AN ADVANCED MEASUREMENT METHOD FOR POWER FLOW IN MV-GRIDS

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ABSTRACT

Grid operators are more and more confronted with emerging distributed energy sources in medium voltage grids, creating active and reactive power flows which are sometimes difficult to predict or to simulate. Daily operations can suffer under these uncertainties. Laborelec has investigated the problems of congestion during the parallel coupling of multiple substations using special equipment. Measurement campaigns have been performed, in order to characterize the differences in voltage and angle between the substations, before the coupling of substations, and the exchange currents during the coupling of substations. During several days, up to 20 voltages and currents were measured synchronously at five distinct locations. The evolution during several days of the angle and voltage deviation between the different substations was shown, as well as the exchange of active and reactive power.

INTRODUCTION

Power grids experience an increasing penetration of decentralized energy production, leading to more complex and less predictable active and reactive energy flows. Unpredictability of solar and wind power generates important deviations from deterministic patterns typical for industrial and residential loads. As a result, predictive load flow calculations deviate from practice. More problems are experienced during daily operations, such as for example voltage control. [1][2][3][4] The results from different measurement campaigns are presented here. These campaigns were taken out in medium voltage (11 kV), at locations where it was not always possible to perform parallel couplings.

THEORETICAL CONSIDERATIONS

Parallel operation in medium voltage is the result of a switching action, with the intention to achieve the transfer of load between different feeders. In this case, the load on a feeder of a transformer would be transferred to a feeder of another transformer. During this transition the load remains un-interrupted. The reason of this action could be a maintenance action needed to be performed on the specific feeder or substation. [1] During this action, a compensation current will flow in the temporarily connected feeders. The consequences of this compensation current can be the tripping of the feeder line-protection devices, and in some cases the tripping of substation protection devices. Next to that, the current could be reactive in nature, and therefore hard to interrupt when the parallel operation is undone. [2]

Exchange of active and reactive power between parallel substations

In a first step the influences of difference in voltage angle and amplitude between the different substations, in relation to the line parameters are assessed.

Considering a simple network (Figure 1) allows us to evaluate the following equations:

$$V_1 = |V_1| \cdot \angle\theta_1$$

$$V_2 = |V_2| \cdot \angle\theta_2$$

$$Z = R + j.X$$

$$\delta = \theta_1 - \theta_2$$

$$S_{12} = P_{12} + j.Q_{12}$$

$$V_1 - V_2 = Z.I_{12}$$

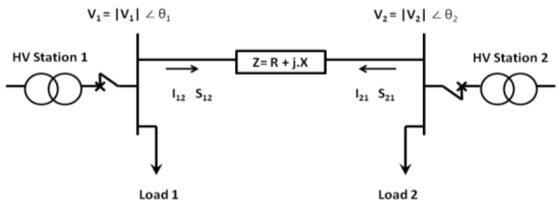

Figure 1: Power flow between two parallel connected substations.

Hence, from these equations, it is possible to formulate the following equations, assuming that in general the ratio between $X/R >> 1$ and $\cos\delta \approx 1$:

$$P_{12} = \frac{|V_1|.|V_2|}{X}\sin\delta$$

$$Q_{12} = \frac{|V_1|}{X}\left(|V_1| - |V_2|\right)$$

We can conclude from these equations when δ is positive, the phase angle of substation 1 leads that of substation 2. Active power will be sent from substation 1 to substation 2. If the voltage magnitude of substation 1 is greater than that of substation 2, reactive power will be sent from substation 1 to substation 2. [1]

In general, it is possible to say that **differences in angle between the substations give lead to a flow of active power between both substations**. Next to that, **differences in voltage between substations give lead to a flow of reactive power between both substations**. That is, of course, if assumptions $X/R >> 1$ and cos $\delta \approx 1$ are respected. The **higher the line reactance, the less power (active or reactive) will flow**.

Influence of transformer characteristics on the change of phase angle and voltage variations

The impedance equivalent of a HV/MV power transformer can be modelled by an equivalent resistance in series with an equivalent reactance.

$$Z_{TR,EQ} = R_{EQ} + j.X_{EQ}$$

Typically R_{EQ} is 20 to 30 times smaller than X_{EQ}, so the impedance can be assumed:

$$Z_{TR,EQ} \cong j.X_{EQ}$$

The equivalent reactance can also be calculated as:

$$X_{EQ} = \frac{u_k.V^2}{100.S_n}$$

With:
V the nominal (primary) line voltage in [kV]
S_n the nominal power of the transformer in [MVA]
u_k the short-circuit voltage in [%]
From this it can be seen that increasing U_k elevates the equivalent reactance X_{EQ}.
Next to that, it is possible to evaluate the effect of the load current of the transformer on the angle and voltage deviation (Figure 2).

