PMU-BASED POWER SYSTEM ANALYSIS OF A MV DISTRIBUTION GRID

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ABSTRACT

The installation of PMUs by Enduris, one of the Distribution Network Operators (DNO) in the Netherlands to monitor their 50 kV ring distribution grid has resulted in increased observability of the power flows and voltages. However, with the increased observability, there is a need to analyse the distribution grid based on the data generated by the PMU monitoring system. This paper provides steady state and dynamic analysis of the 50 kV Enduris ring distribution grid in terms of voltage and power flow behaviour based on the real time data acquired from the PMUs. First, the Enduris 50 kV distribution grid under study is modelled in PowerFactory software. This model is subsequently used for analysis of the distribution grid behaviour for two contingencies. The contingencies are actual grid events observed by the PMUs, and using this data, the contingencies are simulated and analysed. The analysis results of each contingency are compared with the data from the PMU monitoring system.

INTRODUCTION

The need for a better distribution grid monitoring infrastructure, due to increasing penetration of renewable energy sources has prompted Enduris[1], one of the Distribution Network Operators (DNO) in the Netherlands, to install Phasor Measurement Units (PMUs) in their 50 kV ring distribution grid. By this, an increased observability of their 50 kV distribution grid is achieved [1]. In [1], details about the need of using PMU infrastructure for monitoring the Enduris 50 kV distribution grid, the description of the 50 kV ring distribution network and the possible applications of PMUs in the distribution grid is provided.

This paper provides an analysis of behaviour of the Enduris distribution grid based on the power flow behaviour and the voltages in the 50/10/0.4 kV distribution grid by using the real time data acquired from the PMU measurements. First, the Enduris 50 kV distribution grid is modelled in PowerFactory software. Subsequently, two grid contingencies, one in the 50 kV distribution grid and one in the 10/0.4 kV sub-distribution grid, are identified and described by making use of the PMU measurements.

Next, a methodology is described to calculate the approximate aggregated generation and load in the distribution grid using the real time power flow values from PMU and SCADA measurements. This methodology forms the basis for calculating the initial load flow condition during each of the grid contingencies.

From the simulation results, the power flow behaviour and voltages in the distribution grid are analysed and the response of the distributed generation is predicted during both events. The analysis results are compared with the actual PMU measurements and conclusions about the grid behaviour are drawn based on the studied contingencies.

THE MODELLING OF THE DISTRIBUTION GRID

50/10/0.4 kV grid modelling

The network of the Enduris 50 kV distribution grid shown in Figure 1 and further described in paper [1] is modelled using PowerFactory software. The ring distribution grid consists of six substations connected to each other via 50 kV cables. (except for the Gsp-150 150 kV to Gse-50 50 kV substations which is a 50 kV line connection) The ring network is connected to the 150 kV parallel transmission lines through 150/50/10 kV three winding power transformers as shown in Figure 1. The 150 kV transmission network is represented by an external infinite grid connected at the Gsp-150 150 kV substation modelled as a slack bus, to perform power balancing of the distribution grid. This is an assumption of a 50 kV distribution grid containing distributed generation set as PQ nodes, and the external grid acting as a reference bus providing grid balancing [2].

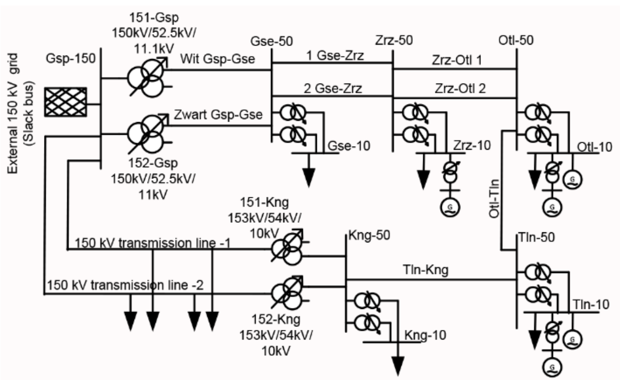

Figure 1- Schematic Enduris 50 kV distribution grid model

The analysis is concentrated on the five 50 kV substations of Gse, Zrz, Otl, Tln and Kng and their respective 10 kV bus, which form the 50 kV ring distribution grid monitored by PMUs. The connection between the 50 kV and its

1 Delta Network Group (DNWG) is per January 2016 renamed as Enduris, the name used in this paper.

respective 10 kV bus is through parallel two winding 52/11.1 kV distribution transformers with only one transformer in service at a given time.

