns and data memory size for readily available dedicated monitoring systems. Higher measurement periods would mask extreme voltage variations as we noticed that people react relatively quickly to the highest drops (the ones that have noticeable effects on appliances) by shutting off the most powerful ones within a short time.
The load balancer has rugged zigzag transformers with heating time constant of more than an hour, making it highly tolerant to over currents in the minute range. Some peak measurements were made only when necessary, in the presence of high starting currents due to large motors not equipped with soft start means.

A dedicated simulation tool was then setup to evaluate the voltage conditions at every point of the line under all possible current consumptions or injections. The model was fine tuned using the measurement data and line parameters. Measurements and theoretical data generally fit well but it was noticed that actual line impedance is often slightly higher in reality than by calculating from the on site length and wire size. This is more the case with bundled aluminum than copper bare wire lines and probably explained by poorer contact resistances at wire junctions and possibly wire temperature.

The model takes into account the usual appliances power consumption changes as a result of improved voltage conditions, which is far from negligible when dealing with 20% voltage drops: with resistive loads, lower voltage entails lower supply currents (associated with generally longer ON time to reach target temperatures). Improving voltage quality is thus made more than linearly difficult, especially upon very degraded values such as encountered in the project. An apparent reduction of the line impedance by a factor 2 will not make 20% voltage drops turn into 10 but rather around 12%.
Similar effect is observed for power injection determined by a given energy source, voltage increases tend to reduce currents, and therefore mitigating the variations is generally harder than with simple linear calculation.

The model makes it possible to determine if the installation of one or several load balancers along the line is able to mitigate the measured worst line voltage variations. It also calculates the maximum current in the balancer, to check if one unit can handle it. As a result, the number of balancer was optimized and the cost effectiveness further improved.

As a first project using the simulation tool, it was decided to extend the study with 2 more weeks to measure the voltage variations after the solutions were installed. This enabled to check the realism of the models and user satisfaction at the same time.

FEEDBACK ON SIXTY CASES

In the study, over 60 cases with load balancer implementations have been assessed and the following table presents the main characteristics of these networks.

# of Clients End of line	# of cases
1	12%
2-3	43%
4-5	33%
6-10	12%

Table 1: Number of clients in the last 500m of the line

The relatively low number of clients connected to the last portion of the loaded lines is no surprise: one major goal of the project was to find cost effective solutions, especially for the cases with a very high “reinforcement cost per client” that had not been solved for a long time for budget reasons. Secondly, extensive detailed monitoring was easier to implement and cheaper as the number of line clients to measure tended to be lower.

The average line resistance in the sample is very high since many cases arose from client complaints. It appears that people tend to be disturbed by large variations only, those which alter appliances normal behavior. 80% of the cases had more than 14% voltage drops from the nominal voltage. Such high variations only occur for long lines.

Line + Neutral observed network resistance		
Min	Average	Max
0,4 Ohm	0,9 Ohm	1,9 Ohms

Table 2: Impedance of the line upon furthest client

The average (Phase+Neutral wire) resistance of line upon furthest client equals 0.9 Ohm and corresponds to a 800 m long bundled line 3xAL70 + AM54 on the neutral wire which is the most commonly found in French rural areas.

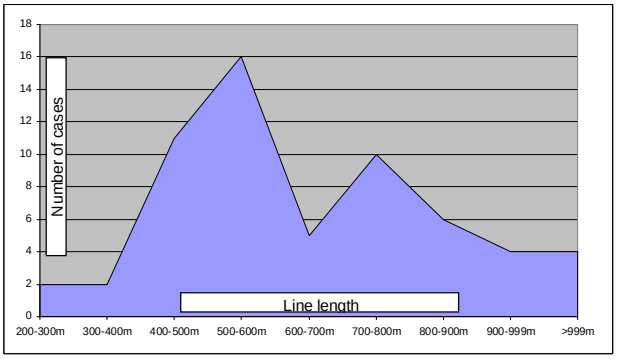


Fig. 5: Network line length from feeder to most remote client

Voltage quality improvements

The limit of allowed voltage variation was set to +10/-10% for every single 1 minute average sample during the 2 weeks measurements in worst climate period. Using this criteria, 95% of voltage quality issues were solved with the LV Network Load Balancer.

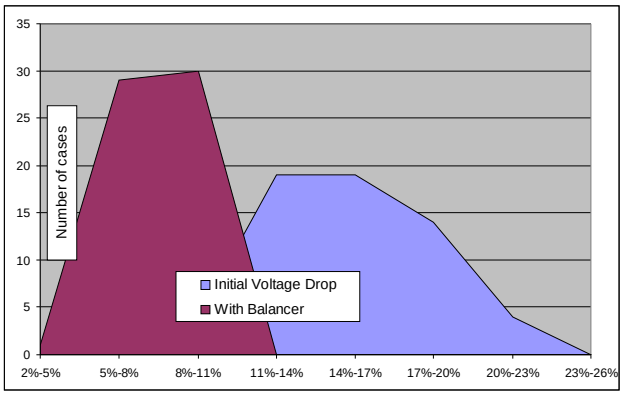


Fig. 6: Highest voltage variation in % - 1min worst sample

After installation of the balancer, 3 cases had slightly higher variations than forecast, due to line current increase: as voltage quality improves, some clients tend to use more appliances and power. The debate is still open whether the preliminary studies should use the actual observed consumption patterns measured on site or the contracted power, which may be much higher in many cases.

