

APPLICATIONS OF PHASOR MEASUREMENT UNITS IN DISTRIBUTION GRIDS – PRACTICAL RETURN OF EXPERIENCE

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ABSTRACT

Phasor Measurement Units are a well-established technology in high voltage transport networks, but lately they have proven to be useful in medium voltage networks as well. Integrating this technology in MV networks presented various technical challenges, such as the use of an adequate transducer or the access to a reliable communication network. Several concrete applications have been tested and validated in multiple Proof of Concept (PoC) PMU architectures in Belgium. The prediction of parallel couplings exchange current between two substations via the monitoring of the phase angle difference between them has been tested and validated in various locations. Thanks to a long-term monitoring, a planning of such manoeuvres can be established to guarantee successful operations. Finally, transient recordings of phase angle events as well as short-circuit power estimations are additional PMU applications which have been assessed and that bring additional observability to the DNO on its network stability.

INTRODUCTION

Synchronized phasor measurements have been used for decades in the transport network. Large phase differences occur between high voltage stations when high powers flow between them and a monitoring of the voltage phasor instead of only the voltage magnitude is thus necessary to obtain a proper view on the network state and the power flows.

In the past power flows in the distribution grid were much more predictable. Emerging renewable energy production and changing load patterns nowadays lead to much greater power flows in the Medium Voltage (MV) grid, often unpredictable with the classic monitoring means. PMU technology can provide a gain in observability and help with estimating the impact of daily operations. The technology needed however to be adapted for use in MV-grids, and to be used in new identified use cases.

In this context, Laborelec joined forces with Belgian DNO's to build Proof of Concept PMU architectures in MV-grids and study several use cases.

PMU ARCHITECTURE IN MV NETWORKS

Various Proof-of-Concept (PoC) architectures have been tested in the past three years. The study of the accuracy limits achievable and the different possible use cases depending on said accuracy have led to an evolved set-up,

much more simplified. The Return of Experience (REX) leading to these decisions are detailed here after.

The first set-up used, depicted in Figure 1, was quite a complex one, with PMU's located not only in MV substations but also in MV cabinets. The idea at that time was to assess the feasibility of such measurements even in MV cabinets, where the absence of proper measurement transducer can be problematic (see here after). Furthermore, additional measurement devices had to be used to measure the MV/LV power flow through the MV/LV power transformer. The goal was to attempt a phase angle correction to the phase shift brought by the transformer. As it will be explained here after, this method had rather poor results.

The REX gathered thus far guided the set-up of the next PoC's, with PMU's only in the substations and accompanied by synchronized current measurements as well, as it can be seen in Figure 2. Indeed, a view on the currents details such as the evolution of the power factor besides the current magnitude helped a lot in the simulations accuracy by fine-tuning the model's inputs. The methodology of said simulations is exposed here after.

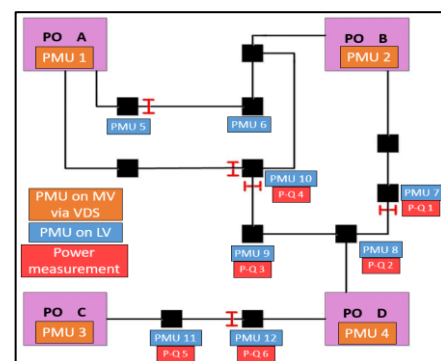


Figure 1: Example of PoC PMU architecture with LV voltage measurements in cabinets

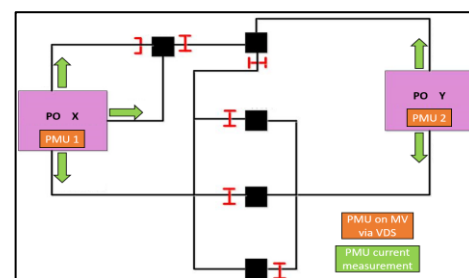


Figure 2: Example of simplified PMU architecture for parallel couplings

CHALLENGES OF MV INTEGRATION

Implementing a HV technology in MV induces a few considerable technical challenges. Among those, the most notable are the use of appropriate measurement transducers and the requirements in mobile and GPS communications.

