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Analyzing Rotational Inertia, Grid Topology and their Role for Power System Stability

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Abstract: Large-scale deployment of Renewable Energy Sources (RES) has led to significant generation shares of variable RES in power systems worldwide. RES units, notably inverter-connected wind turbines and photovoltaics (PV) units that do not provide rotational inertia, are effectively displacing conventional generators and their rotating machinery. This has implications for frequency dynamics and power system operation: Since frequency dynamics are faster in power systems with low rotational inertia, this can lead to large transient frequency and power oscillations in multi-area power systems. Grid topology also has a key role for frequency dynamics as meshed grids are more resilient to disturbances than non-meshed grids.
This paper investigates the role of low rotational inertia and different grid topology setups on power system stability for a three-area power system. The presented contributions, both analytical and simulation-based insights, extend previous results for a two-area power system.

Keywords: Power System Stability, Rotational Inertia, Frequency Control, Grid Topology

1. INTRODUCTION

Traditionally, power system operation is based on the assumption that electricity generation, in the form of thermal power plants, reliably supplied with fossil or nuclear fuels, or hydro plants, is fully dispatchable, i.e. controllable, and involves rotating synchronous generators. Via their stored kinetic energy they provide rotational inertia, an important property of frequency dynamics and stability. The contribution of inertia is an inherent and crucial feature of rotating synchronous generators. Due to electromechanical coupling, a generator's rotating mass provides kinetic energy to the grid or absorbs it from the grid in case of a frequency deviation Δf. The kinetic energy thereby provided is proportional to the rate of change of frequency $\Delta\dot{f}$ (Kundur, 1994). The grid frequency f is directly coupled to the rotational speed of a synchronous generator and thus to the active power balance. Rotational inertia renders frequency dynamics more benign, i.e slower, and increases the available response time to react to fault events such as line losses, power plant outages or large-scale set-point changes of either generation or load units.

Maintaining the grid frequency within an acceptable range is a necessary requirement for the stable power system operation of power systems. Frequency stability and in turn also stable operation both depend on the active power balance, meaning that the total power feed-in minus the total load consumption, including system losses, is kept close to zero. In normal operation, small variations of the power balance occur spontaneously. Deviations from the frequency's nominal value f_0, e.g. 50 Hz or 60 Hz depending on region, should be kept small, as damaging vibrations in synchronous machines and load shedding may occur otherwise. This can influence the whole power system, in the worst case ending in fault cascades and black-outs. Low levels of rotational inertia, caused in particular by high shares of inverter-connected RES, i.e. wind turbine and PV units that normally do not provide any rotational inertia, have implications on frequency dynamics. They are becoming faster in power systems with low rotational inertia. This can lead to situations in which traditional frequency control schemes become too slow for effectively coping with fast disturbance dynamics and preventing large frequency deviations and the resulting consequences.

The loss of rotational inertia and its increasing time-variance due to the fluctuating RES power feed-in lead to new frequency instability phenomena in power systems. Frequency and power system stability may be at risk. With the rise of inverter-connected RES units, low inertia situations will become more widespread and with it faster frequency dynamics and the associated operational risks. This effect is analyzed using a dynamic model of the Continental European power system, including the existing primary and secondary frequency control schemes. While in previous work of the authors, the focus was on one-area and two-area power system models (Ulbig et al., 2014), here the focus is on three-area power system models as this allows to study the impact of differences in grid topology, namely meshed and non-meshed topologies, on grid frequency dynamics and power transients.

The remainder is organized as follows: Section 2 illustrates the role of rotational inertia for power system frequency dynamics and assesses to what extent inverter-connected generation units reduce inertia and render it time-variant. Section 3 presents analytic results of the role of the grid topology and rotational inertia for power system frequency dynamics. This is complemented by a simulation-based analysis in Section 4, followed by conclusions in Section 5.

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2. ANALYSIS OF ROTATIONAL INERTIA AND IT'S ROLE FOR POWER SYSTEM STABILITY

In the following, the basic modeling concepts for rotational inertia in power systems as well as synchronous power systems in general and the impact of high RES shares are presented.

2.1 Modeling Inertial Response in Power Systems

The rotational energy stored in the rotating masses of synchronous power generators is given as

$$E_{\mathrm{kin}} = \frac{1}{2} J (2\pi f_{\mathrm{m}})^2 \quad , \tag{1}$$

with J being the moment of inertia and f_{m} the rotating frequency. The machine's inertia constant H is defined as

$$H = \frac{E_{\mathrm{kin}}}{S_{\mathrm{B}}} = \frac{J(2\pi f_{\mathrm{m}})^2}{2 S_{\mathrm{B}}} \quad , \tag{2}$$

with S_{B} denoting the rated power of the generator and H the time duration during which the machine can supply its rated power solely with its stored kinetic energy. Typical values for H are in the range of 2–10 s (Kundur, 1994, Table 3.2). The classical swing equation, a model representation for synchronous generators, describes the inertial response as the change in rotational frequency f_{m}, or rotational speed $\omega_{\mathrm{m}} = 2\pi f_{\mathrm{m}}$, of the synchronous generator following a power imbalance as

$$\dot{E}_{\mathrm{kin}} = J(2\pi)^2 f_{\mathrm{m}} \, \dot{f}_{\mathrm{m}} = \frac{2 H S_{\mathrm{B}}}{f_{\mathrm{m}}} \, \dot{f}_{\mathrm{m}} = (P_{\mathrm{m}} - P_{\mathrm{e}}) \quad , \tag{3}$$

with P_{m} as the mechanical power supplied by the generator and P_{e} as the electric power demand. Noting that frequency excursions are usually small deviations around the reference value, we replace f_{m} by f_0 and P_{m} by $P_{\mathrm{m},0}$, and complete the classical swing equation by adding frequency-dependent load damping, a self-stabilizing property of power systems, by formulating

$$\dot{f}_{\mathrm{m}} = -\frac{f_0 k_{\mathrm{load}}}{2 H S_{\mathrm{B}}} \, f_{\mathrm{m}} + \frac{f_0}{2 H S_{\mathrm{B}}} (P_{\mathrm{m},0} - P_{\mathrm{e}}) \quad . \tag{4}$$

