Transient stability of conventional power generating stations during times of high wind penetration

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The requirement to increase the level of energy produced from sustainable sources resulted in wind turbine generators and solar photo voltaic installations becoming major contributors into the energy pool. However, studies, recent measurements and experience in the island of Ireland show that the increase of these generation sources influence the ability of the frequency in the transmission and distribution system to remain stable after a transient disturbance. This weakening of the grid frequency strength is observed by an increase of the Rate of Change of Frequency (ROCOF). Furthermore, the frequency of the transmission system oscillates in a higher frequency range which triggers further oscillations in transmission connected synchronous generators. The development of an understanding of the behaviour of synchronous generators, connected to such a system with high wind penetration during transient disturbances, required a new modelling technique. A model was developed and verified by comparing it with actual measurements on various generators. It will allow to highlight limitations to the operational range of synchronous generators and could also be used to identify limits to the amount of grid connected non synchronous generators such as wind turbines and solar photo voltaic installations.

1. Introduction

Initially localized, rapidly changing time varying disturbances applied to a transmission system such as a trip of a generator or disconnection of a large consumer result in a change in frequency and voltage in the transmission system. The reason being that such electrical disturbances and the ensuing transient responses affect the electromagnetic torque in the air gap of grid connected synchronous generators, inducing *inter alia* a rotor angle oscillation resulting in mechanical torsional oscillations in the shaft line of the turbo or hydro-generator and turbine accompanied by electrical power output oscillations. To enable one to initially quantify the influence of such more severe ROCOF events on the operation and the integrity of a turbo or hydro-set it is necessary to define an appropriate model which we can mathematically analyse to be able to calculate the ensuing electrical and mechanical behaviour of the sets in order to assess the consequences to individual components. The starting point of our analysis will be the traditional method of deriving the swing equation for a turbo-generator. Furthermore the swing equations will be used in MatLab to analyse the behaviour of a specific turbine generator set.

2. Traditional Swing Equation

Some traditional methodologies use a model which is based on a mechanical analogon which can be described as a sphere oscillating in a bowl. When the disturbance is too large, the sphere oscillating in the bowl, will go over the edge. The generator would slip. To come to a better understanding of the behaviour of a generator under transient disturbances we derive the equation of motion.

During stable operation of a synchronous generator the electromagnetic torque in the air-gap of such machine is equivalent to the mechanical torque applied to the shaft by the driving turbine. The accelerating torque is zero.

$$\vec{\tau}_a = \vec{\tau}_m - \vec{\tau}_{el} = 0 \tag{1}$$

However, during a disturbance the turbine generator shaft will be accelerated. We can denote taking into consideration that:

$$J_{gen}\dot{\omega}_m(t) = \tau_m - \tau_{el} \tag{2}$$

with ω_m being the angular velocity of the turbine generator shaft. To get the equation of motion we substitute the angular acceleration of the generator turbine shaft with the derivative of the rotor angle:

$$\omega_m(t) = \dot{\delta}(t) \tag{3}$$

it becomes:

$$J_{gen}\ddot{\delta}(t) = \tau_m - \tau_{el} \tag{4}$$

After introducing the inertia constant $H = \frac{\frac{1}{2}J\omega^2}{S_N}$, the damping coefficient K_D and normalizing with the nominal grid frequency ω_0 we get:

$$\frac{2H}{\omega_0}\ddot{\delta}(t) + \frac{K_D}{\omega_0}\dot{\delta}(t) = \bar{\tau}_m - \bar{\tau}_{el} \tag{5}$$

With B_R and B_S being the magnetic fields of the generator stator and rotor, k is a generator parameter and δ is the angle between the stator and the rotor field we can also write for the electromagnetic torque in the air gap of the generator:

$$\bar{\tau}_{el} = \frac{k}{\omega_0}B_R B_S \sin\delta(t) \tag{6}$$

The equation of motion for a generator operating in an infinite grid becomes:

$$\frac{2H}{\omega_0}\ddot{\delta}(t) + \frac{K_D}{\omega_0}\dot{\delta}(t) + \frac{k}{\omega_0}B_R B_S \sin\delta(t) = \bar{\tau}_m \tag{7}$$

And for small disturbances we assume $sin\,\delta(t)=\delta(t)$, so we obtain:

$$\frac{2H}{\omega_0}\ddot{\delta}(t) + \frac{K_D}{\omega_0}\dot{\delta}(t) + kB_R B_S\delta(t) = \bar{\tau}_m \tag{8}$$

This equation is commonly used in the analysis of the dynamic response of a synchronous generator in an infinite grid. Analysing this equation and finding a mechanical analogy, we are able to construct an analogon in the form of a rotating pendulum. The bar which symbolizes the grid is moving according to the grid frequency and is of an infinite mass, meaning that it cannot be influenced by the inertia of a single generator (Fig. 1).