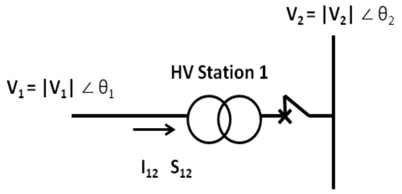

Figure 2: Determination of phase angle and amplitude difference over a HV transformer.

$$S_{12} = P_{12} + j.Q_{12} = \sqrt{3}.V_1.I_{12}^*$$

This can be rewritten as:

$$I_{12}^* = \frac{V_1 - V_2}{\sqrt{3}.(R_{EQ} + j.X_{EQ})}$$

Assuming that: $\theta_1 = 0$ (primary voltage has the reference phase), $\theta_2 = \theta$, being a small value (some degrees), $R_{EQ} << X_{EQ}$ leads to the following results:

$$P_{12} = \frac{|V_1|.|V_2|}{X_{EQ}} \sin\theta$$

$$Q_{12} = \frac{|V_1|}{X_{EQ}} \left(|V_1| - |V_2|.\cos\theta\right)$$

From these equations, it can be seen that **a higher active power flow through the transformer results mostly in an effect on the phase angle difference between primary and secondary. A higher reactive power flow through the transformer results mainly in a difference in voltage relative to the primary voltage** (set by the transformer ratio).

CASE STUDY : PARALLEL COUPLING IN AN URBAN AREA

The goal of the measurement campaign is to identify and to characterize the behavior of the urban grid during a parallel between two separately fed medium voltage substations. The measurements were performed by Laborelec in collaboration with Sibelga, one of the Belgian Distribution Grid Operators (DGO) and Elia, the Belgian Transmission Grid Operator (TGO).

Measurement Setup

In this campaign, up to six measurement devices were used. The device used is a Data Waveform Recorder (DWR), an IEC61000-4-30(2008-10) class A measuring and recording equipment for acquiring electrical signals equipped with 8 channels developed by Laborelec. The data was sampled and stored at a rate of 48 kS/s. The devices were synchronized in time using a GPS system. The time accuracy achieved through the whole setup, including accuracy of voltage and current transformers, is estimated to be around 0,6° in a 50 Hz-system (~33 µs). The devices were used to measure up to 20 voltages and currents synchronously during several days at five different substations.The setup permitted to show the evolution of difference in voltage and angle between the different substations:

- Schaarbeek – Heliport 36 kV
- Schaarbeek – Quai des Usines - Heliport 11 kV

Heliport 11 kV can be fed by Heliport 150 kV or Heliport 36 kV.

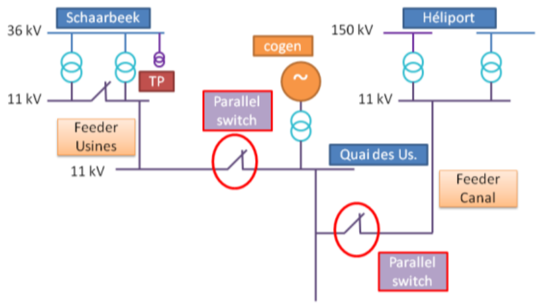

Figure 3 : Overview of the urban high voltage grid (Brussels – Sibelga)

Measurement Results

The evolution of the voltage difference and angle difference during a two day period is shown in Figure 4. During this period, the substations were not coupled in parallel. Heliport 11 kV was fed by Heliport 150 kV.
It was seen that a voltage difference, as well as a phase angle difference exists between the different substations, namely on the 36 kV-level as well as on the 11 kV-level. This was explained by the fact that the two substations were fed by two different 150/36 kV transformers, which had different loadings. Also the loading of the 36/11 kV transformer plays a role. A cyclic pattern in the angle difference can be recognized during the two day period. This can be related to

the use of loads which is more extensive during day time (mainly offices). The voltage difference between the substations is continuously adjusted by on load tapchangers, which explains the sudden variations in the voltage curves. The voltage difference at the 36 kV level reaches 500 V (1.4 %), the angle difference goes up to 2°. The voltage difference at the 11 kV level goes beyond 200 V, the angle difference goes also up to 2°. The maxima do not occur simultaneously on both voltage levels.

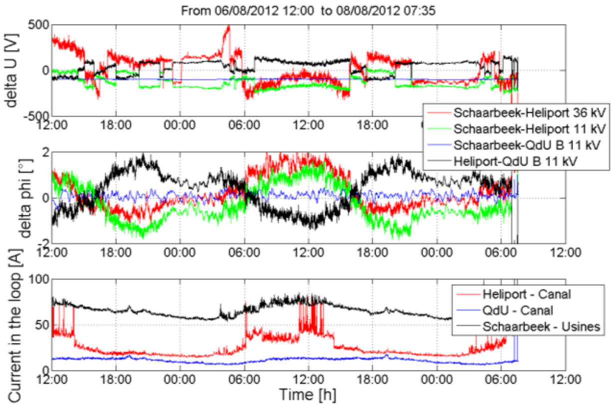

Figure 4 : Voltage and angle differences between substations and currents - 06/08/2012 12:00 - 08/08/2012 07:35 - Phase 1 – 100 ms averages.

Following specific guidelines and grid reconfigurations by the DGO, both 11 kV substations were fed by two different 36 kV grids. Multiple parallel couplings (Figure 5) were done, revealing that the angle difference was responsible for the large transfer of active power between the two 36 kV grids, through 11 kV grid. Angle differences exceeding 6-7° at the 11 kV level and voltage differences exceeding 300 V occurred, following an active power flow of more than 5 MW (currents up to 400 A), sometimes tripping the protection relay in the loop.