Each of the 10 kV buses has a mix of distributed generation and loads connected down to 0.4 kV voltage level. The distributed generation consists a mix of wind farms and combined heat and power (CHP) plants. The DG sources at each of the 10 kV buses are modelled as single machine representation of total aggregated wind power and CHP plants.

For wind turbines, generic doubly fed induction generator (DFIG) models connected at 0.4 kV bus available in PowerFactory with pre-defined control parameters are used with a step-up transformer connecting the DFIG to the 10 kV bus [3]. The CHP plants are modelled as single machine synchronous generator directly connected to 10 kV bus and equipped with voltage control and speed governor control. The loads are modelled as general static constant impedance; inductive load with a voltage dependency [4] directly connected to the 10 kV bus. The approach similar to [5] is used here for similar distribution grid studies.

EVENT DESCRIPTION BASED ON PMU MONITORING

Contingency in the 50 kV distribution grid

The contingency considered here is an actual event, namely the disconnection of one of the 2 overhead lines connecting the Gse-50 kV substation with the Gsp-150 substation (See Figure 1).

The PMU measurements of the contingency are available in the form of snapshots from the PMU which monitors the Gse-50 kV substation.

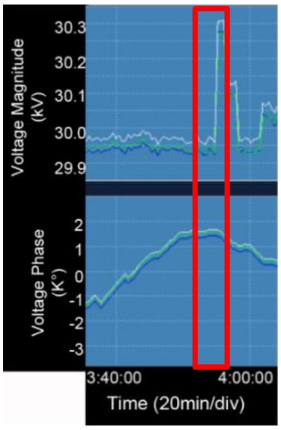

Figure 2-PMU snapshot highlighting in red the change in voltage and voltage phase angle as a result of 50 kV overhead line disconnection at the Gse-50 50 kV substation

The PMU snapshot of the contingency shown in Figure 2 shows the real time variation of per phase voltage (V_{ph} in kV) and the continuous voltage phase angle variation (δ in degrees) at the Gse-50 50 kV substation over a period of 20 minutes with the time instant of overhead line disconnection highlighted in red. As observed, the per phase voltage (V_{ph} in kV) at the Gse-50 50 kV substation increases slightly from approximately 29.95 kV to 30.3 kV. For the purpose of the analysis, the distribution grid is considered as a balanced 3-phase network, hence the jump in voltage when calculated to three-phase line to line voltage (V_{LL} in kV) is from 51.87 kV to 52.48 kV. The rated voltage of the distribution grid is 52.5 kV (1 p.u.). Hence, the change in the voltage at the Gse-50 50 kV substation in terms of p.u. quantities is within 0.988 p.u. to 0.99 p.u. The change in the voltage phase angle (δ in degrees) at the Gse-50 50 kV substation too, is hardly noticeable after the contingency. The changes seen are well within the grid voltage limits of 1.05 p.u. and 0.95 p.u. indicating no voltage stability issues within the distribution grid.

The PMU snapshot from Figure 3 shows the real time variation in total three phase active power P and reactive power Q flow on the 2 Gse-Zrz 50 kV cable, measured at the Gse-50 50 kV substation in a time interval of around 2 minutes with the time instant of overhead line switching highlighted in red. From the highlighted section, the change in total power flow can be observed. The negative values of 3-phase active and reactive power (P and Q) mean power flow into the Gse-50 50 kV substation from the 2 Gse-Zrz cable. The total active power flow into the Gse-50 kV substation increases from approximately 0.4 to 1 MW (white plot), and the total reactive power flow decreases from 8.8 to 7.4 MVAR (green plot) approximately. Identical amount of power flows into the Gse-50 50 kV substation from the 1 Gse-Zrz 50 kV cable connected in parallel with 2 Gse-Zrz 50 kV cable. (See Figure 1)

