Improved Understanding of Actual System Events using Synchrophasor Visualization

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Abstract

Electric power grids throughout the world are being impacted by changes in generation mix resulting from regulatory mandates. The German grid has seen a massive increase in non-traditional generation and is in the process of removing nuclear based generation. These changes have not caused new power lines to become easier to get added to the system. This has resulted in changes to power flows that result in operating conditions never anticipated as the system evolved over the past decades.

TenneT TSO, one of the four transmission system operators in Germany, has had a synchrophasor monitoring system in place since 2009. Several system-wide events have demonstrated the usefullness of such a monitoring system to help operators understand both long term and short term conditions impacting grid stability. Visualization and analysis tools applied to synchrophasors have improved and changed during this time in order to become a system that goes beyond simple phase angle trending.

This paper looks at a number of system events that occurred during the period that synchrophasor records have been kept. These events include loss of generation, line tripping and effects from distribution side. Different techniques are described that illustrate how a number of methods are necessary to help operators follow events without flooding them with data. How synchrophasors provide understanding beyond traditional SCADA- or EMS based systems is detailed.

Conclusions based on these events as well as looking at how the monitoring system must continue to change to keep up with power system changes is provided to help power system professionals determine how to apply new synchrophasor tools to improve system reliability, stability and economy.

1. Introduction

TenneT TSO GmbH is one of the four German TSOs. It belongs to the company TenneT Holding B.V. based in the Netherlands. TenneT operates in total 21.000 km of high voltage lines

(400kV to 110kV), 403 substations, 67 GW installed generation and 182.000 km2 supplied area (about the size of Oklahoma, slightly bigger than Missouri). Fig 2 shows the supply area of TenneT TSO GmbH in Germany. It reaches from the North Sea to the Alps. The TenneT transmission system is part of the European transmission system organized in ENTSO-E (European network of transmission system operators for electricity). Europe had over 8 GW of offshore wind [European Wind Energy Association] in 2014 with over 2.9 GW awaiting connection.

