A new approach using load control to dampen interarea frequency oscillations

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***Abstract*—The European electricity grid has faced significant changes over the past decades, inlcuding the interconnection of previously separated grids. This development has led to a phenomena called interarea modes where the frequencies of regions several hundred miles apart oscillate against each other. This paper elaborates on the possibilities of load control to oppose such instabilities. Using a simplified model of the European grid, it is shown that an additional controller attached to part of the load in the grid can, in principle, increase the damping of interarea oscillations. Various control approaches are examined and a statement for future usability is given.**

***Index Terms*—frequency oscillations, interarea modes, distributed control, load management, power oscillations, frequency control**

I. Introduction

The constant enlargement of the European power grid and an increase in market-forced power flows has prepared the ground for previously less prevalent phenomena such as large scale power oscillations between distant areas within a power system. Many observations of the past decades have shown that the electric frequency in a power grid is not identical in every part of a large power grid but sometimes exhibits significant differences depending on where the observations are made. These differences are not stationary, in fact, oscillations of the frequency were discovered. It can happen that the frequency in Greece is slightly above 50 Hz and in Spain slightly below. Very few seconds later, the frequency deviations have changed and the regions show exactly the opposite frequencies. These periodic changes in frequency are caused by oscillatory power shifts between the regions and are generally referred to as interarea frequency oscillations or interarea modes.

The interarea oscillations are a threat as they have led to system disconnections or, however less frequently, to (partial) system blackouts. A list of major disturbances caused by interarea modes can be found in [1]. In any case, the disturbances caused by frequency oscillations are undesirable which requires counteractive measures to be taken. State of the art is to dampen interarea modes through power system stabilizers (PSS) [2]. These control devices are placed at a few generators in the system where the damping effect is believed to be highest.

In more recent times, FACTS (Flexible AC Transmission Systems) have also been used for mitigating interarea oscillations. A FACTS can counteract the power shifts directly, whereas a PSS usually tries to influence generator input variables such that interarea modes are reduced.

The new approach which shall be analyzed in this paper directs the attention to the potential of the load to dampen interarea oscillations.

Following this introduction, the second section elaborates on the model that was used to investigate the effects of a load control on interarea modes. The third sections provides information about how the load control was implemented, which variables were manipulated and discusses various approaches to do so. The following section compares the results of the different controller approaches and points out advantages and disadvantages. The fifth and last section draws a conclusion based on the results that were obtained.

II. Simulation environment

A. Simulation model and software

The proper choice and development of an appropriate model consumed a significant part of the total time spent on this project. The original idea was to find a simplified grid model whose characteristics are known entirely. The major advantage of such a closed form model would be the much greater variety of controller design possibilities. If the model and its relevant parameters are known a model-based controller design is possible. Instead of having to use scientific guessing to find a solution the model-based controller can be designed and specified to meet requirements that can be determined in advance. The model-based approach is depicted in figure 1. For each block in figure 1 we would like to find a linear model that completely describes the system for a certain input and a set of states. The controller block is the one to be designed, the load model varies depending on the desired level of detail. The main difficulty is to model the grid.

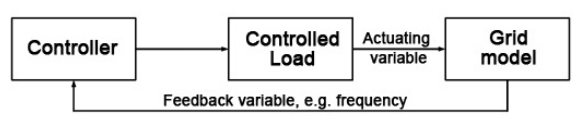

Fig. 1. Approach for the load control

A legitimate means of modeling a power grid is the description through a system of differential-algebraic equations (DAE). Analyzing the dynamics of the relevant parts of the electricity grid like generators, transmission lines and loads leads to a set of differential equations. Power flow consistencies add the constraints captured with a set of algebraic equations. To allow the usage of linear control theory principles a linearization of the non-linear system of DAEs around one specific operating point is required. After the linearization a system matrix can be obtained that completely describes the system for small variations. This system matrix is the model for the system in direct vicinity of the operating point. The linear state space model of a power system described in this fashion is given through

$$\Delta\dot{\mathbf{x}} = \mathbf{A}_{\mathbf{sys}}\Delta\mathbf{x} + \mathbf{B}\Delta\mathbf{u} \quad (1)$$

$$\Delta\mathbf{y} = \mathbf{C}\Delta\mathbf{x}, \quad (2)$$

where $\mathbf{A}_{\mathbf{sys}}$ is the system matrix mentioned before. The detailed derivation can be found in [3]. $\mathbf{x}$ includes all state variables, $\mathbf{y}$ the output variables and $\mathbf{u}$ the input variables. The interarea oscillations now can be found analyzing some specific state variables. The state space model includes one state variable for the frequency for each generator in the system. One will find that the frequencies of each generator are not identical. In fact, for generators located spatially far apart from each other one will observe frequencies that are phase shifted by approximately 180°.