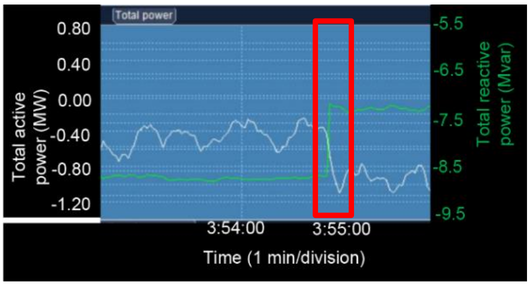

Figure 3- PMU snapshot highlighting the change in active and reactive power on the 2 Gse-Zrz 50 kV cable due to 50 kV overhead line disconnection

Contingency in 10/0.4 kV sub-distribution grid

The second contingency considered is the loss of distributed generation from the Zrz wind farm at the Zrz 10 kV bus. Apart from the variation in the wind, which influences the power output from the wind farm, as per the inputs from the distribution network operator (DNO)

Enduris, the power output from some of the DG sources is also dependent on the energy market. The case considered here is during a specific day when a controlled drop in power output from rated power of 10 MW to zero from the Zrz wind farm takes place. The sudden drop in power output is reflected as voltage oscillations and results in redistribution of power flows in the 50 kV distribution grid logged by the PMU at Zrz-50 50 kV substation shown in Figure 4 and Figure 5.

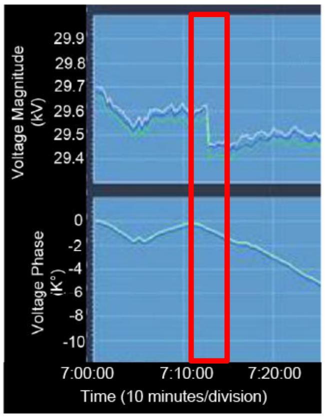

Figure 4- PMU log showing the per phase voltage and instantaneous voltage phase angle at the Zrz-50 50 kV substation during sudden drop in wind power at Zrz-10 kV bus

Notable observations from the time instant highlighted in red in Figure 4 are a slight drop in the per phase voltage (V_{ph} in kV), approximately from 29.6 kV to 29.4 kV at the Zrz-50 50 kV substation. The consideration of a balanced 3-phase network translates to 3-phase line to line voltage (V_{LL} in kV) from 51.3 kV to 51 kV (0.977 p.u. to 0.971 p.u.) at the Zrz-50 50 kV substation. The continuous plot of the voltage phase angle (δ in degrees) at the Zrz-50 50 kV substation shows a very small change. The changes in voltage are attributed to the sudden drop of power generation from 10 MW to zero from the wind farm at Zrz 10 kV bus.

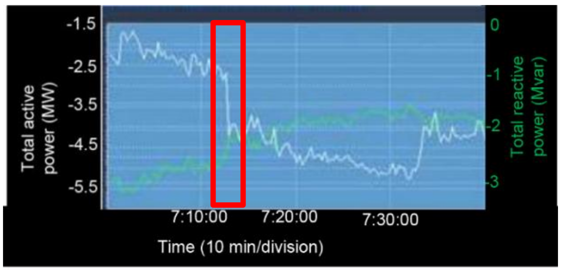

Figure 5- PMU log showing the power flows on the Zrz-Otl 1 cable during sudden drop in wind power at Zrz 10 kV bus

Figure 5 shows the real time variation in total three phase active power P and reactive power Q flowing on the Zrz-Otl-1 cable. Notable observation from the time instant highlighted in red is the variation in total active power, which increases from approximately 2.9 MW to 4.4 MW (white plot) with a small change in the total reactive power (green plot). The negative values indicate power flowing into the Zrz-50 50 kV through the Zrz-Otl 1 cable.