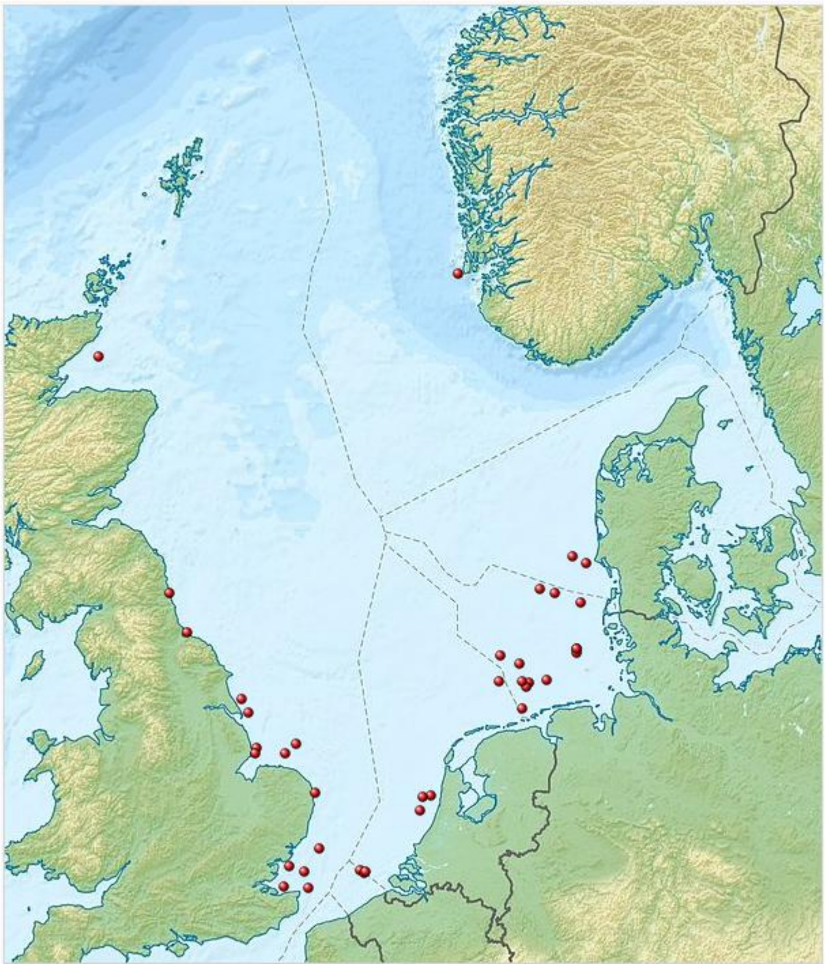
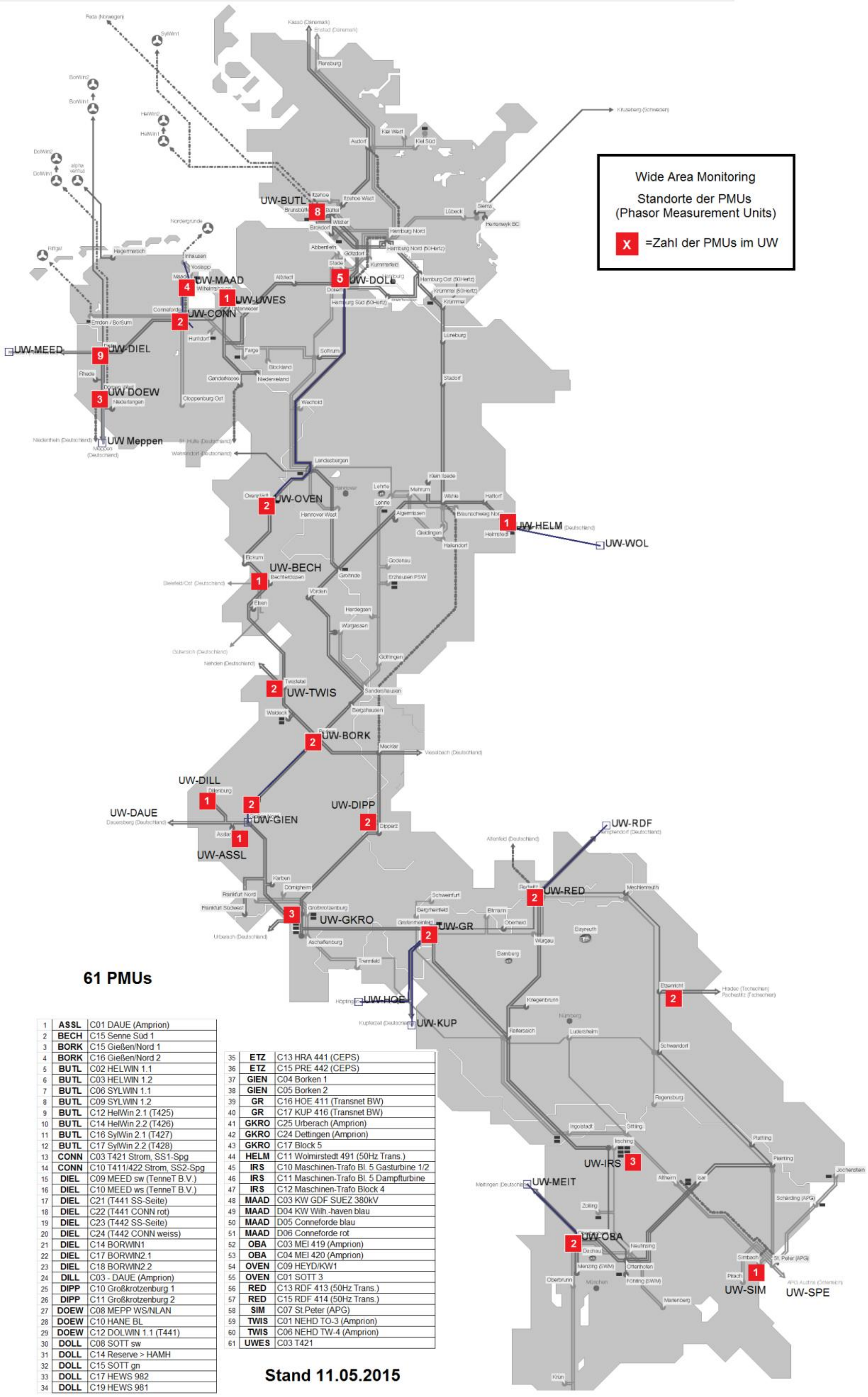


Figure 1 Wind Farm Locations on the North Sea

Note the map in Figure 1 shows the location of these wind farms, with a large number clustered along the German portion of the North Sea. While there are significant loads in the area (Amsterdam and Hamburg) a lot of power needs to be transported to load centers such as Frankfurt, Cologne, and Munich. The Phasor Monitoring Units (PMUs) connected along this power transfer path, along with a number of the lines, are shown in figure 2. Currently, 61 PMUs are installed on 400kV level in the supply area of TenneT TSO Gmbh (red squares in the figure 2). They report to a Wide Area Monitoring System Phasor Data Concentrator, which has been in service in Bayreuth since 2009. Having PMUs spread throughout the system provides a powerful view of changing system conditions. The quantities available for viewing include more than just phase angle. Power flow, frequency, voltages and phase angles are all viewable in trending and real time views for system operators.



