IMPACT OF DISTRIBUTED GENERATION ON GRID PROTECTION AND VOLTAGE CONTROL

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ABSTRACT

This paper deals with the influence of renewables on the power system operation - voltage and dynamic stability.

INTRODUCTION

One of the important operating tasks of system operators and power utilities is to keep voltage and frequency within an allowable range for high quality customer services. Electric power loads vary from minute to minute and output from renewable sources change as well. These two phenomena cause changes of power flows, node voltages and system frequency. This paper demonstrates these aspects of power system operation on dynamic model from transmission and distribution systems point of view.

In the first part we deal with loop flows caused by wind generation in central European region (in terminology of ENTSO-E so called Central East Europe – CEE) and frequency protection of distributed renewable sources especially photovoltaics (PV).

The second part of this paper deals with model of distribution network in northern Bohemia regards to simulation of behavior of PV plants and their impact on voltage and reactive power flows.

IMPACT ON TRANSMISSION SYSTEM

For the investigation of loop flows effects (which mainly occur during high electricity production from wind farm in the Northern Germany) and their mitigation (using of phase shifting transformers –PST) equivalent Pan European dynamic model was used. This model was introduced in [1] and it was created on the base of detailed network model used in frame of EWIS study (see [2]). The one-line scheme of the model is depicted in Fig. 1. Each control area of the European continental interconnection was reduced into one so called hub node (with concentrated load and generation) and several border nodes (including terminals of DC lines to Great Britain, Sweden and Norway). Moreover Germany was divided into three parts – corresponding to two transmission system operators (TSOs - 50hertz Transmission and TenneT TSO) and rest of Germany was marked DE. The detailed model was reduced from 8521 to just 82 nodes. This size reduction is important for enhancing simulation speed, moreover it enables the data transfer between the results of the Market Model (described in [3]) and the input data (load and generation) for network simulation (the MODES simulator was used – see e.g. [4]–[6]).

Fig. 1 Simplified one-line scheme of equivalent Pan European network model (CEE part)
**Loop flows in the CEE region**

In the EWIS project ([2]) it was found that some situations with high wind generation in Northern Germany altogether with high export from Germany to southeastern Europe may cause network overloading in the Central European region. Among important mitigation measures to preserve present level of operational security belong:

1. line reinforcement by increasing its ampacity,
2. variable line ampacity according weather condition.

Transmission system will get that way one of the attributes (optimization of asset utilization and operation efficiency – see [7]) of so-called smart grids.

Installation of phase shifting transformers (PST) is not considered to be an efficient measure (in the long run perspective). The EWIS analysis has shown that the installation of PST generally cannot be considered a sustainable measure for solving the overload in the CEE region. It is advisable that the influence of PST installation could be investigated on Pan European network model as well. This model was complemented by two PSTs between Czech Republic (CZ) and Poland (PL). Last week of 2015 (it corresponds to so-called High North Best Estimation scenario from the EWIS study) was selected for simulation. Hours from market model were shortened to 15 minutes in equivalent model to speed up calculations. Power changes (load, generation setup and DC lines transfer) were carried out in each time interval. Fig. 2 shows time courses of power flows for 3 variants:

1. Var1 without PST,
2. Var2 with PST on 50hertz – PL border and
3. Var3 with PSTs on 50hertz – PL and CZ borders.

It is seen large fluctuation of power flows during day caused by brisk trading on electricity market in Europe. The PSTs are controlled automatically to limit power flows from 50hertz to CZ and PL. During strong wind conditions in the Northern Europe at the end of the week PST in Var2 decreases loop flows through PL, but increases power flows in CZ. Installation of PST on 50hertz – CZ border decreases power flows significantly in Var3, but it moves overloading to neighboring systems.

**Disconnection of photovoltaic panels (PV)**

Presently the impact of automatic disconnection of PV due to frequency deviation is analyzed and investigated. About several thousand MW of PV generation may be disconnected in case of over frequency above 50.2 Hz. The power deficiency caused by the PV disconnection could threat the operational security of the interconnected European power system. Case study based on Pan European model was carried out to examine this risk. The model was complemented by six PV sources, which represent risk of disconnection at frequency 50.2 Hz.