Hence, from PMU logs at the Zrz-50 50 kV substation, we observe a drop in voltage and increased power flow into the Zrz-50 50 kV substation as a result of the loss of generation from the Zrz wind farm. The voltage observations show that the system remains stable, but produces slight noticeable voltage and power oscillations at the Zrz-50 50 kV substation.

SIMULATION METHODOLOGY

In the simulation of both contingencies, the total aggregated values of power generation (P_{gen} and Q_{gen}) from the DG sources (wind power and CHP plants) and the total loads (P_L & Q_L) at each 10 kV bus is calculated separately for each contingency, since the power flow behaviour in the 50 kV grid was different during the time of each contingency. Furthermore, the actual total generation and load in the distribution grid was not available from the PMU and SCADA monitoring system during each contingency. Hence, the SCADA data was used, which provided the power exchange data between 50 kV and 10 kV bus. Based on this observed power exchange data, the total aggregated active and the reactive power generation (P_{gen} and Q_{gen}) from DG sources at the 10 kV bus and the total aggregated load (P_L & Q_L) at the 10 kV bus was approximately calculated, to match the pre-contingency power flow and voltages in the distribution grid. This was done separately for each of the two considered contingencies based on simple equations described below;

$$P_{ex} = P_{gen} - P_L \quad (1)$$

$$Q_{ex} = Q_{gen} - Q_L \quad (2)$$

Where P_{ex} & Q_{ex} are the active & reactive power exchange between 50 kV and 10 kV bus, P_{gen} & Q_{gen} are the aggregated active & reactive power generation at the 10 kV bus from DG sources (wind farm + CHP plants), and P_L & Q_L are the aggregated active & reactive power load at the 10 kV bus.

Positive values of P_{ex} & Q_{ex} indicate surplus total aggregated power generation from DG sources over total aggregated load and negative P_{ex} & Q_{ex} values indicate that the total aggregated load is more than the total aggregated generation at each 10 kV bus. Whether there is surplus power generation or load at the 10 kV bus or not, was inferred by power flow values at each 50 kV/10 kV transformers available from the SCADA data during the time of the two contingencies.

The time domain based RMS analysis functionality from PowerFactory was used to separately simulate the switching out of the 50 kV overhead line and the switching out of aggregated single DFIG wind generator of 10 MW to investigate both contingencies. The results of these analyses are presented in the next section.

RESULTS & ANALYSIS

Contingency in the 50 kV distribution grid

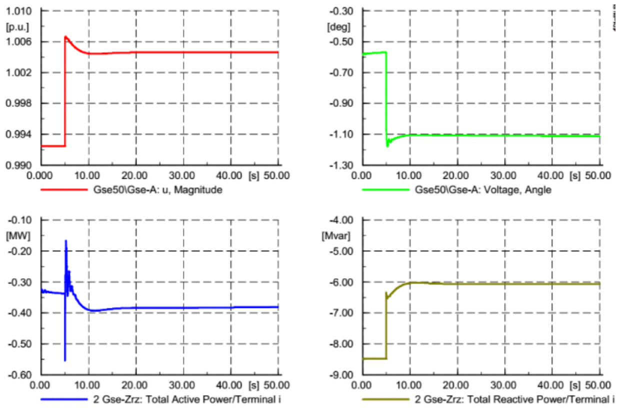

Figure 6-Simulated voltage and power flow on 2 Gse-Zrz cable measured at Gse-50 50 kV substation (terminal i)

Figure 6 shows the results of the simulation of the first contingency. At the instant when the overhead line is switched off at 5 seconds, the voltage at the Gse-50 50 kV substation increases from pre-contingency value of 0.993 p.u. (52.13 kV) to a new steady state value around 1.005 p.u. (52.7 kV). In terms of magnitude, the voltage rise is very small and within the steady state limits of 1.05 p.u. indicating voltage magnitude stability. The corresponding change in voltage angle is also small. The total load at the Gse-10 10 kV bus supplied by the Gse-50 50 kV substation although constant, is modelled by voltage dependency. The slight increase in the 50 kV voltage at the Gse-50 50 kV substation is also reflected in the total active power flowing into the Gse-50 50 kV substation (terminal i). The part of the load is fed by Gse-Zrz 1&2 parallel cables where the total active power flow from each 1&2 Gse-Zrz 50 kV cable is increased slightly from 0.34 MW to approximately 0.39 MW while the total reactive power flow decreases from 8.5 MVAR to 6 MVAR (negative values by convention mean power flow into Gse-50 50 kV substation from the 2 equal-impedance Gse-Zrz cables).