On the one side, distribution networks sizing integrates a diversity factor depending on the clients number and characteristics. But on the other side, when dealing with very low dwelling numbers, the distributor has to be able to supply the contracted power with adequate voltage quality at all time.

Proper communication with the clients seem to be the answer as their interest also lies in finding a quick and affordable solution when line reinforcement cannot be financed readily. Discussion can determine if the power consumption is likely to increase in the mid-term or not. On site contacts is anyway very useful to determine potential additional clients or needs on the lines, so as to validate the solution over a 5 or 10 years horizon.

Return on Investment

The global economical outcome of the project is a cost reduction of 83% compared to line reinforcement as shown in the table below. Due to extensive monitoring before and after balancer installation, studies costs amounts were even higher than hardware and installation costs, but they may very well be reduced in further projects: a ten days monitoring period of three phase voltage measurements at the end of the line and also at the feeder should provide enough data to size, locate and check case compliancy of the load balancer.

☞ Economical Outcome (incl. VAT 20%) :

Avoided line reinforcement costs	4 200 k€
Monitoring / Studies	444 k€
LV Network Load Balancer	269 k€

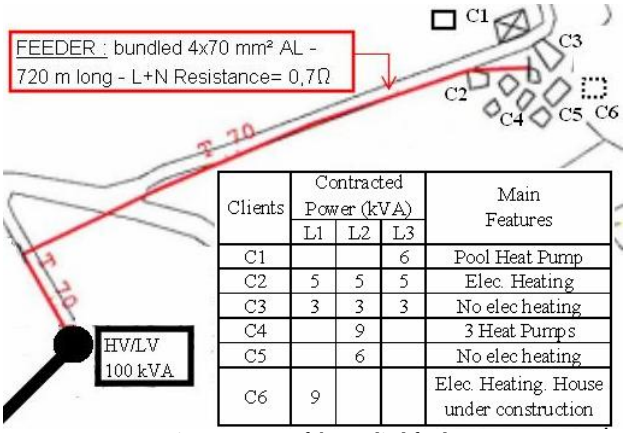
The average installed cost of a load balancer is 4.5 k€.

Long term reliability

More than 100 load balancers have been installed from 2009 to 2014. As several units were not part of the initial project with detailed measurements before and after installation, they were not taken into account in the main results of the study, but still, contacts with the manufacturer made it possible to assess the device failure rate and return for repair; it appears that after 5 years for the oldest units, none of the device asked for service, for an estimated accumulated usage of 2.8M unit x hour.

CASE STUDY

In order to illustrate the potential of the load balancer, the study of a typical case is presented in detail:



Clients	Contracted Power (kVA)			Main Features
	L1	L2	L3	
C1			6	Pool Heat Pump
C2	5	5	5	Elec. Heating
C3	3	3	3	No elec heating
C4		9		3 Heat Pumps
C5		6		No elec heating
C6	9			Elec. Heating. House under construction

Fig. 7: Layout of the studied feeder

The monitoring campaigns before and after implementation of the solution consisted in measuring Voltage and Active Power at a 1 min. time step at the 5 clients' switchboards.

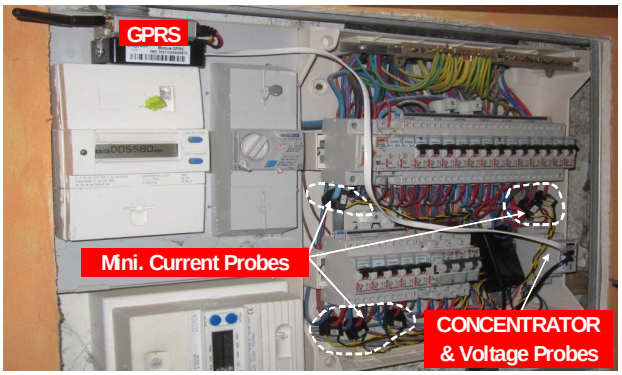


Fig. 8: Detailed monitoring in a client's switchboard

Based on the monitoring data, typical worst case clients loads and voltage drops are identified. Observed loads are used as inputs to verify first the simulation model and secondly the load balancer compliancy:

Clients	WITHOUT LOAD BALANCER Observed currents (at 12:43, see Fig. 9)		
	L1	L2	L3
C1			20 A
C2	5 A	12 A	5 A
C3	10 A	14 A	7 A
C4		33 A	
C5		8 A	
C6	0		
TOTAL	**15 A**	**67 A**	**32 A**
Loc. C3	SIMULATED VOLTAGE VARIATIONS		
	L1	L2	L3
	4%	-14%	-2%
	240 V	198 V	225 V