Both inertias, the generator turbine shaft J_{gen} and the grid J_{grid} rotate horizontally around the *z*-axis. They rotate with the angular velocity ω_0 corresponding to the nominal grid-frequency of 50Hz. During transient faults on the system like a trip of a generator or a disconnection of a large load, the grid-frequency changes. Accordingly the generator will experience an additional torque as the grid inertia changes its angular velocity. This disturbance leads to an oscillation of the rotor angle $\delta(t)$. The rotor angle oscillations result in a power output oscillation. With $P_{el} = P_{max}\sin\delta(t)$ the equation of motion for the turbine generator rotor becomes the product of an exponential function with negative coefficient and a sine wave. When plotting the results of such disturbance one can see that the rate of change of the grid frequency is of major importance as seen Figure 2 where a grid frequency change of df/dt = -0.25Hz/s and t = 4s duration was imposed. The results were compared with those of disturbances with (-0.5Hz/s | 2s), (-1Hz/s | 1s) and (-2Hz/s | 0.5s) respectively. The graphs shown in Fig. 2 illustrate that both, the electrical and mechanical stresses on the turbine and the generator increase as the ROCOF value is increased.

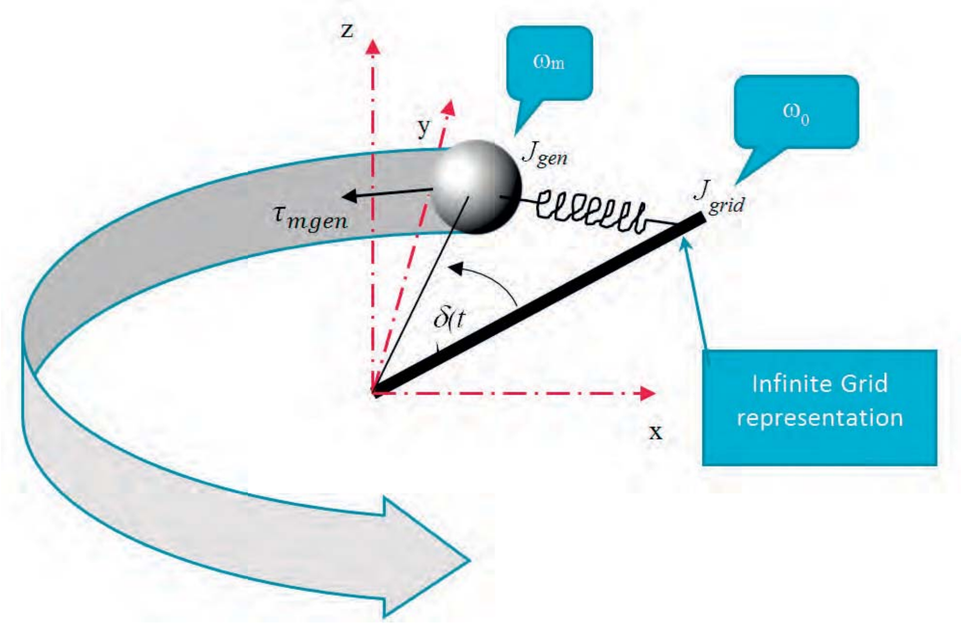

Figure 1: Single mass model showing the grid as an infinite inertia

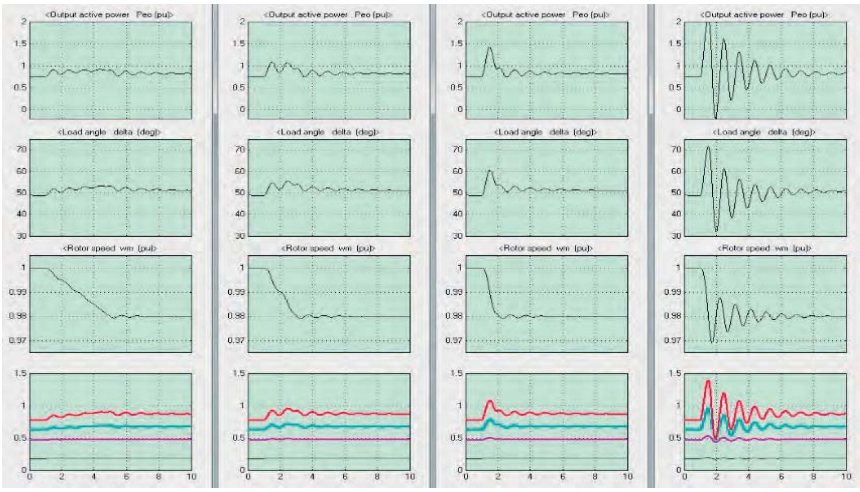

Figure 2: *Responses with negative ROCOF on electric power, load angle, rotor speed and torques*

When reviewing the oscillation with results of measurements of analysed units in the Island of Ireland one realises that the units observed did not oscillate in such a way. The example shown below is of a generating plant within the Dublin region (Fig. 3).

When reviewing the measured data, one can see that the grid frequency shows also a slight oscillation which is in phase with the power oscillation indicating that these two are influencing each other. As the grid inertia in the Island of Ireland is not infinite any transient disturbance induces a rotor angle oscillation which leads to a grid oscillation. Hence, the assumption that is valid for an infinite grid, that there is no feedback of the oscillation experienced by the turbine generator shaft back to the grid, leads to the conclusion that the mechanical analogy is not useful when applied on grids with light inertia.