Disconnection of one line in the parallel line section between the Gsp-150 150 kV and Gse-50 50 kV sub-stations doubles the impedance between these substations. As a result, the total current flow decreases as observed from Figure 7 where the shift in current flow on Zwart Gsp-Gse overhead line decreases from an initial value of 0.258 kA (twice of 0.129 kA) to a reduced value of 0.208 kA This is accompanied by the slight reduction in the reactive power flow out of Gse-50 50 kV substation from around 22 MVAR (twice of 11 MVAR) to 17 MVAR subsequently reducing the reactive power flow on the 1&2 Gse-Zrz cables (again, positive values indicate power flow out of the Gse-50 50 kV substation). Figure 7 shows that the total shift of the active power flow on the Zwart Gsp-Gse 50 kV overhead line into the Gse-50 50 kV substation from 3.8 MW to approximate 7.75 MW measured at the Gse-50 50 kV substation. This power is supplied to the 50 kV distribution grid from the 150 kV transmission network represented by a slack bus.

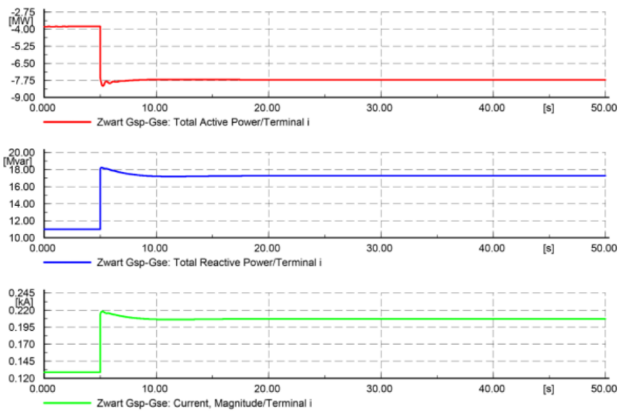

Figure 7-Simulated current and power flow on Zwart Gsp-Gse 50 kV line measured at Gse-50 50 kV substation (terminal i)

Practically, the strong transmission network balances the power needed by the distribution grid where the 50 kV cable loadings are below 50% in this specific case. The results of power flow, current and voltages at the Gse-50 kV substation are in line with the observations from the PMU data of the contingency.

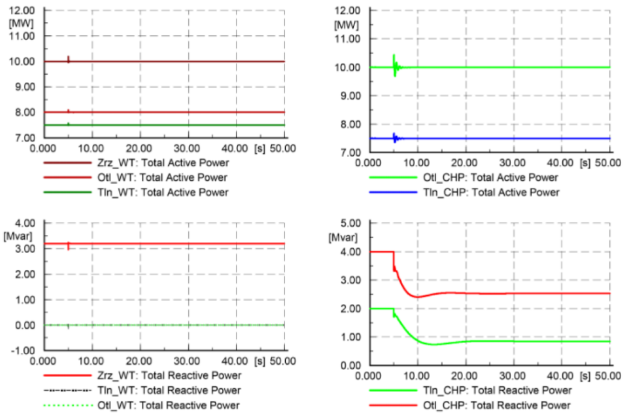

Figure 8-Simulated active and reactive power output from the DG sources

The disconnection of the 50 kV overhead line does not have any noticeable effects on the total supply and load demand of the distribution grid. The balancing of the distribution grid by the external slack bus (the external infinite grid connected at the Gsp-150 kV substation), means the aggregated output powers of the generators (P_{gen} & Q_{gen}) rapidly return to their steady state values following the disturbance as seen from Figure 8. The change in the total reactive power supplied by the CHP generators is only affected slightly because of the action of the voltage controller.