61 PMUs

1	ASSL	C01 DAUE (Amprion)
2	BECH	C15 Senne Süd 1
3	BORK	C15 Gießen/Nord 1
4	BORK	C16 Gießen/Nord 2
5	BUTL	C02 HELWIN 1.1
6	BUTL	C03 HELWIN 1.2
7	BUTL	C06 SYLWIN 1.1
8	BUTL	C09 SYLWIN 1.2
9	BUTL	C12 HelWin 2.1 (T425)
10	BUTL	C14 HelWin 2.2 (T426)
11	BUTL	C16 SylWin 2.1 (T427)
12	BUTL	C17 SylWin 2.2 (T428)
13	CONN	C03 T421 Strom, SS1-Spg
14	CONN	C10 T411/422 Strom, SS2-Spg
15	DIEL	C09 MEED sw (TenneT B.V.)
16	DIEL	C10 MEED ws (TenneT B.V.)
17	DIEL	C21 (T441 SS-Seite)
18	DIEL	C22 (T441 CONN rot)
19	DIEL	C23 (T442 SS-Seite)
20	DIEL	C24 (T442 CONN weiss)
21	DIEL	C14 BORWIN1
22	DIEL	C17 BORWIN2.1
23	DIEL	C18 BORWIN2.2
24	DILL	C03 - DAUE (Amprion)
25	DIPP	C10 Großkrotzenburg 1
26	DIPP	C11 Großkrotzenburg 2
27	DOEW	C08 MEPP WS/NLAN
28	DOEW	C10 HANE BL
29	DOEW	C12 DOLWIN 1.1 (T441)
30	DOLL	C08 SOTT sw
31	DOLL	C14 Reserve > HAMH
32	DOLL	C15 SOTT gn
33	DOLL	C17 HEWS 982
34	DOLL	C19 HEWS 981
35	ETZ	C13 HRA 441 (CEPS)
36	ETZ	C15 PRE 442 (CEPS)
37	GIEN	C04 Borken 1
38	GIEN	C05 Borken 2
39	GR	C16 HOE 411 (Transnet BW)
40	GR	C17 KUP 416 (Transnet BW)
41	GKRO	C25 Urberach (Amprion)
42	GKRO	C24 Dettingen (Amprion)
43	GKRO	C17 Block 5
44	HELM	C11 Wolmirstedt 491 (50Hz Trans.)
45	IRS	C10 Maschinen-Trafo Bl. 5 Gasturbine 1/2
46	IRS	C11 Maschinen-Trafo Bl. 5 Dampfturbine
47	IRS	C12 Maschinen-Trafo Block 4
48	MAAD	C03 KW GDF SUEZ 380kV
49	MAAD	D04 KW Wilh.-haven blau
50	MAAD	D05 Conneforde blau
51	MAAD	D06 Conneforde rot
52	OBA	C03 MEI 419 (Amprion)
53	OBA	C04 MEI 420 (Amprion)
54	OVEN	C09 HEYD/KW1
55	OVEN	C01 SOTT 3
56	RED	C13 RDF 413 (50Hz Trans.)
57	RED	C15 RDF 414 (50Hz Trans.)
58	SIM	C07 St.Peter (APG)
59	TWIS	C01 NEHD TO-3 (Amprion)
60	TWIS	C06 NEHD TW-4 (Amprion)
61	UWES	C03 T421

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Fig.2: Supply Area of TenneT TSO in Germany

In the following, some events which illustrate the capability of different recordings have been will be discussed.

2. Results from German transmission network measurements

2.1 Loss of generation

In July 2009, a large power plant was shut off unplanned in the TenneT TSO area. The resulting measurements are shown in the next figures.