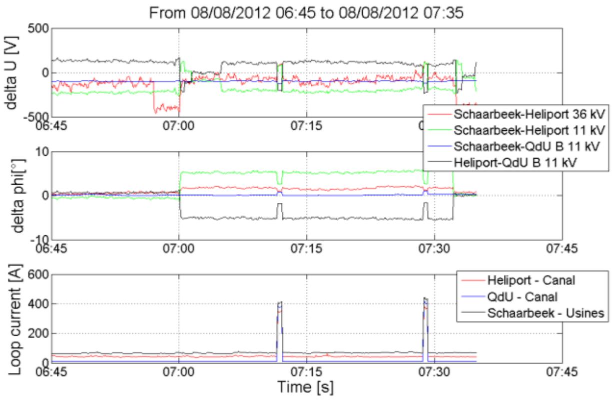

Figure 5 : Voltage and angle differences between substations and currents - 08/08/2012 during parallel couplings - Phase 1 – 100 ms averages.

Because of differences in voltage between the two substations, it was noticed that a reactive power flow of about 800 kVAr occurred in the opposite direction compared to the transfer of active power (Figure 6).

The influence of a 1,5 MW cogeneration unit at 11 kV (Quai des Usines) was also investigated. The unit was injecting mainly active power but also a reasonable amount of reactive power, contributing to the voltage levels at 11 kV. The effect of the cogeneration unit can be positive, when it supplies loads nearby with active and reactive power, reducing the injection of active power in the loop feeder at the substations.

Occasionally, the influence was negative, because the injected power of the unit was added to the loop power, leading to an even higher loading of the feeder in the loop at the power receiving substation (Figure 7).

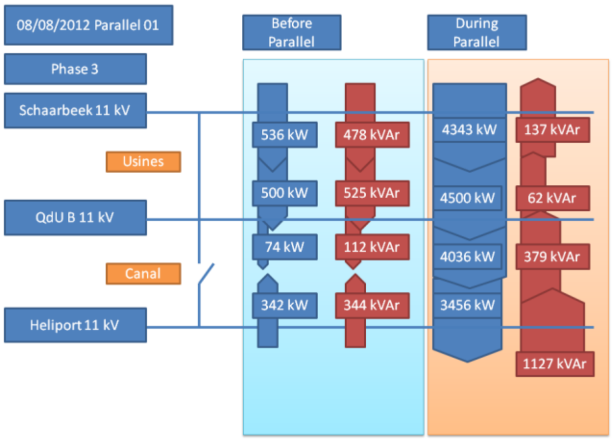

Figure 6 : Evolution of the power flow before and during a parallel coupling without the cogeneration unit being active.

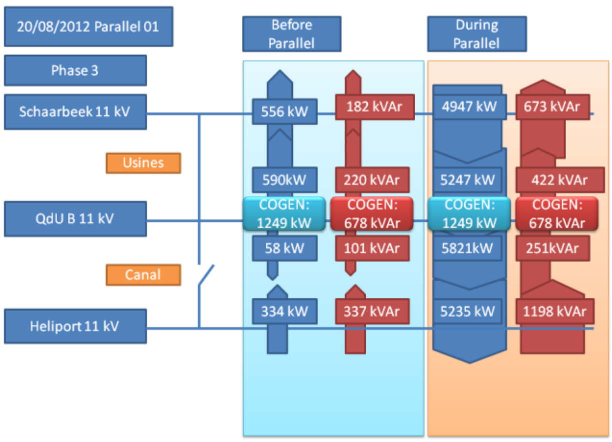

Figure 7 : Evolution of the power flow before and during a parallel coupling with the cogeneration in operation.

CONCLUSIONS

In general differences in angle between the substations give lead to a flow of active power between both substations when they are coupled in parallel. Differences in voltage between substations give lead to a flow of reactive power between both substations. The loading of the substation can have a significant effect on the voltage as well as the angle deviation compared to the upper higher voltage level. Also distributed generation influences this phenomenon. A measurement campaign taken out showed that angle differences up 6-7° at the 11 kV-level and voltage difference exceeding 300 V occurred, following an exchange of active power of more than 5 MW between the two coupled substations. Next to that, a reactive power of about 800 kVAr was exchanged between the substations in the opposite direction. The effect of distributed generation placed in the loop of the parallel coupling can be positive, when it supplies loads nearby with active and reactive power, thereby reducing the loop current locally. It can also have a negative effect when additional power is injected in the loop and transferred on top of the compensating current in the loop. More insights gained during parallel couplings helped the grid operators in defining additional guidelines. An important factor is the state of the upstream high-voltage grid of both substations. In preference the upstream source should be the same, yet this is not always possible in practice. Close interaction between the DGO and the TGO is needed in order to choose the best configuration of the whole grid. The timing of the action is also of great importance, in order to reduce the effect of the loads. Usually the best moments are early in the morning or late in the evening, but this should be evaluated case per case. The results were compared to the state estimators used by DGO's and TGO's, and to grid simulators in order to refine the calculations.

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