Although this approach may seem to be a workable solution to find a model for the grid, it has two significant disadvantages. Firstly, the model does not provide the desired input variables. As we would like to introduce a control scheme that uses the power load as actuating variable, this variable would have to be an input variable of the grid model. However, this is not the case as the state space model described above only provides input variables directly related to the generators (the mechanical torque and the bus reference voltage).

Secondly, when a power load controller is included the state space model is not time constant anymore. The calculation of the state space model is based upon load flow results. As the current load power directly influences the load flow results and the algebraic equations in the DAE system, the state space model itself is altered constantly through the load controller. Therefore the state space model is not time constant anymore and a closed-form model as shown in figure 1 cannot be realized. Also, linear control theory which is only valid for time-invariant systems cannot be applied. This represents a major drawback of the state space model in its described form.

Although no attempt led to a satisfying result, a possible solution would be to manipulate the DAE system such that a variable directly influencing the load ends up as an input to the grid model. The main difficulty here is the iterative nature of the load flow calculation which makes it impossible to restructure the DAE system.

Despite the disadvantages, the state space model is still a very powerful tool to calculate the state variable's values over time. Through a repeated linearization of the current DAE system and the solution of the corresponding state space model the state variable's values over time can be found. This characteristic enables the state space model to still be used for the design of a power load controller. The approach of the controller design simply has to be modified. Instead of specifying the effects of the controller in advance and then designing the controller, one has to design a controller and then investigate its effects through simulation experiments. The state space model can be used to do just that as it is easily possible to incorporate the differential equations added with the controller.

The simulation software was to be *PowerFactory* from the company DigSilent GmbH. Their program offers simple composition of even sophisticated power grids and controllers and their simulation over time. Therefore it is a tool that allows to test the same power grid with different controllers.

The model itself was constructed according to a compromise between desired detail, controllable complexity and usability for the problem. Of course, the model had to exhibit interarea modes which can only be realized with two or more generators. In the end, the model followed the example of [4] where a five-generator-model is used to represent the European grid in a very simple fashion. One generator represents a major region, the generated power of all five identical generators adds up to one tenth of the peak load of the European grid (300 MW, [5]). The connections in between the generators are realized through 380 kV, 240Al/40St transmission lines. The general idea is shown in figure 2. Despite the simplifications, it is sufficient to model interarea oscillations, whereas the model parameters for generators and lines were specified such that the interarea modes imitate the ones really occurring in the European power grid.

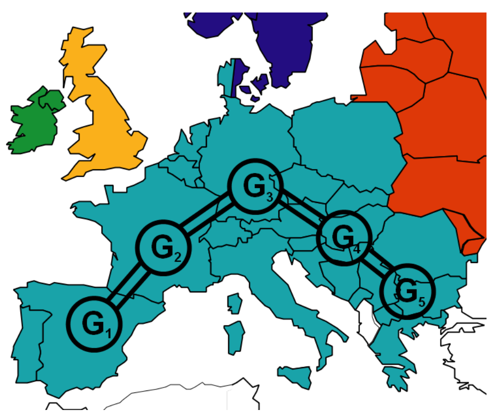

Fig. 2. Structure of the model used for the simulation

B. Verification

To validate the simulation results a comparison of the frequency oscillations of the simulation with actual measurements from the European electricity grid is helpful. In 2009 there was a major outage of a generator in Spain and the effects concerning frequency were measured by the IFK of the University of Stuttgart at different points across Europe. The measurement data was used to validate the simulation results. Figure 3 and 4 show that the period is for both, the simulation and the measurement, around 3 to 5 seconds. The magnitude is significantly smaller in the measurements due to a supposably much smaller power outage in the actual European grid. For the simulation, the equivalent of the worst case scenario of a double plant outage (3 GW) was applied, the outage during the measurements was presumably much smaller. It is not known exactly.