The transducer used traditionally for voltage measurements in MV substations is a measurement transformer, which typically presents an accuracy of 0.2% in magnitude and 0.2 degrees in phase angle. This accuracy, although being close to the order of magnitude of the phase angle drop along a MV feeder (about 0.2-0.5 degree typically in Belgium), is enough for the applications presented in this paper. However, in MV cabinets no such transducer is available, since historically no fixed voltage measurements were required there.

The Voltage Detection System of a MV cabinet can nevertheless be used as an ad-hoc transducer, despite its design which was clearly not intended for accurate measurements. This results in phase angle errors of up to about 1 degree when compared to NEPLAN® power flow simulations. This accuracy limit is well-above the phase angle drop along a feeder and thus renders the use of PMU in cabinets very limited if not non-existent. Such installations are thus not used in the applications presented here below. More details about the use of VDS as transducer in MV cabinets can be found in [1].

Another possible transducer is simply the MV/LV power transformer of the cabinet, although it is not made for accurate measurement either. Such method provides better accuracy (around 0.5° of error), although it is still not sufficient and furthermore it requires the use of power measurements to apply the phase angle correction, as it can be seen in Figure 1. The use of a MV/LV resistive divisor could theoretically improve greatly the accuracy of the phase angle measurement, but it has not yet been tested. Other small phase angle errors exist in the process, although they are negligible in view of the two aforementioned accuracies. The complete system sources of error are shown in Figure 3, for the case of the MV/LV transformer as transducer.

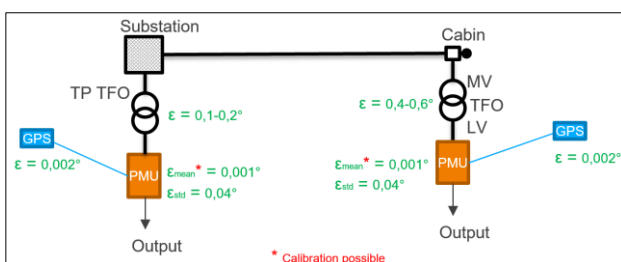


Figure 3: Sources of phase angle error in distribution grids for PMU measurements

The transfer of measured data to a centralized server is a paramount step of the process. Indeed, what would be the

interest of having accurate measurements with a high sampling frequency if one cannot retrieve them and act on it almost immediately? A strong and reliable mobile network is thus necessary to transfer regularly these data. Such requirement is often hard to come by in remote locations like in the country side. During first PoC's, a lot of data were lost due to the communication losses that occurred sporadically. The solution implemented to mitigate this issue was a data buffer of about 30 minutes which allowed for communication cuts shorter than this period of time without any data loss. This effectively considerably enhanced the data retrieval rate.

Finally, the use of a GPS signal is mandatory for the synchronization process of the PMU's. The acquiring of a functioning GPS signal require the access to a relatively clear sky, to be able to access at least three satellites among the 10+ satellites that should be available in a totally clear sky. Such requirement is easily met in the country side, while it can sometimes be more difficult in cities where substations and cabinets can be located underground or in streets with a lot of high buildings. The location of the GPS antenna must thus be carefully chosen.

PARALLEL COUPLINGS

Parallel couplings between two MV substations always induce some exchange current at the coupling point. One part of this exchange current is simply due to the fact that one substation will feed some of the loads that were originally fed by the other one. In other words, a sharing of the loads on the common feeder between the two substations occurs.

But the exchange current is also composed of power which is purely exchanged from one substation to the other, and must travel all the common feeder to that end. This part of the exchange current results from the voltage phasors difference between the two substations and the impedance of the path between the substations. Practically, it has been observed that the current is almost entirely dependent of the phase angle difference, the voltage magnitude difference having a very small impact.