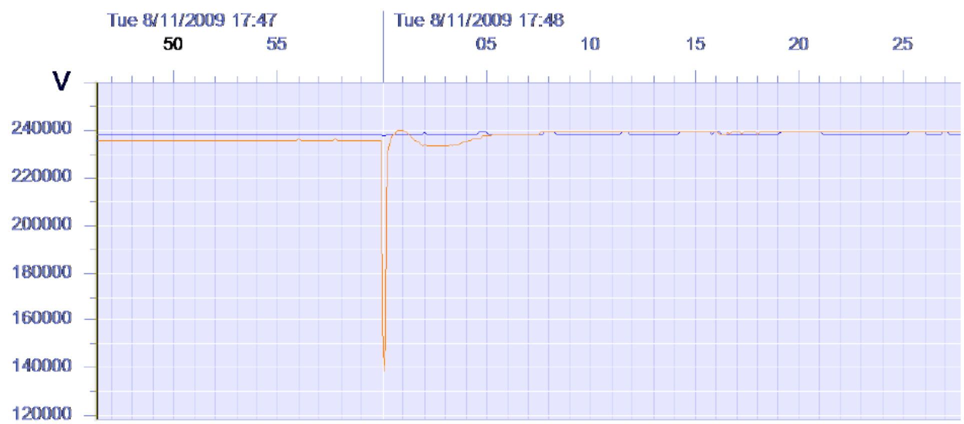

Fig. 3: Voltage in the northern region (orange) and in the southern region (blue)

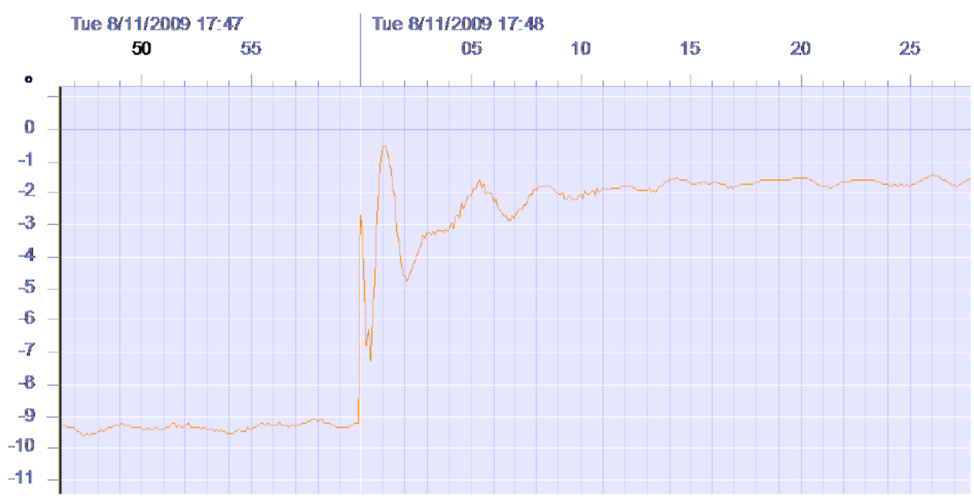

Fig. 4: Phase angle difference between north and south

Fig. 3 shows a voltage collapse of about 10 seconds duration, measured close to the power plant (orange. Northern PMU) from 220kV to 140kV, while the southern PMU, approx. 700 km away, shows nearly no impact on the voltage. Fig. 4 shows the phase angle difference between north and south, resulting in a delta phi of approx. 7 degree between pre-event status and post-event status. This is an indication for the changed power flow in the system for the post-event case. From the equation $P=V_1V_2\sin\Theta/X$ it can be shown that the power flow from North to South decreased by almost 80% (by observing that the voltage before and after the event was practically unchanged, and assuming the inductance between North and South was unchanged). The power and var flow transients from a different event is shown in figure 6 below.

2.2 Influence of power plant schedule on frequency

During the daily schedule for the power plants, generation is switched on and off, typically at the full hour. The effect can be seen from the frequency measurements, see fig. 5. In the morning at 6:00 and 7:00, power plants are starting and in the evening starting at 20:00, they are switched off again. From the frequency difference, it is possible to determine the active power: According to ENTSO-E operational handbook, 0.2 Hz means +-3000 MW. So at 6:00 we can see that the frequency goes from 49.975 to 50.100 Hz, a change of 0.125 Hz or +1875 MW. Comparing this measured value with that value given in the operational handbook provides a check to ensure model validity.