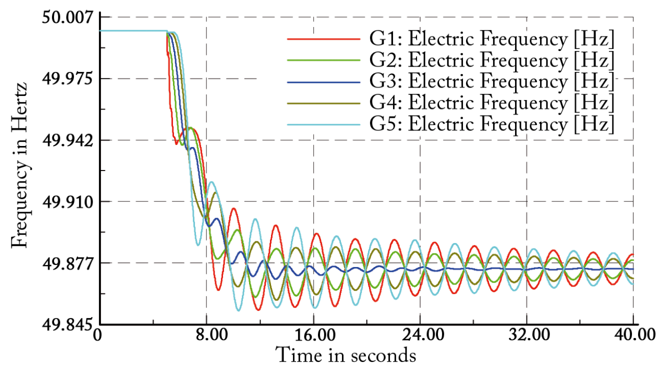

Fig. 3. Simulation of the interarea modes in the model with five generators

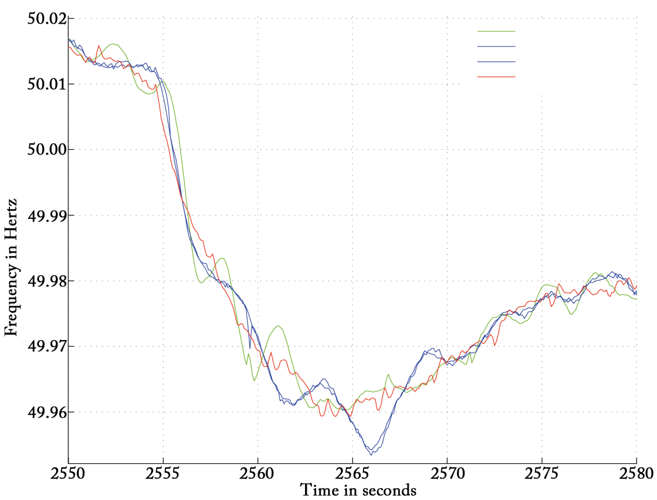

Fig. 4. Measurements of the frequency after a major generator outage in Spain, August 5th, 2009. Data provided by: Institute of Combustion and Power Plant Technology (IFK), Department Power Generation and Automatic Control, University of Stuttgart

III. Approach for Load Control

A. Feedback loop and controller

The main goal of the additional load control is to stabilize the frequency on the same value in every part of the system. It is not relevant which value that may be. For all controllers, the general idea is to measure the local frequency and use this measurement in a load controller which will then adjust the power of the load so as to dampen the frequency oscillations.

Having a closer look at figure 3 reveals the first approach to design a controller. It is clearly visible that the frequency of the central region, represented by generator 3, shows a frequency with very small oscillations. Approximately 20 seconds after the disturbance there is even barely any oscillation present. Furthermore the frequency in the center approximates the root mean square value of all other frequencies quite well. Thus it could serve as a reference value for a load controller.

A second approach is to extract the reference signal from the local measurement of the frequency. In both, the measurements and the simulation of the interarea modes, one finds that the oscillations seem to have an approximately identical root mean square value. This value can be calculated through a low-pass filter from the local measurement of the frequency. A major advantage is, that no additional transmission of another measurement is needed.

B. Implementation

A controller that implements the first approach is displayed in figure 5. A PI controller was chosen to avoid any remaining deviation of the frequencies within the grid. It needs to be remembered that, for example, generator 1 and 3 may very well be several hundred kilometres apart from each other. Therefore the dead time block accounts for the transmission time of the measurement signal from generator 3 to the load controller (0.5-1 sec for wide area measurements, q.v. [6]).

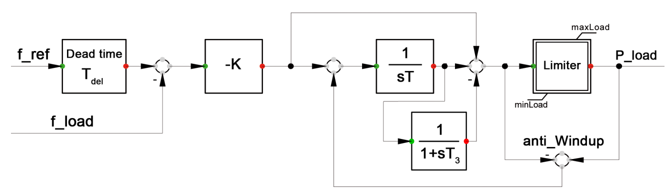

Fig. 5. Block diagram of the PI controller with the reference frequency from generator 3

The second approach uses a low-pass filter with three stages to calculate the reference signal. The cutoff frequency of all three lowpass filters was set to 1 Hz.

The additional PT1-block was added in both designs to cancel out the effect of the integrator during steady state conditions. In other words, this PT1-block forces the controller output back to zero in steady state. This is necessary as the controller shall not take over the responsibilities of the primary control. The influence on the actual control behaviour is negligible as the time constant of this particular PT1 block was chosen significantly larger than all other time constants.