The monitoring of the phase angle at both substations could thus be used to predict the exchange current that would occur during a parallel coupling. These predictions can be performed with a simple calculation module based on Ohm's law via this basic formula:

$$\bar{I}_{exchange} = \frac{\Delta \bar{V}}{\bar{Z}_{parallel}}$$

A more accurate calculation would also take into account the loads along the feeders, which have a significant impact on the global power flow. These simulations have been performed with the tool NEPLAN®. The complete prediction process is shown in a schematic in Figure 4.

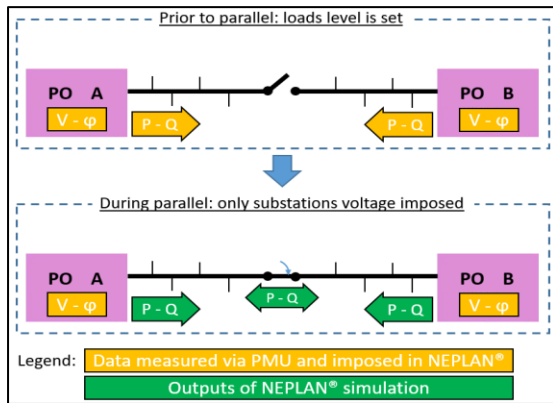


Figure 4: Simulation process in NEPLAN® for exchange current prediction

Tens of parallel couplings have been performed in several PoC's and the results are promising, with most couples of substations and parallel pathways yielding quite accurate predictions. Some errors are of course still present (unknown presence of DER in feeders, accuracy of substations measurement transformers, etc.) but the accuracy reached (order of 10-20% of maximum error for most parallels) seems enough in view of the end goal.

Ultimately the end use for the DNO is a decision tool for performing parallel couplings (Go/No Go decision), depending on the exchange current estimated and whether it could exceed the feeders' breaker limit. This would prevent the occurrences of "failed" parallel couplings due to excessive exchange currents.

LONG-TERM MONITORING & PREDICTION

Leaving the PMU's in measurements for a long period of time allowed for the gathering of long-term data, especially regarding the phase angle difference between several couples of substations. An example of long-term monitoring can be seen in Figure 5.

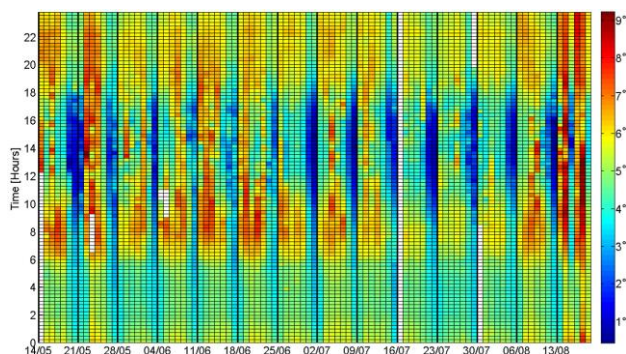


Figure 5: Phase angle differences between two substations

When using the voltage differences in term of phase angle and magnitude, one can compute the approximate predicted exchange current that would occur if a parallel coupling was performed, as explained here above. Such results are shown in Figure 6. It is worthy to mention that

the two figures are very similar, with very slight differences barely noticeable with the naked eye. This tends to confirm that exchange currents are almost solely determined by the phase angle difference and very little by the magnitude difference.

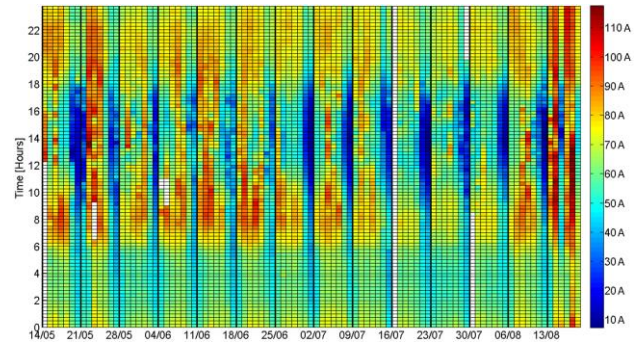


Figure 6: Exchange currents predicted thanks to voltage phasors

Clear night/day and week/weekend patterns can be observed. Such patterns could quite easily be used for the planning of successful parallel couplings, for each couple of substations and each specific path between them. Seasonal patterns could also be obtained to plan further ahead, although this would require a year-long monitoring period.

