LARGE SCALE PHASE BALANCING OF LV NETWORKS USING THE AMM INFRASTRUCTURE

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ABSTRACT

The deployment of the Linky Automated Meter Management system is a promising approach to significantly improve network investments. The new data obtained opens interesting possibilities in terms of voltage profile and copper loss monitoring, and calls for a completely new method for modelling loads and identifying constraints. For instance, the true individual load curves and phase connections will be known. This is important for LV networks where constraints are often due to unbalanced loads, whose presence leads to additional losses, voltage drops and constraints on current ratings.
In this context, ERDF and EDF R&D are examining the feasibility of a large scale LV networks phase balancing. This paper presents different aspects of the process, including the analysis of unbalanced networks, the phase balancing method using an efficient genetic algorithm (GA), and finally the implementation of phase swapping on the field.

INTRODUCTION

Low voltage networks often operate in an unbalanced way, especially rural networks where there are few connected consumers. Indeed, as the connected phase of existing consumers is not identified in the Geographic Information System (GIS), it may not be possible to choose the best phase to connect a new customer. Due to this randomly based connecting scheme, important voltage drops and additional losses can occur. The AMM infrastructure currently deployed by ERDF in the LINKY Project will provide the utility knowledge of real phase connection and individual load curves. One ambition of this SmartGrid project is to implement a prototype information system able to detect unbalanced LV feeders before complaints occur and propose a correction based on a multiobjective optimization.

ANALYSIS OF UNBALANCED NETWORKS

In this context, ERDF is developping a data processing prototype which will perform daily network calculations and analysis during ERDF LINKY pilot project. The figure 1 shows a simplified diagram of the system. The data needed will be provided by the GIS for network description and by the AMM Information System for daily load curves. On a daily basis, Load Flow calculations results will be summarized into “Network Dashboards” containing relevant figures for network design.

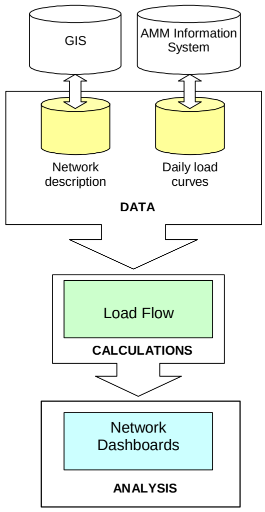

Figure 1 – AMM Data Processing

The unbalance will be described with a specific set of metrics such as an unbalance coefficient, measures of voltage quality and technical losses. Thus, the most unbalanced LV feeders will be detected and given priority within a specific phase balancing algorithm.

PHASE BALANCING METHOD USING GENETIC ALGORITHM

The GA based method has already been tested in the phase balancing problem [1]. It is obviously a powerful method for a large scale combinatorial optimization problem. The following section presents the method and the proposed improvements to ensure good optimization results using the limited data storage requirements available while ensuring moderate simulation times.

Problem formulation

There are several options for the optimization process. For example, solving the problem by minimizing the power losses on a feeder or the voltage drops could be an option but it may lead to a solution that needs many phase swaps, which is not realistic.
For a more realistic approach, workforce cost has to be

included into the equation. The losses and voltage drops, which are the results of an unbalanced power flow, have to be converted into costs. The cost of energy losses is assumed to be the medium price considering the historic evolution of electricity futures.
On the other hand, the cost of voltage drops is harder to evaluate. As it represents a disturbance in the quality of supply to the consumers but not a loss of supply, we suppose that **the cost of voltage drops is the cost of energy not supplied that would result of a fictive power cut of consumers whose voltage drop exceeds 10%.**
It is assumed that when a phase balancing is operated on a LV feeder, the connection scheme will be kept for many years. Thus the costs of losses and voltage drops are accumulated over 10 years.
The objective function used in the optimization process is then the total cost of phase balancing and can be stated as:

$$F = C_{losses} + C_{vd} + C_{workforce} \quad (1)$$

where:
C_{losses} : present value of cost losses upon 10 years.
C_{vd} : present value of 10 years of disturbance due to the voltage drops.
$C_{workforce}$: total cost of the phase swapping operations on the LV feeder.