Contingency in 10/0.4 kV sub-distribution grid

The second contingency concerns the switching off of the 10 MW wind generator at the Zrz 10 kV bus. The immediate observation of this event at t = 4 seconds in Figure 9 is a drop in voltage reflected at the Zrz-10 10 kV bus and the Zrz-50 50 kV bus. The drop in voltage at Zrz-10 10 kV bus is from 1.01 p.u. (10.7 kV) to 0.989 p.u. (10.5 kV). The rated voltage of the Zrz-10 10 kV bus is 10.6 kV (1 p.u.). The drop in voltage at the Zrz-50 50 kV bus is from 0.992 p.u. (52.08 kV) to 0.986 p.u. (51.765 kV).

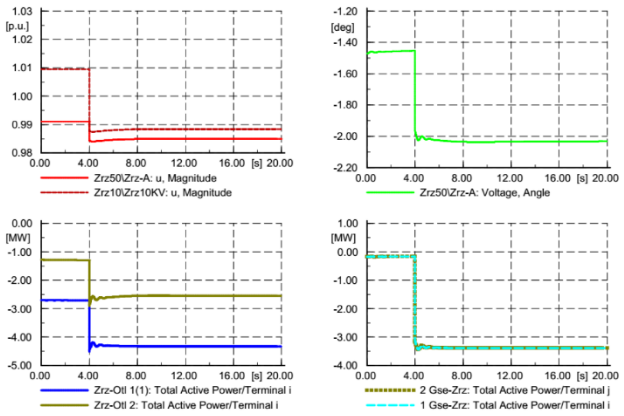

Figure 9-Simulated voltages and power flow at the Zrz-50 kV substation during the second contingency

The observed drop in voltage and voltage angle at the Zrz-10 kV and the Zrz-50 50 kV buses resulting from the loss of 10 MW generation at the Zrz 10 kV bus is marginal and within the system voltage stability limits of 1.05 and 0.95 p.u. respectively. Furthermore, from Figure 9 an increase is observed in the total active power flow into the Zrz-50 50 kV from the corresponding 50 kV cables (negative values mean power flow into the Zrz-50 50 kV bus) to meet the total load demand at the Zrz-10 kV bus as a result of loss of 10 MW generation.

The total load requirement is met collectively by the slightly increased total active power flow from Otl-50 50 kV substation having surplus power generation over load at that time instance. The rest of the active power requirement is balanced by the infinite grid of the 150 kV transmission network, which contributes a higher percentage of active power necessary for power balancing. The results from the simulation analysis compare very well with the PMU measurements at the Zrz substation.

Lastly, the response of the DG sources is similar to what is seen during the first contingency in Figure 8, with the total active power output of the generators (wind+CHP) at the 10 kV buses very quickly returning to steady state values following the disturbance. The surplus power flow from the Otl-10 10 kV side and external grid has enough capacity to balance the power loss without significantly affecting the power output from the distributed generation (DG) at the 10 kV sub-distribution levels.

CONCLUSION

The strong rise of distributed renewable energy generation has increased the need for real-time monitoring of distribution grids. In the Enduris 50 kV grid, PMU monitoring has significantly enhanced the observability of grid voltages and power flow behaviour. The analysis of the grid behaviour for two contingencies in the grid as given in this paper has proved the added value of the real-time PMU monitoring system.

From the observed PMU data and the simulations, it is concluded that the occurrence of both contingencies resulted in slight changes in voltages and redistribution of power flow in the distribution grid. The voltage fluctuations were well within the stable operating limits. A possible explanation for this is the connection of the Enduris 50 kV ring distribution grid to a secure 150 kV transmission network. The transmission network also ensures the power balancing of the distribution grid in both cases without having a significant impact on the response of the distributed generation.

Lastly, the research described in this paper has yielded a better understanding of the Enduris distribution grid behaviour based on the analysis of actual monitored data from the PMU monitoring system. The work done supports the overall Enduris-VSL project described in [1] aimed at efficient and effective management of the 50 kV distribution grid using PMU technology.

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Acknowledgments

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