TRANSIENT PHASE ANGLE EVENTS

The PMU's can also be used to capture transient recordings, if the trigger used is for example a phase angle jump between two cycles. This functionality, implemented in several PMU's placed at various location allows for a wide-area monitoring of such transient events and adds an additional observability mean for the DNO.

Such recordings were tested in the last PoC PMU architecture. The trigger threshold is of course an important decision to take, as it will dictate how many events the PMU captures during a certain period of time. Too high and it will capture no events at all, too low and it will capture too many. In order to set a first arbitrary trigger level which made sense, the regular phase angle shift that occurs when the frequency is a little bit off the 50Hz reference has been computed in the following fashion with 49.95 Hz as an example:

$$\Delta^\circ = \frac{50 - 49.95}{50} * 360 = \frac{0.36^\circ}{\text{cycle}} = \frac{18^\circ}{\text{second}}$$

In view of this, a first threshold level was set at 0.6°/cycle, under the assumption that such regular frequency deviation would not often occur. Such phase shift would thus be the indication of a transient event. With a period of measurement of two weeks and 9 PMU's installed at various locations in Wallonia, 183 events were recorded. A second measurement period of two weeks was performed with a threshold at 0.4°/cycle, during which 1101 events were captured.

Some of these events were local, meaning that only one PMU captured them, while others were global, being measured by several PMU's. Figure 7 illustrates the proportion of events that were local or global. Furthermore, it is worthy to mention that some substations were particularly more subjected than others to event occurrences, indicating that they are less resilient to steps of power change or equivalently subjected to more violent steps.

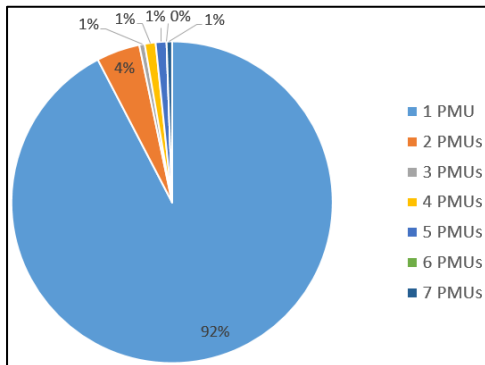


Figure 7: Proportion of events being captured by one or several PMU's

Figure 8 illustrates how a phase angle event can be local, while intuitively one would assume that since the frequency is the same everywhere in the network, phase angle events would be always global.

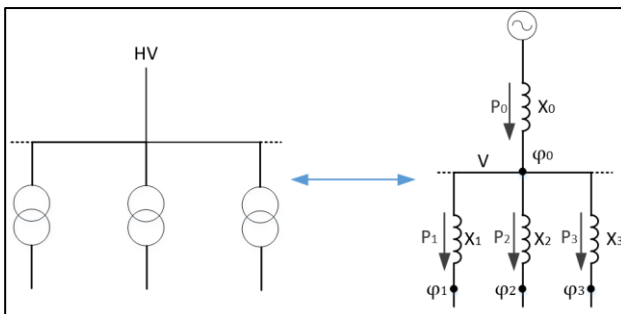


Figure 8: Schematic of the phase angles in part of a HV/MV grid

The power flow respects the following equations:

$$P_0 = \frac{v^2}{x_0} \varphi_0 \quad P_1 = \frac{v^2}{x_1} (\varphi_1 - \varphi_0) \quad P_2 = \frac{v^2}{x_2} (\varphi_2 - \varphi_0) \quad P_3 = \frac{v^2}{x_3} (\varphi_3 - \varphi_0)$$