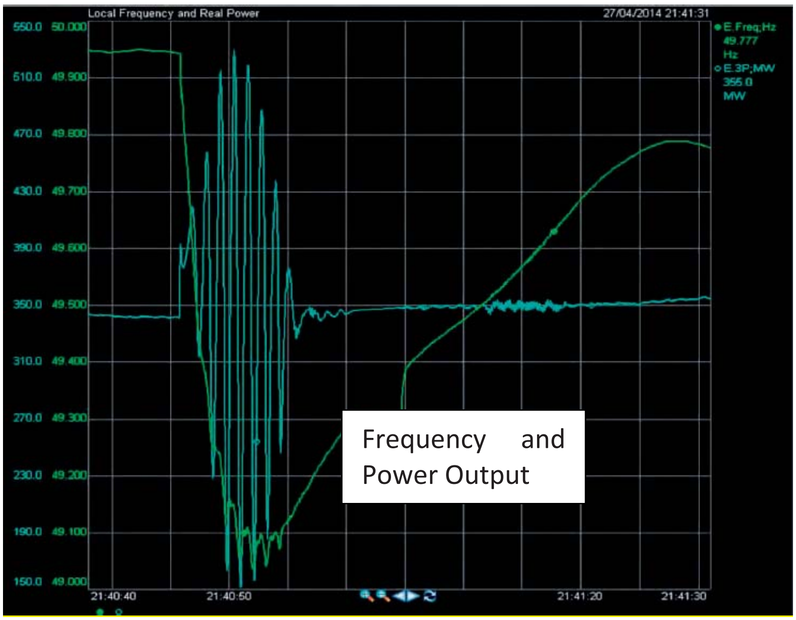

Figure 3: Power output of a 400MW synchronous generator as a response of a real ROCOF event

3. The two mass pendulum

A new mechanical analogon, showing the grid as a rotating mass (Fig. 4), is used to obtain a model representing a lighter grid which correlates to a grid operated with high amount of non-synchronous penetration. This would be the case in the island of Ireland during times of a strong generation by wind turbines.

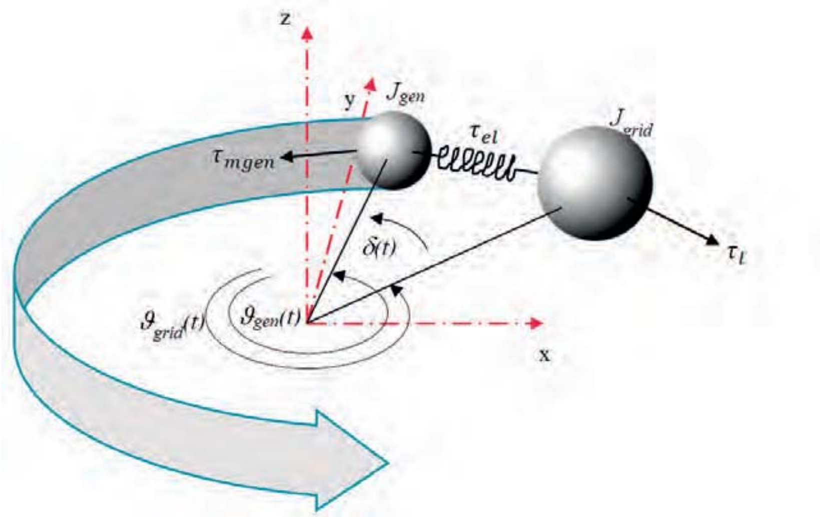

Figure 4: two mass model showing the grid as a finite inertia

To obtain the equations of motion of a double pendulum we need to define the torques which are applied to our turbo-generator shaft.

τ_{mgen} : Torque applied by the turbine to the generator

τ_{el} : Electromagnetic torque in the air-gap of the generator

τ_{mgrid} : Sum of all turbine torques within the grid (without the tested generator)

τ_{lgrid} : Torque which represents the loading of the grid (without the tested generator)

τ_d : Damping torque between grid and generator

We simplify the torques by relating them to the generator and grid respectively:

$$\tau_1 = \tau_{mgrid} - \tau_{lgrid} \tag{9}$$

and:

$$\tau_2 = \tau_{mgen} \tag{10}$$

With the maximum electromagnetic torque in the air-gap being τ_{elmax} and the damping between grid and generator being K_D we can write the two equations of motion for the two inertias as:

$$\tau_1(t) + \tau_{elmax} * \sin\left(\vartheta_{gen}(t) - \vartheta_{grid}(t)\right) + K_D * \left(\dot{\vartheta}_{gen}(t) - \dot{\vartheta}_{grid}(t)\right) = J_{grid} * \ddot{\vartheta}_{grid}(t) \tag{11}$$

Equivalent for the Generator we can write:

$$\tau_2(t) + \tau_{elmax} * \sin\left(\vartheta_{gen}(t) - \vartheta_{grid}(t)\right) - K_D * \left(\dot{\vartheta}_{gen}(t) - \dot{\vartheta}_{grid}(t)\right) = J_{gen} * \ddot{\vartheta}_{gen}(t) \tag{12}$$

For small rotor angle oscillations we can discard the sine.