GA method

In this paragraph, we describe the basic principle of the application of GA to the balancing problem. The algorithm is expected to give the connection scheme of single-phase consumers along the processed LV feeder which is minimizing the objective function. A connection scheme will be called a chromosome. For example, for a 10-consumer feeder, a possible chromosome will be 1 3 1 2 2 1 2 3 1 3. The electric description of the feeder, based on the GIS, does not vary through the algorithm but is essential for the power flow calculation.
In the initialization phase, several chromosomes **near the initial distribution** of consumers per phase are **randomly generated**. Indeed, as we already explained, it is preferred that only a few consumers will have their connections swapped. We fix a maximum of 25% of consumers whose phase is randomly modified. Following this, an unbalanced power flow is run and the objective function is evaluated. While the weakest chromosomes are eliminated, the best ones are selected and then used to generate new chromosomes following mutation and crossover operations. The algorithm is stopped after a predefined number of iterations.

Comparison of 3 optimization methods

According to the data taken into account, the computation of the costs can be carried out using methods of different levels of precision. The following three methods have been tested.

Method based on the consumers nominal demand
The consumers' demand is assumed to be constant and equal to their nominal demand. This method needs only a limited amount of data but is less precise. Indeed, the variations of the individual loads through the time lead to a conservative evaluation of losses and voltage drops.

Method based on the annual load curve
As the AMM infrastructure will give access to the historical consumer data, this method uses the annual individual load curves. Instead of a fixed demand method, this method is more accurate but it needs a huge amount of data and a demanding simulation time. Indeed, for each iteration of the GA and for each chromosome, the power flow has to be executed as many times as the number of time points in the load curve.

Method based on the load peak of the LV feeder
The consumers' demand is assumed to be constant and equal to their demand at the peak moment. This method needs to identify the load peak and to store only the loads of the consumers at this moment. The computation is then similar to the method based on nominal demand, but the loads are synchronized.

The three methods were tested on 10-, 24- and 50-single-phase consumer LV feeders with randomly based phase connection schemes. Once the algorithms proposed an optimal connection scheme, the annual load curves of each consumer were used to calculate the real values of energy losses, voltage drops, and thus the real total cost of phase balancing including the cost of phase swapping operations. The Table 1 presents the detailed results of the methods for a 50-consumer unbalanced feeder. The computation time is given for a desktop computer.

	Before balance	**Method based on annual load curve**	**Method based on load peak**	**Method based on subscr. demand**
Energy loss on the year (kWh)	6221	4766	5025	5010
Max. voltage drop (%)	12.6	7.8	8.7	8.7
10' points exceeding voltage limits	157	0	0	0
Phase swaps	/	4	9	11
Total cost (€)	10 657	2 519	3 373	3 667
Computation time	/	300'	5'	5'

Table 1 – results of the methods for a 50-consumer unbalanced LV feeder

The tests show that the method based on annual load curve is the most accurate and should be adopted as a computation reference, as the same data were used to optimize and to calculate the costs afterwards. This method, however, suffers from an overly demanding simulation time and needs considerable access to data, which makes it less feasible for a large scale application. As the method based on the load peak does not suffer these drawbacks, we present on the next section an improvement for this method in order to make it more accurate.

Improvements of the method based on load peak

Improving the accuracy of the evaluation of losses

First, the fact that the losses are calculated at the peak moment leads to a conservative evaluation of losses, and thus requires too many phase swaps. We propose to introduce the relationship between load and loss factor to better evaluate the total losses of the feeder [2].

Load factor (LF) is the ratio between the average power ($P_{average}$) and the maximum power (P_{max}), in a period of time T.

$$LF = \frac{P_{average}}{P_{max}} = \frac{1}{P_{max}} \frac{\int_0^T P(t)dt}{T} \qquad (2)$$

Loss factor (LSF) is the ratio between the average power losses ($L_{average}$) and the losses at the peak load moment (L_{max}).

$$LSF = \frac{L_{average}}{L_{max}} = \frac{1}{L_{max}} \frac{\int_0^T L(t)dt}{T} \qquad (3)$$

Thus, the energy losses (E_{losses}) of the feeder during the period of time T can be stated as:

$$E_{losses} = \int_0^T L(t)dt = LSF \cdot T \cdot L_{\max} \qquad (4)$$

The relationship broadly used between the load and loss factors is:

$$LSF = a \cdot LF + (1-a) \cdot LF^2$$

where a is a constant coefficient that can be determined by studying the load-duration curve of the most appropriate equipment. For LV networks, ERDF usually fixes the value 0.05 for the coefficient a.