A change of active power ΔP_1 in the feeder 1 would thus have the following impact:

$$\Delta \varphi_0 = \Delta \varphi_2 = \Delta \varphi_3 = \frac{x_0}{v^2} \Delta P_1 \quad \Delta \varphi_1 = \frac{x_0 + x_1}{v^2} \Delta P_1$$

$$\Delta \varphi_1 > \Delta \varphi_0 = \Delta \varphi_2 = \Delta \varphi_3$$

A change of active power at one MV substation will thus cause a higher phase jump at that substation than at the others. The local or global nature of an event is thus in the end a matter of threshold level for its capture, since an event will always impact other parts of the network to some extent.

SHORT-CIRCUIT POWER ESTIMATION

A final application that has been tested for PMU's in MV networks is the estimation of the short-circuit power at an MV substation. This method does not in itself need the synchronicity of multiple PMU's in a wide area but takes rather advantage of the long-term precise local voltage and current phasors measurements offered by such infrastructure. The principle of the method is in itself well-known and has been used in the past for intermittent short-circuit power measurement. It relies on a Thevenin equivalent of the upward network as seen from a MV substation, as shown in Figure 9.

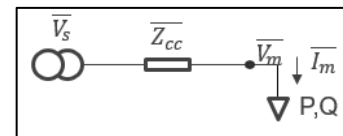


Figure 9: Thevenin equivalent of the upward HV network

When measuring at two separate times with different global power consumption, one can deduce the upward short-circuit impedance Z_{cc} via the following formula:

$$\overline{Z_{cc}} = \frac{\overline{V_{m2}} - \overline{V_{m1}}}{\overline{I_{m1}} - \overline{I_{m2}}}$$

with I_m the total current drawn from the HV/MV transformer and V_m the voltage at the MV side of the transformer.

Classically this method was applied with good results thanks to the manual activation of a large capacitor bank, in order to obtain a large sudden power deviation which could be measured to compute Z_{cc} . With long-term monitoring of both the voltage and current phasors, one can use the natural power deviations in the MV downward grid to assess continuously the short-circuit power. The last PoC PMU architecture mentioned here above has been used to investigate this method in the field.

The anticipated issue was the need for sudden power changes large enough to be accurately measured. Such power swings should be as rapid as possible, in order to validate the assumption that the perfect voltage source in the Thevenin equivalent remains constant between the two measurements. For a typical Belgian MV substation which presents a nominal voltage of 10 kV and that can present up to 400 MVA of short-circuit power, the impact of an active power variation of 1 MW can be easily calculated in theory and induces notably a voltage phase angle variation of 0.14 °/MW. The equivalent calculation for a reactive power variation of 1 MVar yields notably a voltage level variation of 25 V/MVar.

Such variations are spot on the accuracy limits of the measuring transformers in MV substations, which

present an accuracy of 0.2° and 0.2% of nominal voltage level, equivalent to 20 V for a 10 kV network. Furthermore, 1 MW/MVAr power variations in a short timeframe do not occur often in a typical network. All of the above pointed towards the fact that this methodology, although being sane on paper, could reveal hard to implement in the field due to measurements accuracy constraints. If the threshold for power variation capture is too low, the accuracy will be mediocre, while if it is too high, almost no power variation will be captured. Following the same logic, allowing a large timeframe for the detection of power variations large enough increases the number of potential captures, but it also degrades the validity of the Thevenin equivalent used.

Examples of results with different power variations thresholds and different allowed timeframes for power variation captures are shown in Figure 10 to Figure 12 for a period of measurement of about two weeks in a Belgian substation. It can be seen as expected that the accuracy and consistency is very variable depending on the constraints of the captures. However, it must be noted that the average values of the S_{cc} is always roughly correct, with a reference S_{cc} value of about 240 MVA indicated by the transport network operator.