We translate this into matrix coefficients:

$$[J] = \begin{bmatrix} J_{grid} & 0 \\ 0 & J_{gen} \end{bmatrix} \tag{13}$$

$$[K_D] = K_D \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \tag{14}$$

$$[\tau_{elmax}] = \tau_{elmax} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \tag{15}$$

With

$$\{\vartheta(t)\} = \begin{pmatrix} \vartheta_{grid}(t) \\ \vartheta_{gen}(t) \end{pmatrix} \tag{16}$$

and

$$\{\tau(t)\} = \begin{pmatrix} \tau_1(t) \\ \tau_2(t) \end{pmatrix} \tag{17}$$

The equation of motion for this system becomes:

$$[J] * \left\{\ddot{\vartheta}(t)\right\} + [K_D] * \left\{\dot{\vartheta}(t)\right\} + [\tau_{elmax}] * \{\vartheta(t)\} = \{\tau(t)\} \tag{18}$$

This equation of motion of the double pendulum can also be solved by using the Lagrange method. However, the equation has limitations as it does not take into account the stored energy present in the impedances of the windings which form electromagnetic fields in the individual generators and around lines as well as the energy losses due to resistances in the generators and lines.

4. Introducing the electrical circuits

To obtain the equations of motion including the magnetic fields as part of an electrical circuit we assume use the Lagrange methodology. K_e being the Kinetic Energy in the system, V the potential Energy and P the damping, or here also the heat losses in the stator and line resistances, we are using the Lagrange equation as shown below:

$$\frac{d}{dt}\left(\frac{\partial K_e}{\partial \dot{q}_i}\right) - \frac{\partial K_e}{\partial q_i} + \frac{\partial P}{\partial \dot{q}_i} + \frac{\partial V}{\partial q_i} = Q_i \tag{19}$$

By using the Park transformation (dq0) for synchronous generators specifically the three currents i_d, i_q and i_0 we can define for a single generator on an infinite grid has 4 degrees of freedom as we use 3 degrees for the charges of the currents and one for the mechanical motion of the generator rotor:

$$\frac{d}{dt}\begin{pmatrix} \frac{\partial K_e}{\partial(\dot{q}_1)} \\ \frac{\partial K_e}{\partial \dot{q}_2} \\ \frac{\partial K_e}{\partial \dot{q}_3} \\ \frac{\partial K_e}{\partial \dot{q}_4} \end{pmatrix} - \begin{pmatrix} \frac{\partial K_e}{\partial q_1} \\ \frac{\partial K_e}{\partial q_2} \\ \frac{\partial K_e}{\partial q_3} \\ \frac{\partial K_e}{\partial q_4} \end{pmatrix} + \begin{pmatrix} \frac{\partial P}{\partial \dot{q}_1} \\ \frac{\partial P}{\partial \dot{q}_2} \\ \frac{\partial P}{\partial \dot{q}_3} \\ \frac{\partial P}{\partial \dot{q}_4} \end{pmatrix} + \begin{pmatrix} \frac{\partial V}{\partial q_1} \\ \frac{\partial V}{\partial q_2} \\ \frac{\partial V}{\partial q_3} \\ \frac{\partial V}{\partial q_4} \end{pmatrix} = \begin{pmatrix} Q_1 \\ Q_2 \\ Q_3 \\ Q_4 \end{pmatrix} \tag{20}$$

Consequently, for a system with n generators the equation of motion becomes:

$$\frac{d}{dt}\begin{pmatrix} \frac{\partial K_e}{\partial(\dot{q}_{11})} \\ \frac{\partial K_e}{\partial(\dot{q}_{12})} \\ \frac{\partial K_e}{\partial(\dot{q}_{13})} \\ \frac{\partial K_e}{\partial(\dot{q}_{14})} \\ \vdots \\ \frac{\partial K_e}{\partial(\dot{q}_{n1})} \\ \frac{\partial K_e}{\partial(\dot{q}_{n2})} \\ \frac{\partial K_e}{\partial(\dot{q}_{n3})} \\ \frac{\partial K_e}{\partial(\dot{q}_{n4})} \end{pmatrix} - \begin{pmatrix} \frac{\partial K_e}{\partial q_{11}} \\ \frac{\partial K_e}{\partial q_{12}} \\ \frac{\partial K_e}{\partial q_{13}} \\ \frac{\partial K_e}{\partial q_{14}} \\ \vdots \\ \frac{\partial K_e}{\partial q_{n1}} \\ \frac{\partial K_e}{\partial q_{n2}} \\ \frac{\partial K_e}{\partial q_{n3}} \\ \frac{\partial K_e}{\partial q_{n4}} \end{pmatrix} + \begin{pmatrix} \frac{\partial P}{\partial(\dot{q}_{11})} \\ \frac{\partial P}{\partial(\dot{q}_{12})} \\ \frac{\partial P}{\partial(\dot{q}_{13})} \\ \frac{\partial P}{\partial(\dot{q}_{14})} \\ \vdots \\ \frac{\partial P}{\partial(\dot{q}_{n1})} \\ \frac{\partial P}{\partial(\dot{q}_{n2})} \\ \frac{\partial P}{\partial(\dot{q}_{n3})} \\ \frac{\partial P}{\partial(\dot{q}_{n4})} \end{pmatrix} + \begin{pmatrix} \frac{\partial V}{\partial q_{11}} \\ \frac{\partial V}{\partial q_{12}} \\ \frac{\partial V}{\partial q_{13}} \\ \frac{\partial V}{\partial q_{14}} \\ \vdots \\ \frac{\partial V}{\partial q_{n1}} \\ \frac{\partial V}{\partial q_{n2}} \\ \frac{\partial V}{\partial q_{n3}} \\ \frac{\partial V}{\partial q_{n4}} \end{pmatrix} = \begin{pmatrix} Q_{11} \\ Q_{12} \\ Q_{13} \\ Q_{14} \\ \vdots \\ Q_{n1} \\ Q_{n2} \\ Q_{n3} \\ Q_{n4} \end{pmatrix} = \begin{pmatrix} u_d \\ u_{1q} \\ \tau_{mgen} \\ 0 \\ \vdots \\ u_d \\ u_{nq} \\ \tau_{nmgen} \\ 0 \end{pmatrix} \tag{21}$$