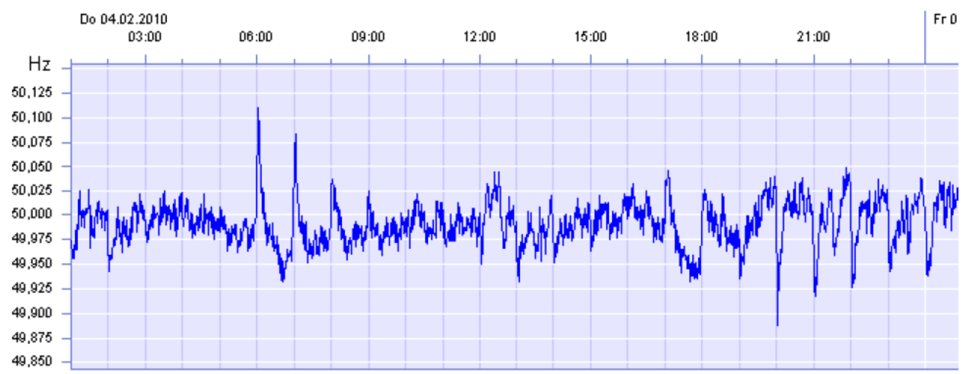

Fig.5: Frequency measurement from PMU along the day

2.3 Power swings after line trip

With the PMU measurements, the full amplitudes of power swings can be clearly seen. As fig. 6 shows, after a line trip the exact behavior of P and Q is viewable on the operator´s screen. With state estimation results, this is not possible. The state estimator could anticipate the loss of 12 Mvar and 50 MW from the line trip but the oscillation of 1.67 Hz and the swing amplitude of 30 MW could not be forseen. Understanding natural frequency modes of the system are a unique contribution of synchrophasors in the system.

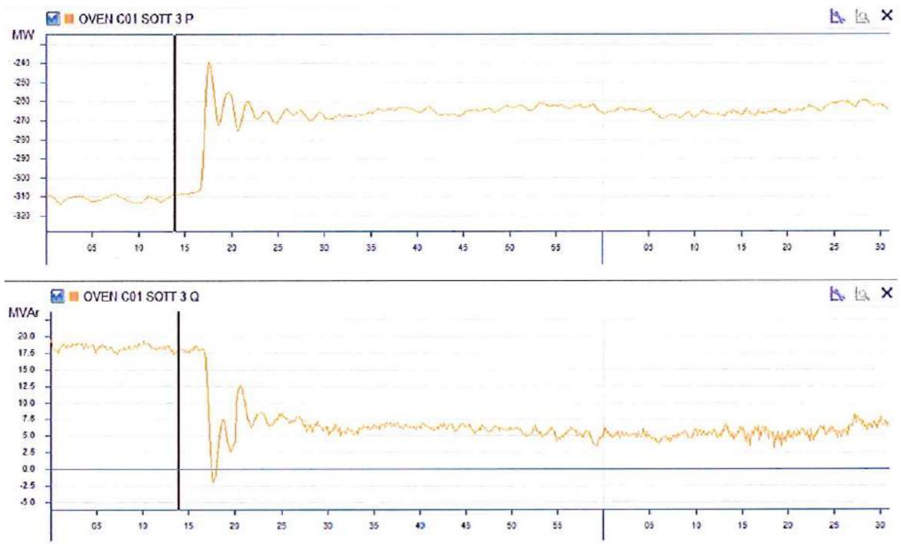

Fig. 6: Measurement of P and Q after line trip

2.4 Phasor View in high load situation

The power system illustrated in figure 2 does not show all the parallel paths in systems around that owned by TenneT. Because information sharing between operating companies is never perfect, knowing the load flow on a single line, or path, will not give a complete picture of the overall regional load flow. Fig. 7 shows 14 voltage phasors from the 400 kV system and 1 from 220kV system in a common phasor view. The phase angle between North and South in the 400kV system is approx. 50 degree which gives a clear indication to large power flow from north to south, even without knowing the load flows on lines outside the TenneT system.