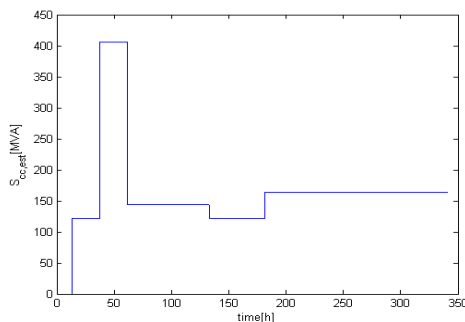


Figure 10: Estimation of S_{cc} with $\Delta t=5\text{min}$ & $\Delta Q_{\min}=600\text{ kVAR}$

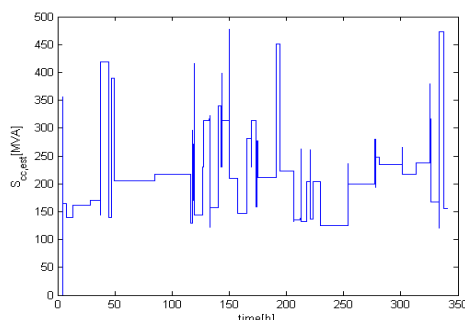


Figure 11: Estimation of S_{cc} with $\Delta t=3\text{min}$ & $\Delta Q_{\min}=400\text{ kVAR}$

Finally, it is worthy to mention that this method, although being valid for the estimation of the upward Z_{cc} , is not entirely correct for the estimation of the S_{cc} . This is due to the fact that with the increasing penetration of decentralized energy resources, a significant proportion of the power is produced by power electronics-based units which are decoupled from the grid (= grid-following units) and do not participate to the voltage regulation of classical

power plants. They are thus not taken into account in the Thevenin equivalent mentioned here above, although they will deliver some short-circuit power in case of a nearby fault. The estimation method mentioned here above is thus an estimation *a minima*, and the potential short-circuit contribution of DER units should be added for a more accurate S_{cc} estimation.

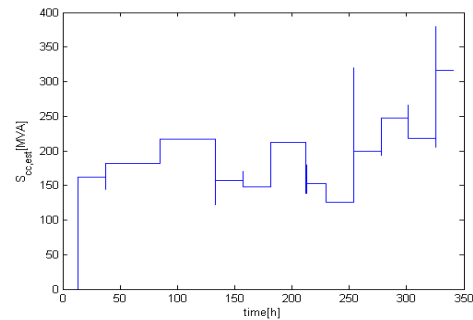


Figure 12: Estimation of S_{cc} with $\Delta t=2\text{min}$ & $\Delta Q_{\min}=500\text{ kVAR}$

CONCLUSIONS

PMU technology is more and more found in MV networks lately due to new applications for the DNO's. Although challenges exist for the integration of this technology especially in MV cabinets, multiple applications have been tested and validated to some extent. The most concrete and direct application is the prediction and thus planning of successful parallel couplings between two substations, with a basic prediction module based on voltage and current phasors measurements.

Transient recordings of phase angle events can also be used to assess the stability of the various part of the network as well as the network as a whole, by using the number of events recorded during a specific period of time as a Key Performance Indicator. The last application investigated was the estimation of short-circuit power via continuous and long-term monitoring of substations voltage and current phasors, which yielded mixed results but with leads of improvements.

With the current accuracy limits in MV technologies, the return of experience on multiple applications and PoC architectures tends to confirm the added value of deploying PMU's in MV substations but not in MV cabinets. During their installation, a particular attention must be paid to the placement of the GPS antenna as well as the access to reliable mobile communication network. Long-term monitoring can yield a great added value in terms of observability and operational management.

REFERENCES

- [1] Q. Antoine, S. Uytterhoeven, D. Lopez Martinez, D. Empain, 2019, "Use of Voltage Detection Systems as transducer – Practical return of experience", *CIRED conference*, paper 114.