Specifically we assigned the four degrees of freedom. For the direct axis:

$$q_1 = \int i_d \, dt \equiv \frac{i_d}{s} \tag{22}$$

$$\dot{q}_1 = i_d \tag{23}$$

$$Q_1 = u_d \tag{24}$$

Equivalent we define for the q axis:

$$q_2 = \int i_q \, dt \equiv \frac{i_q}{s} \tag{25}$$

$$\dot{q}_2 = i_q \tag{26}$$

$$Q_2 = u_q \tag{27}$$

For the mechanical system we can write:

$$q_3 = \vartheta_{gen} \tag{28}$$

The first derivative:

$$\dot{q}_3 = \frac{d\vartheta_{gen}}{dt} = \dot{\vartheta}_{gen} = \omega_{gen} \tag{29}$$

And for applied torque we can denote:

$$Q_3 = -\tau_{mgen} \tag{30}$$

For the fourth degree of freedom we use the current in the star point of the generator, even though many generators would have a high ohmic star point. As a consequence, this part can be neglected and the equation has only 3 degrees of freedom. For the 4^{th} degree of freedom we can write:

$$q_4 = \int i_0 \, dt \equiv \frac{i_0}{s} \tag{31}$$

$$\dot{q}_4 = i_0 \tag{32}$$

$$Q_4 = 0 \tag{33}$$

For the electrical energy stored in the electrical circuits we can write:

$$K_{ee} = \frac{1}{2} L_{d1} \dot{q}_{11}^2 + L_{dq2} \dot{q}_{11} \dot{q}_{12} + \frac{1}{2} L_q \dot{q}_{12}^2 + \cdots \tag{34}$$

Which can be written for n generators as:

$$K_{ee} = \sum_{k=1}^{n} (\frac{1}{2} L_{dk} \dot{q}_{k1}^2 + L_{dqk} \dot{q}_{k1} \dot{q}_{k2} + \frac{1}{2} L_{qk} \dot{q}_{k2}^2) \tag{35}$$

For the mechanical kinetic energy for one generator:

$$K_{em} = \frac{1}{2} J_{gen} \dot{q}_{13}^2 \tag{36}$$

And for a system with n generators:

$$K_{em} = \sum_{k=1}^{n} \frac{1}{2} J_{kgen} \dot{q}_{k3}^2 \tag{37}$$

with:

$$K_e = K_{ee} + K_{em} \tag{38}$$

For the kinetic energy of a system with n generators we find:

$$K_e = \sum_{k=1}^{n} \left(\frac{1}{2} L_{dk} \dot{q}_{k1}^2 + L_{dqk} \dot{q}_{k1} \dot{q}_{k2} + \frac{1}{2} L_{qk} \dot{q}_{k2}^2 + \frac{1}{2} J_{kgen} \dot{q}_{k3}^2 \right) \tag{39}$$

By solving the equation of motion, using numerical methods in MatLab we can graphically show how the Generator behaves during atransient disturbance in the system, specifically a frequency drop with a high ROCOF value and a system operated with relatively light inertia. Comparing the result of our calculation (Fig. 5) with the actual measurement (Fig. 3) one can see that the behaviour is adequately modelled.

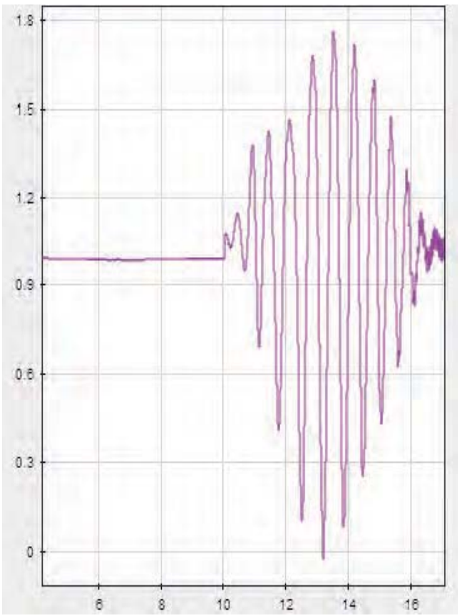

Figure 5: Calculated Power output as a response of a ROCOF event in a light inertia system

5. Discussion

Clearly, as the results of the analysis show, they highlight potential risks when a unit is exposed to a disturbance in a very light system, a system with high wind penetration and low inertia. Where in traditional high inertia systems the oscillation is steadily decreasing we can see that on systems with low inertias the stress on the unit can also increase. The mechanical torques might not reach a level where we might see an immediate crack development in a turbo shaft component but the amount of oscillations experienced might introduce an additional crack-propagation when a crack already exists. Further risks are found. These risks could be broadly categorized as operational risks covering the responses of automatic control systems and protection circuits on the one hand and on the other hand risks to the integrity of the mechanical and electrical components used in the generation of electricity.