Finally, the energy losses in a year can be approximated by:

$$E_{losses} = 8760 \cdot L_{max} \cdot \left[a \cdot \frac{P_{average}}{P_{max}} + (1-a) \cdot \left(\frac{P_{average}}{P_{max}} \right)^2 \right] \qquad (5)$$

This new value of energy losses modifies the cost of losses in the original objective function.

Improving the accuracy of the evaluation of moments when voltage drops exceed the limits

Secondly, as the voltage drop is calculated at the peak moment, the cost of energy not supplied along the year is also conservative, which contributes to require needless phase swaps. Indeed, a consumer may see an undervoltage at the peak moment and be supplied well throughout the rest of the year.

Thus, we propose the introduction of a threshold t_{bs} corresponding to the maximum real time of the voltage disturbance.

$$t_{bs} = \frac{\sum_{feeder} n_i}{N_{bs}} \cdot T_{step} \qquad (6)$$

where:

T_{step} : time step used by the Linky metering system.

n_i : for the consumer i, number of moments in the year when the voltage drop exceeded the limits.

N_{bs} : number of consumers who experienced at least once in the year a voltage drop that exceeded the limits.

Parameters n_i and N_{bs} are expected to be recorded by the Linky metering system.

From now on, at each step of the algorithm, each consumer for whom the voltage drop exceeds the limits at the peak moment will generate a cost of energy not supplied during the period t_{bs} instead of the whole year.

Results

In a similar manner to preceeding studies, the proposed method was tested on the same set of LV feeders. As there was no constraint with time simulation, the initial population of chromosomes and the number of iterations was increased.

	Before balance	Method based on annual load curve	Improved method based on peak moment
Energy loss on the year (kWh)	6 616	5 125	4 833
Max. voltage drop (%)	12.2	8.7	9.6
10' points exceeding voltage limits	231	0	0
Phase swaps	/	6	2
Total cost (€)	14 939	2 963	2 245
Computation time	/	300'	5'

Table 2 – Results of the methods for a 50-consumer unbalanced LV feeder.

The Table 2 presents the detailed results for a 50-consumer unbalanced feeder. The Table 3 shows that **the proposed improvements increase the effectiveness of the method based on the peak moment**. These results shall be taken with care: the method based on the annual load curve is still considered to be the reference method, but the simulation time limit does not allow it to reach the best optimum.

	Before balance	Method based on annual load curve	Improved method based on peak moment
Test 1	14 939	2 963	2 245
Test 2	3 481	2 736	2 345
Test 3	4 883	2 454	2 202
Test 4	4 119	2 374	2 353
Test 5	6 968	2 643	2 418
Test 6	395 299	3 434	2 868
Test 7	3 858	2 341	2 086
Test 8	2 843	2 110	2 843
Test 9	14 425	2 330	2 290
Test 10	2 111	1 993	2 024

Table 3 – Total costs (in €) for 10 tests executed on 50-consumer randomly based unbalanced LV feeders.

AN IMPLEMENTATION OF PHASE SWAPPING ON THE FIELD

The previous sections have described the mathematical part of the process. Once balancing opportunities have been identified, they will be transferred to the Operation Department. This section presents two possible options for field application.
The first one entirely relies on the AMM system : phase connexion of a given meter is determined in real time by its concentrator and updated into the meter if needed. The operational team will use the results of the optimization process described previously in order to make physical changes to the connexions.
They will receive a message like "Change phase connexion of Customer X from N°1 to N°2". After changing the phase connexion, the operational team will then read on the meter and check if the new phase is indeed N°2. The advantage of this solution is that no additional equipment is needed. However, an appointment with the customer may be necessary to access the meter. During the LINKY pilot project this solution will be tested in priority in order to evaluate how easy phase balancing can be performed.
The second solution relies on traditional phase balancing equipments such as phase transceiver. In this case, the operational team will receive a message like "Change phase connexion of Customer X into the same of Customer Y". Emitting a signal in Customer Y connexion phase, the crew will be able to receive this signal at Customer X connexion point and choose the right phase. This solution is transparent for customers but could be time consuming while installing equipments.

CONCLUSION

AMM deployments are opening a new opportunity for ERDF to identify unbalanced LV networks and to consider the possibility of large scale balancing plans.
In this paper, a method for the balancing of LV feeders was presented. The study showed that a stochastic method such as a genetic algorithm could be adapted to address this issue.

REFERENCES

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