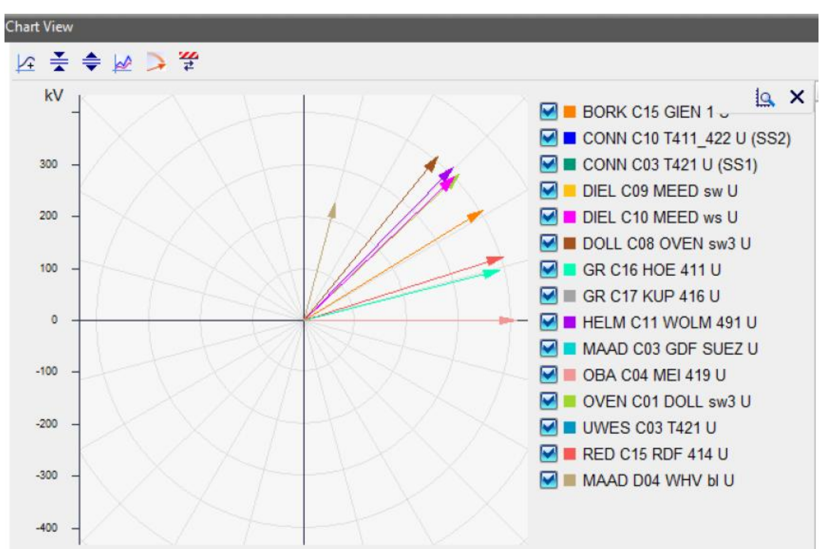

Fig.7: Voltage phasors, captured with synchrophasor software

2.5 Automatic Power Swing Recognition

With the Phasor Data Processor (PDP), it is possible to automatically search the PMU data stream for power swings. If they occur with a previously identified critical frequency with amplitude and damping of a magnitude that could cause system problems, an alarm is given and the detected modes are displayed. An example is shown in Fig. 8.

The power swing recognition works on a phase angle difference as input (alternatively active power from one PMU is possible but more limited). It continuously processes the input stream and watches for characteristic frequencies. These modes are signaled when they occur. In the example shown in figure 8, the 0.25 Hz Mode and the 0.4 Hz mode are detected and indicated.

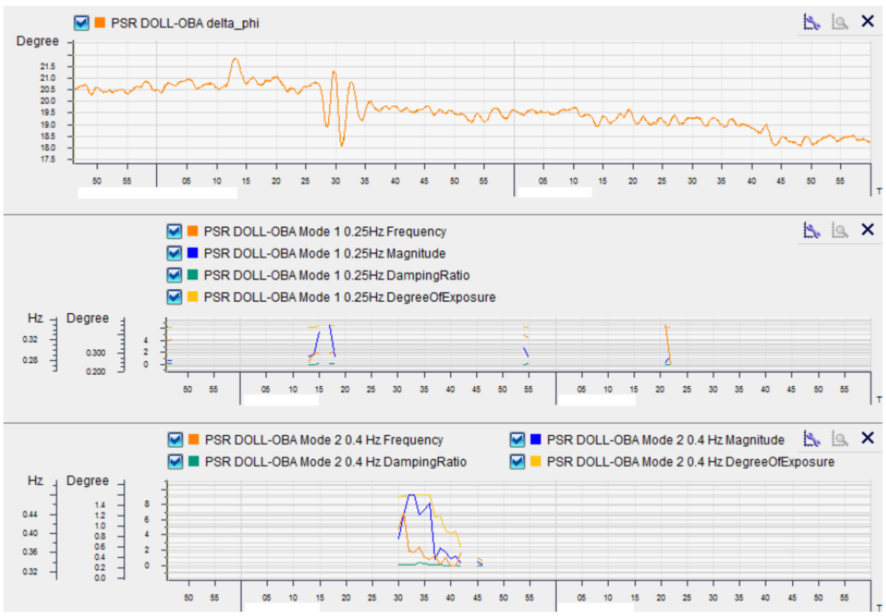

Fig.8: Power swing, detected by PSR functionality of PDP

2.6 Influence of power plant trip in southern Europe

In 2010, a power plant in southern Europe was suddenly switched off. The effect was recorded by the PDP system.