The technical risks can be broadly associated to three driving processes

a. large changes in electrical power output affecting controllers such as excitation systems, power system stabilizers, turbine controller and unit controllers and affecting the mechanical integrity of the turbo-set

b. large changes in MW input from the prime mover due to governor response

c. inherent response of a unit to falling frequency such as gas compressor performance or inertial energy delivery.

Controllers and Operational Issues

Operational events such as those experienced during a frequency change in the grid require a very fast response from plant control systems. Demands on the control system will be exacerbated when ROCOF is larger because the rapid change of the grid frequency also directly influences the underlying process. Clearly various power generation technologies are subjected to different operational phenomena during rapid transients such as those experienced during ROCOF events. Examples of these occur in combined cycle and open cycle gas turbine technology, where the electrical power output of the plant reduces with the rotational speed of the gas turbine rotor and hence the electrical frequency. Here the volumetric flow through the compressor reduces as the rotor slows down leading to an increase in turbine inlet temperature and changes in the air fuel ratio in the combustion system with the potential for undesirable operational events such as turbine over temperature or flame blow out. Other examples of potential unwanted operational phenomena include hydraulic transients in hydro-plant associated with changes in flow. Therefore undesirable pressure oscillations may result, leading to pressure rises and consequential breach of design limits of mechanical components giving rise to potential rupture of metallic penstocks or mechanical failures of the turbine and its subcomponents. In particular, plants with longer penstocks or tail race tunnels are more susceptible to such events. For all plant, high ROCOF events cause rapid reduction in the rotational speed of synchronous plant. Thus as the shaft slows down, kinetic energy is ultimately translated into electrical energy via the turbine and generator shaft, causing a higher short term peak in electrical output power.

The result of situations such those illustrated above is that *significant* additional demands are placed on plant control systems during events with high ROCOF values. Plant controllers must be designed so as to accommodate an increased governor reaction and also to compensate for high speed transient effects within the process itself. Failure to adequately control such extreme events can lead to automatic plant protective actions and to cascade tripping of generation plant. Thus speed and load controllers as well as voltage controllers of all rotating plant must be reviewed to determine if they can respond to a stronger ROCOF event. Further implications of an extreme ROCOF event are as follows:

Auxiliary Plant

It is not known if auxiliary plant containing high inertia motors such as boiler feed pumps, mills, fans or gas compressors will be able to respond in a manner such that they continue to operate during a pronounced ROCOF event. Operational behaviour of these devices will be affected by both changes in voltage and in frequency. Each individual item of plant will need to be analysed to determine if there will be any implications due to a powerful ROCOF event. High speed bus transfers will also need to be reviewed, if applicable.

Protection Devices

Generator Protection: The introduction of so called ROCOF relays should be investigated. In small island grids ROCOF relays and phase shift relays are used to determine potentially high ROCOF values which may impact on the integrity of individual components within the turbine and generator. However, the currently available ROCOF relays in the market are not built to the quality standards normally specified for larger generation units. This is true, particularly in relation to redundancy and failure rates of which there is no experience either within the ESB or in most other generation utilities. Regarding existing generator protection functions there is a need to re-calculate and recalibrate the settings, such as the pole slip protection function.

Turbine Protection: Some turbine over-speed protection systems have an embedded logic that anticipates over-speed based on rate of speed change. It is unclear without further study whether increasing ROCOF limits will cause these protection systems to inadvertently trip the unit. A rapid drop of the electrical power output due to power swings caused by ROCOF could falsely be interpreted as due to the opening of a remote breaker. In particular, the load controller of the turbine closes its associated control valves during such events and additional generation loss would therefore be experienced.

Excitation Systems: In the ESB power generation fleet, various technologies are used to control the voltage of generators. Mechanical rolling sector voltage regulators as well as numerical multichannel voltage regulators are used. Irrespective of the basic differences in the design, the behaviour of the various automatic voltage regulators (AVR) may be significantly different. For example for historical reasons, some units lack any over and under-excitation limiters. Others may have different types of power system stabilizer circuits. In addition, the tuning of these devices may be different which would never be a reason of concern at relatively low ROCOF values. It follows that the dynamical behaviour of a power system stabiliser and more generally the generator and the entire turbo-set will need to be evaluated to determine the response during a ROCOF event at the higher limit value.