Here f_0 is the reference frequency and k_{load} denotes the frequency-dependent load damping constant. $P_{\mathrm{m},0}$ is the nominally scheduled mechanical generator power. Another definition of load damping is D_{load} with $D_{\mathrm{load}} = \frac{1}{k_{\mathrm{load}}}$. Please note that concurrent labeling, i.e. k_{l} (or simply k) and D_{l} (or D), are also in wide use in literature.

The high share of conventional generators is translated into a large rotational inertia of the here presented power system. The larger the inertia constant H, the slower and more benign are frequency dynamics, i.e. for identical faults frequency deviations f_m and their derivatives $\dot{f}_m$ are smaller. A power system's stability region is, in fact, directly shaped by the choice of the parameters H_i and k_i. They determine how well *shocks* are absorbed by a power system and how close they drive the system towards the stability boundary (Chiang et al., 1987; Ulbig et al., 2014).

Modeling interconnected power systems, i.e. different aggregated generator and load nodes that are connected via tie-lines, can be realized in a similar fashion as modeling individual generators. Reformulating the classical Swing Equation (4) for a power system with n generators, j loads and l connecting tie-lines, leads to the so-called Aggregated Swing Equation (ASE) (Kundur, 1994)

$$\dot{f} = -\frac{f_0 k_{\mathrm{load}}}{2 H S_{\mathrm{B}}} f + \frac{f_0}{2 H S_{\mathrm{B}}} (P_{\mathrm{m}} - P_{\mathrm{load}} - P_{\mathrm{loss}}) \ , \tag{5}$$

with

$$f = \frac{\sum_{i=1}^{n} H_i \, S_{\mathrm{B,i}} \, f_i}{\sum_{i=1}^{n} H_i \, S_{\mathrm{B,i}}} \ , \ S_{\mathrm{B}} = \sum_{i=1}^{n} S_{\mathrm{B,i}} \ , \ H = \frac{\sum_{i=1}^{n} H_i S_{\mathrm{B,i}}}{S_{\mathrm{B}}} \ ,$$

$$P_{\mathrm{m}} = \sum_{i=1}^{n} P_{\mathrm{m},i} \ , \ P_{\mathrm{load}} = \sum_{i=1}^{j} P_{\mathrm{load},i} \ , \ P_{\mathrm{loss}} = \sum_{i=1}^{l} P_{\mathrm{loss},i} \ .$$

The term f is the Center of Inertia (COI) grid frequency, H the aggregated inertia constant of the n generators, S_{B} the total rated power of the generators, P_{m} the total mechanical power of the generators, P_{load} the total system load of the grid and P_{loss} the total transmission losses of the l lines making up the grid topology and $f_0 = 50\,\mathrm{Hz}$. The frequency damping k_{load} of the system load is assumed here to be a constant and uniform term throughout the grid topology. The ASE model (5) is valid for a highly meshed grid, in which all units can be assumed to be connected to the same grid bus (Center of Inertia). Again assuming small load-frequency disturbances, linearized swing equations with $\Delta f_i = f_i - f_{i,0} = f_i(t_1) - f_i(t_0)$ can be used. Considering the system change (Δ) before (t_0) and after a disturbance (t_1), the relative formulation of the ASE, assuming there is no change in line loss, i.e. $\Delta P_{\mathrm{loss}} = 0$, is

$$\Delta \dot{f} = -\frac{f_0 k_{\mathrm{load}}}{2 H S_{\mathrm{B}}} \Delta f + \frac{f_0}{2 H S_{\mathrm{B}}} (\Delta P_{\mathrm{m}} - \Delta P_{\mathrm{load}}) \quad . \tag{6}$$

Frequency dynamics for a power system with n areas can become chaotic in case $n \geq 3$ (Berggren and Andersson, 1993; Chiang et al., 1987; Kopell and Washburn, 1982). Analyzing the stability properties of swing equation models of power systems constituted a sizable research stream in the 1980s and early 1990s. Although this analysis assumed that rotational inertia could, in principal, vary from one grid region to another, its time-variance caused by inverter-connected RES units was not considered at the time as only very few wind and PV units existed.

Today, with substantial and still rising shares of inverter-connected power system units – both distributed generators as well as load demand – rotational inertia is reduced and highly time-variant due to the fluctuating nature of wind and PV electricity production. This is notably a concern for small power networks, e.g. island or micro grids, with a high share of generation capacity not contributing any inertia as was discussed and illustrated previously, for example, in Tielens and Van Hertem (2012).

2.2 Inertia in Power Systems with high RES shares

An exemplary analysis of the German power system, previously conducted by the authors in Ulbig et al. (2014) and updated here, shows the relevance of the above mentioned trends: Throughout the year 2013 there have been several hours in which 50% or more of overall load demand was covered by wind and PV units. The rotational inertia within the German power system dropped to significantly lower levels than usual due to the temporary lack of