![Fig. 2 Flows between 50hertz TSO and CZ](image)

**Tab. 1 Peak power $P_{PV}$ and location of PV**

<table>
<thead>
<tr>
<th>Location</th>
<th>tennet</th>
<th>DE</th>
<th>CZ</th>
<th>PL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{PV}$ [GW]</td>
<td>8</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Photovoltaics output power $P_{PV}$ was changed in dependency on day time $T$ according equation (1) – details are in [8]

$$P_{PV} = P_{PV0} \cdot e^{-\frac{T^2}{2\sigma^2}}$$

![Fig. 3 Frequency deviations $df$ during day](image)

<table>
<thead>
<tr>
<th>Day</th>
<th>$A$</th>
<th>$\mu$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear winter (for Germany)</td>
<td>0.66</td>
<td>12.33</td>
<td>2</td>
</tr>
<tr>
<td>Cloudy winter (for FR, BE and CZ)</td>
<td>0.49</td>
<td>12.36</td>
<td>2</td>
</tr>
</tbody>
</table>

Tab. 2 Approximation parameters

Peak load was 415 GW, primary and secondary control reserve were 3.4 GW and 3.8 GW (load frequency control is only in Germany). Four variants were investigated:

1. Var 1: without PV
2. Var2: with PV, without disconnection
3. Var3: PV disconnected at $f=50.2$ Hz
4. Var4: export of 600 MW from PV by DC cables.

Results of simulations are in Fig. 3. Frequency deviation $df$ is in the range of ±100 mHz during most of day in normal operation. Maximum $df = 250$ mHz is in midday for Var2 due to ~11 GW PV infeed (compensated by secondary control reserve in Germany and by primary control of the whole system). If approximately 9 GW of PV infeed is disconnected by over frequency relay in Var3 frequency decreases to $df=-180$ mHz, but it stays in the secure limits for the normal system operation. Export of 600 MW to Sweden and Norway through DC cables is enough to prevent PV disconnection in Var4.
IMPACT ON DISTRIBUTION SYSTEM

For the investigation of impact of voltage and reactive power flows a part of distribution network in northern Bohemia was chosen. This part of distribution network is fed from transmission system substation Babylon through one 400/110 kV transformer equipped with on load tap changer (OLTC). Within the distribution network a large PV plant (consisting of four smaller plants, see Fig. 4) is connected through two 110/35 kV OLTC transformers with rated power 63 resp. 40 MVA. Aforementioned PV plants are connected through series of HV cables, see Fig. 4. For simplicity all cables were modeled with identical parameters: 0.0754 Ω/km, 0.21 µF/km, 0.40 mH/km. Total load in modeled 110 kV area is 135.9 MW. This load varies during day according to typical summer daily load diagram. With 70 MWp installed in distribution network it is clear that active power flow will never change its direction.

A 24-hour-long simulation was carried out to properly assess changes in voltage throughout the day. Three cases were simulated. The following voltage control schemes of PV plants in their respective points of connection were set:

A. Constant voltage
B. Constant power factor 1
C. Constant voltage with droop compensation

Voltages in all nodes were monitored as well as tap changes and produced active and reactive power. Simulation is considered successful if voltage in all nodes stays within limits set according to Czech standard ±10% for 110 kV and 35 kV level. Also, the lower the number of tap changes, the better.

A – Constant Voltage Regulation

Before starting the simulation desired voltage in nodes with PV plants were set equal to value from steady-state load-flow. For plant RA301 the set point voltage is 36.3 kV, for RA140 37.0 kV.

B – Constant Power Factor 1

Power factor has to be set before carrying out the simulation. This is very easy since the generated reactive power is set to zero.