Mechanical Integrity

A typical steam or gas turbine-generator rotor system has a number of relatively stiff regions. The main bodies of the turbine rotors support the turbine wheels and blades as well as the part of the generator rotor length containing the winding axial slots. These relatively stiff rotor regions are usually connected by, comparatively speaking, flexible shafts. Now the turbogenerator generates electrical power when a force is applied by the driving medium acting on the turbine blades resisted by the electromagnetic air-gap torque in the generator. These applied torques result in a static torsional displacement along the entire length of the turbine and generator shaft so that one end is twisted in the opposite direction relative to the other. However, during a ROCOF event the electromagnetic torque in the air gap of the generator will suddenly alter, whereas the mechanical torque applied to the turbine shaft via the forces acting on the turbine blades cannot change so rapidly. This torque delay phenomenon is due both to the delay in reaction of the control systems and the higher inertia of the turbine/compressor rotors as well as the steam characteristics of the process. This *variation* in torque causes a transient change of the torsional displacement, with consequent additional twisting of the shaft line connecting turbine and generator. Furthermore in certain cases, the turbine-generator shaft system will torsionally oscillate following a transient event, giving rise to alternating twisting and untwisting motions of the turbine-generator shafts. However, due to the relatively light mechanical damping of turbine-generator shaft systems, we may ultimately have tens of seconds of torsional oscillation following high ROCOF events. In addition multiple events may ultimately lead to fatigue damage of components. Thus, detailed analysis will be required to determine whether any impact on the integrity of the various components exists. An initial assessment of components at risk in gas and steam turbine – generator rotor systems could be couched as follows:

Couplings: In addition to the above mentioned failure mechanisms, coupling bolts may either shear or otherwise accumulate fatigue damage due to high levels of transient torques during a ROCOF event. For example, if a coupling is shrunk onto a shaft it may slip during an extreme ROCOF event resulting in fretting damage which can significantly reduce the fatigue life of the coupling and shaft. Cracks can also be initiated and grow at these locations with subsequent propagation due to either normal or abnormal loading during other transient events.

Rotors and Shafts: Generally the main body regions of an individual rotor have significantly larger diameter sections than the rotor extensions at each end. On turbine-generators these shaft extensions often contain seals and bearing journals with *abrupt* changes of diameter possibly terminating in integral or shrunk-on couplings. These shaft extensions are very flexible relative to the main body regions. Therefore the torsional stiffness characteristics of a turbine-generator are dominated by the relatively low stiffness values of the spans between the main rotor bodies. Thus, during a ROCOF event, these rotor extensions will tend to twist relative to the much stiffer main body regions. Hence, changes of section or keyways will act as stress raisers and initiation of cracking in these locations may be consequently observed.

Turbine Blades: In addition to shaft torsional oscillations, the last few stages of the blades of a low pressure steam turbine rotor can if excited, participate in coupled vibrations resulting in significant motion of the low pressure rotor elements at the axial location where the blades are attached. In particular, if the natural frequency of the underlying low pressure (LP) shaft system mode has a frequency sufficiently close to the natural frequency of a blade, significant vibration coupling can occur. Thus, the shafts and blades will vibrate in unison. Hence the stresses at the blade root or in blade attachment features to the wheels can become large. This may result in fatigue cracking of the blades at these locations. Therefore more information concerning the nature of the ROCOF torque input waveform is needed in order to assess the risk of blade damage due to such coupled vibrations.

Retaining Rings: The retaining rings on turbo-generators have a shrink fit surface at the inner diameter of the in-board end which is tightly shrunk onto a matching circumferential surface at the end of the generator rotor body. Relative motion may occur between the retaining ring and the rotor during a ROCOF event possibly resulting in scoring of the shrink fit surfaces of the retaining rings. Since the shrink fit locations of the retaining rings are highly stressed, the resultant scoring of the surface may act as a stress raiser, thus cracks may initiate and grow in this location.

End Windings: There may be a risk of damage to end windings if voltage dips are considered as possible scenarios within the ROCOF context. Changes to the air gap torque result in changes to the electromagnetic forces which the generator stator end-windings experience. As the end-winding basket is the weakest area of the generator stator these forces and their implications will need to be reviewed.

Gas Turbine Issues: Modern gas turbine compressors are susceptible to damage during disturbance events. There may be a risk of rubbing of compressor blades during a ROCOF event. Also, the implications of a ROCOF event on the interval between overhauls would need to be determined. These issues should be investigated in conjunction with the manufacturers for each type of gas turbine.

Analysis of Potential Consequences

The potential consequences of the issues as described above can be broadly divided into two categories.

The first category may be described as operational consequences, whereby a unit either fails to deliver the required response during a severe ROCOF event, or indeed trips, leading to a further loss of electrical power generation in the system with the potential to initiate further cascade tripping events, leading to load shedding, system islanding or an entire system black-out.

The second category can be broadly described as mechanical integrity issues. Due to mechanisms such as those described, ROCOF events have the potential to result in reduced component life, decreased overhaul intervals, increased inspection requirements, or in the worst case, catastrophic failure. This can happen as a consequence of either a single ROCOF event or cumulative damage caused by a series of such events. Potential exists for consequential machinery damage, forced plant outages and injury to personnel. The likelihood of such events cannot be determined without further analysis; we remark that this is also a function of the nature of the ROCOF events and the regularity of their occurrence.