Clients	WITH LOAD BALANCER Simulated currents		
	L1	L2	L3
C1			21 A
C2	5 A	13 A	5 A
C3	10 A	15 A	7 A
C4		36 A	
C5		8 A	
C6	0 A		
TOTAL	**15 A**	**72 A**	**33 A**
Loc. C3	SIMULATED VOLTAGE VARIATIONS		
	L1	L2	L3
	-1%	-8%	-3%
	228 V	212 V	223 V

Table 3: Voltage simulation results for clients C1 to C6 without and with a load balancer based on observed loads

The next monitoring diagram allows to check the spread out of the 1-phase clients on the 3 lines. It also confirms that client C6 should be connected on the less loaded line L1 when the house is built and that the load balancer solves the voltage issues on this feeder. The worst case voltage drop is reduced from -14% to -8%.

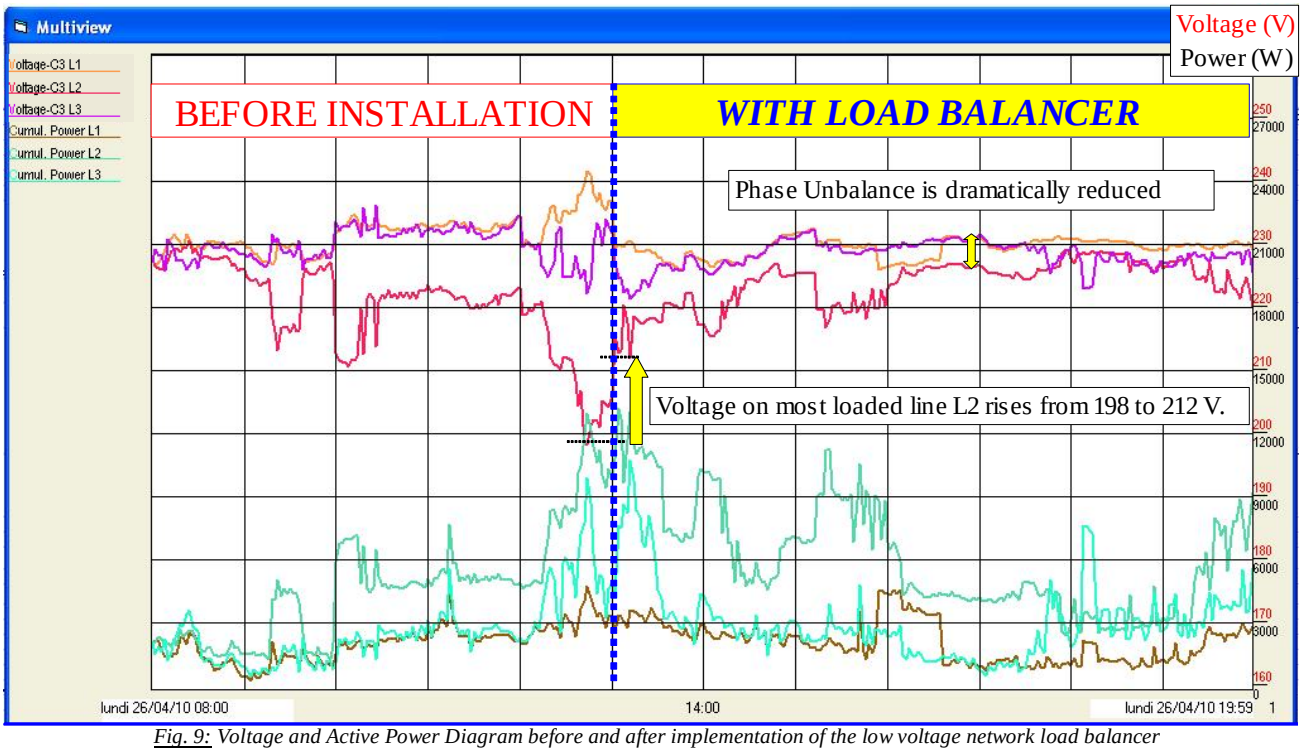


Fig. 9: Voltage and Active Power Diagram before and after implementation of the low voltage network load balancer (Cumul. Power represents the cumulated power of all existing clients of the feeder (i.e. C1 to C5)

TOWARDS FUTURE DEVELOPMENT

The encouraging results of the project and the increased budget constraints in recent times makes the development of such smart yet low tech device an attractive solution to some costly reinforcement needs. But a more widespread usage of distributed devices requires enhanced dissemination of their possibilities. Therefore a simulation tool (http://www.omegawatt.fr/equi8.zip) was developed to make it possible for anyone to check the case feasibility.

It uses the line characteristics and worst case current drawn or injected by the clients, preferably gathered following onsite measurements. The initial voltage variations are then calculated, compared to actual measurements. It consequently validates the model parameters. In a second step, a load balancer can be added at a defined location, and the new currents and voltages are automatically computed. The software immediately shows whether the solution is adequate to mitigate the voltage variations, and if the max current circulating in the load balancer can be safely handled.