C - Constant voltage with droop compensation

This case is different from others because PV plants’ voltage regulator includes active current droop compensation. This means that the PV plant compensates voltage droop caused by active power production. When set properly the PV plant can fully compensate for this droop so no tap changes on transformers are necessary. Voltage in all nodes stays within permitted range in Fig. 7.

Fig. 5 Voltage in selected nodes

Fig. 5 shows that PV plants are perfectly capable of maintaining voltage at connection points. Voltage in node NOVINY_2 (gray) is affected by high active power flows when PV plants produce energy which results in voltage decrease. This is being compensated by tap changes at 110/35 kV transformers.

Fig. 6 Voltage in selected nodes

Fig. 6 shows a great rise of voltage (+2.2 kV) in PV plants’ connection points caused by active power generation. This rise is not compensated for and even exceeds the +10% voltage limit set by grid code (red dashed line).
production in Northern Germany and theirs mitigation by PST installation. Installation of PST may solve problems with overloading in affected parts of interconnection, but it may move problems in other part of network. Further investigation is recommended towards development of the guidelines for PST operation. These guidelines should be prepared in coordinated manner by ENTSO-E.

The second study deals with risk of disconnection of large amount of older FV installations from frequency deviation ±200 mHz (according old standard VDE 0126-1-1 from 2006). There is no significant risk for case of increase in frequency. Provided that the primary and secondary control reserves are sufficient, system is able to absorb FV disconnection. Moreover if there is free export capacity, it is possible to decrease power surplus in continental Europe interconnection by exporting power through DC line e.g. to Norway and to use it in hydro power stations. Possibilities of voltage control in distribution network with large PV plant embedded are examined in the second part of paper. It is also shown how large PV installations could cooperate in maintaining voltage in distribution network with droop compensation in voltage regulator (change of reference voltage according active power output).

For both distribution and transmission system operators it is best when large PV plants maintain constant voltage with active power droop compensation. This minimizes wear on tap changers as well as voltage deviations in distribution network. This behavior is consistent with requirements of the prepared ENTSO-E Network Code [9] and it could a part of Smart Grid concept.

REFERENCES

workInvestmentElectricityMarketsWeber.pdf
[7] Getting smart, IEEE power & energy magazine (ISSN 1540-7977), Volume 8, Number 2, March/April 2010, pg. 42
[9] Network Code for Requirements for Grid Connection applicable to all Generators, draft 1/2012, available online at: http://www.entsoe.eu

**Voltage Regulation Quality**

Voltage regulation quality in node NOVINY_2, where the PV plants are connected to distribution network, is summed up in Tab. 3.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOVINY_2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal voltage [kV]</td>
<td>35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean voltage [kV]</td>
<td>36.0</td>
<td>36.4</td>
<td>36.4</td>
</tr>
<tr>
<td>Standard deviation [kV]</td>
<td>0.344</td>
<td>0.093</td>
<td>0.052</td>
</tr>
<tr>
<td>Tap changes 110/35 kV</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Tap changes 400/110 kV</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Tab. 3 Voltage quality in node NOVINY_2

It turns out that cases B and C are the best in terms of voltage quality and tap changer wear. However, around noon in case B voltage at some nodes in 35 kV grid, where PV plants are connected, exceeds the upper limit (38.5 kV) set by grid code. To avoid this, voltage would have to be set lower to compensate for the rise. This would undoubtedly worsen voltage quality in node NOVINY_2. In case C voltage limits are observed. Case A provides the worst voltage quality (greatest standard deviation).

To assess the impact on transmission network Tab. 4 sums up reactive power infeed from transmission system to distribution system.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean reactive power flow [MVar]</td>
<td>37.6</td>
<td>33.1</td>
<td>36.4</td>
</tr>
<tr>
<td>Standard deviation [MVar]</td>
<td>15.2</td>
<td>4.3</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Tab. 4 Reactive power flow through 400/110kV transformer

CONCLUSIONS

In the first part of paper the risk of renewables sources for transmission system operation is evaluated by dynamic simulation. Two case studies were carried out. The first case study deals with loop flows caused by wind

![Fig. 7 Voltage in selected nodes](image-url)