6. Conclusions and Further Steps

The usage of a simple definition as shown in Eq.(8) in the ROCOF context and in particular during operation of a generator connected to a grid with light inertia exposed limitations. Though accurate mathematical modelling was required to understand the interaction between the generator and the turbine, it was of crucial importance to include in the modelling the interaction between generating plant and grid especially in a small isolated grid as in the island of Ireland. The models also show a strong influence of the magnetic field of the unit which allows to understand how units behave when operated with a leading or lagging power factor. The conventional generating units experience increased mechanical and electrical stresses which need to be further reviewed.

As a further step, the mechanical torques should be measured in order to determine the viability of the mathematical models. These measurements would allow the operator to quantify a possible change of lifetime of the generation assets. They would also provide for the numerical quantification and assessment of the severity of such electrical events vs lifetime implications for the mechanical and electrical components of the generator, associated turbines and their auxiliary systems. The measurement of the actual mechanical torques will enable the verification of the mechanical models, complement the desktop analysis and will enable adjustment of the models so that future theoretical reviews of the components would yield accurate results.

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Deutsche Physikalische Gesellschaft DPG

Arbeitskreis Energie

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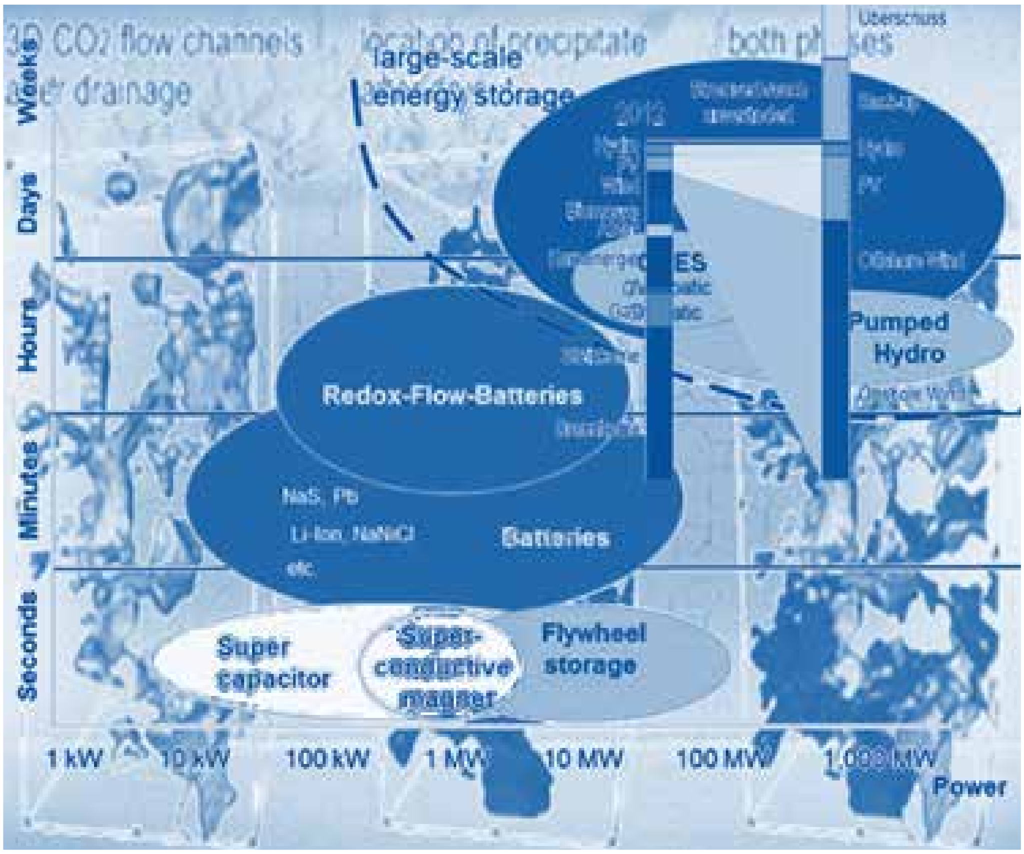
home: http://www.uni-saarland.de/fak7/fze/AKE_Archiv/DPG2015-AKE_Berlin/Links_DPG2015.htm
Urquelle: https://www.dpg-physik.de/veroeffentlichung/ake-tagungsband.html



Energie

Erzeugung - Netze - Nutzung

Vorträge auf der DPG-Frühjahrstagung in Berlin 2015

Herausgegeben von Hardo Bruhns

Arbeitskreis Energie in der Deutschen Physikalischen Gesellschaft

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Frühjahrstagung des Arbeitskreises Energie in der Deutschen Physikalischen Gesellschaft Berlin, 16. bis 18. März 2015

Haupt- und Fachvorträge

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Der vorliegende Band versammelt schriftliche Ausarbeitungen von Vorträgen auf der Tagung des Arbeitskreises Energie in der Deutschen Physikalischen Gesellschaft des Jahres 2015 in den Räumen der Technischen Universität Berlin. Leider ist es nicht gelungen, von allen Vortragenden Manuskripte zu erhalten. Die Präsentationsfolien der meisten Hauptvorträge können auf der Webseite des Arbeitskreises über:

http://www.dpg-physik.de/dpg/organisation/fachlich/ake.html

(von dort gelangt man zum Archiv des AKE) eingesehen werden. Allen, die zu diesem Sammelband beigetragen haben, sei an dieser Stelle sehr herzlich gedankt.

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