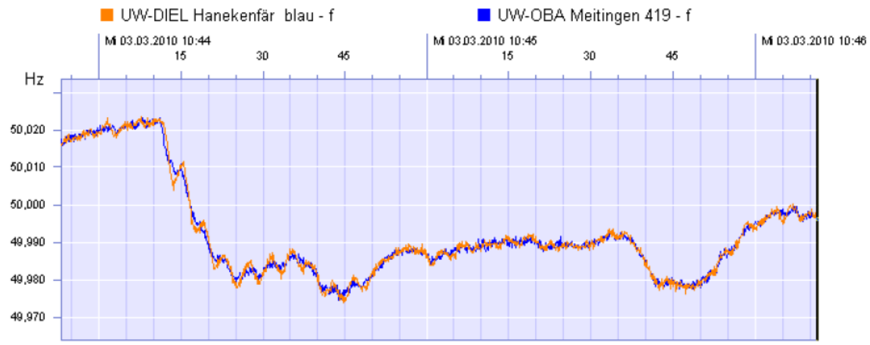

Fig. 9: Frequency measurements

Note from section 2.2 above this indicates a loss of about 600 MW.

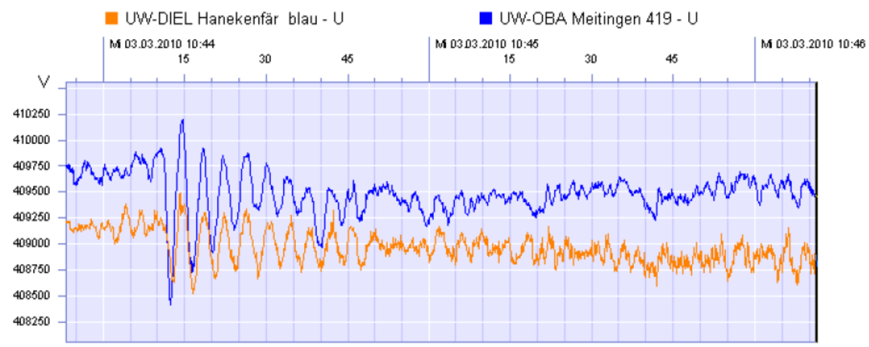

Fig. 10: Voltage measurements

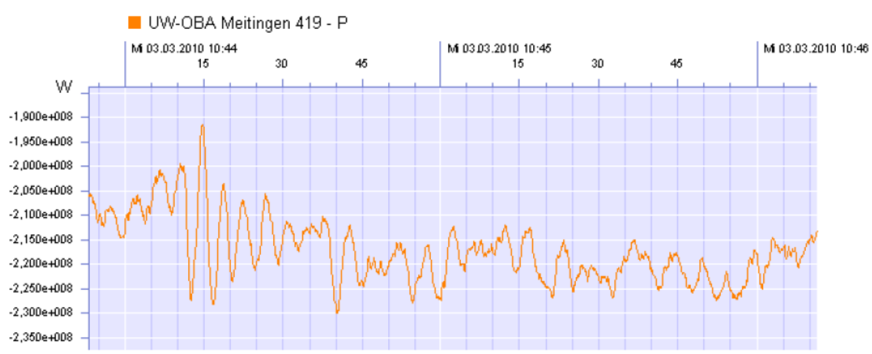

Fig. 11: Active Power measurements

The trip of the power plant initiates the north-south mode of the ENTSO-E network (0.4 Hz). On the far end, in the northern part of Germany, the amplitude of active power (indicated by the frequency swing amplitude, orange curve in fig. 9), is the highest. On the south end of Germany, closer to the event, the amplitude of reactive power swing is larger than in the north, indicated by the voltage (fig. 10). In fig. 11, the amplitude of the power swing on a southern german line can be determined to +- 40 MW. It is interesting to note that 10 seconds after the line trip in section 2.3 the power oscillations were only 5 MW. After that same time following a generator trip (in the southern area) we are seeing 15 MW oscillations. After one minute we are still observing 10 MW oscillations that do not apear to be diminishing.

Conclusions

The amount of data available to system operators is literally beyond human comprehension. Synchrophasor based display and analysis tools provide methods of condensing that data into understandable, and actionable, information. Some of the data, such as voltage and frequency, has always been available. Here synchrophasors improve the accuracy and timeliness of the information. Other data, such as system phase angle, can be calculated by a state estimator, but is only directly viewable with synchrophasors. Some information, here we see the oscillations with calculated magnitude and damping, are only available in real time using synchrophasors and systems such as a PDP to calculate derived values. Future developments in synchrophasors will be needed to meet the demands of a changing power system. More low inertia machines are being added, using solar and wind and other power sources. These will change system dynamics in ways that will require more information be delivered in more actionable ways, to system operators. Real-time controls, based on synchrophasor data, will become necessary as system stability requirements involve faster response than human intervention can provide.