Both controller designs include a block that limits the output to within a fixed minimum and maximum. These limits represent the available amount of power that is controlled for the damping of frequency oscillations. In the simulation the controlled load power was limited to $\pm 0.333\%$ of the total load in one region. This value is arbitrary but was based on the assumption that in 15 to 20 years significant changes in the power grid will have made this amount of load available for the proposed control. Especially electric vehicles may contribute a major part to this development.

As a consequence of the limitation an anti-windup loop is required. It maintains the dynamic of the controller as the

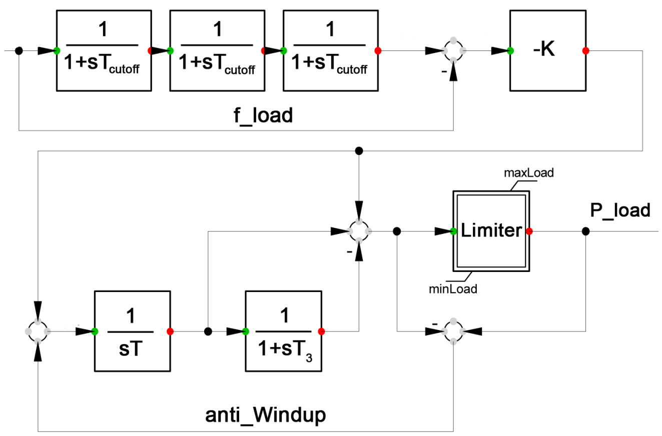

Fig. 6. Block diagram of the PI controller with the reference frequency through low-pass filtering the local frequency

integrator otherwise may drive the output permanently into one limit (q.v.[7]).

Also, the proportional gain K was set to 30 000, the integrator time constant to 0.1 seconds for both controller designs. With this setup the controllers achieved adequate results concerning response time and robustness.

IV. Results

The two approaches discussed in the previous section both led to a good improvement of the damping of the interarea modes. Figure 7 and 8 show the effects on interarea modes when a controller is implemented in one of the five regions. In both cases the interarea modes have almost entirely disappeard after 23 to 26 seconds. When a controller with a filtered reference frequency is implemented in all five regions the improvement is even better. As it can be seen in figure 9, the oscillations have faded completely after about 14 seconds.

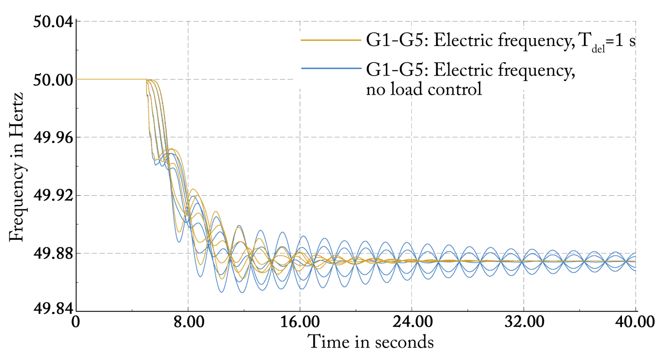

Fig. 7. Improvement of the damping of interarea modes through a controller with the reference frequency measured at gen. 3

In every simulation one controller could always only control ±0.333% of the total load in one region. How this controllable load is used is exemplarily shown in figure 10 for the controller with measured reference frequency. It is worth noticing that the controller output shown there does not necessarily represent the power demand of one particular load. The curve in figure 10 merely shows what the accumulated controlled load profile

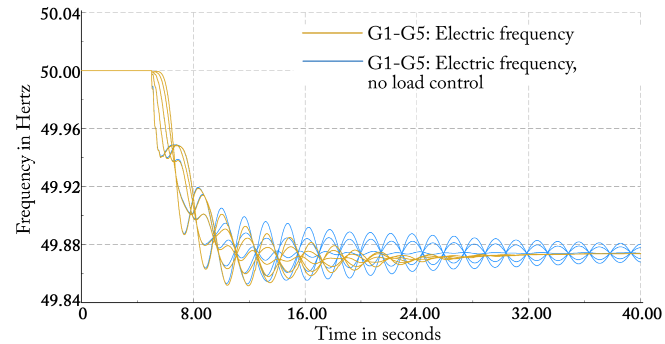

Fig. 8. Improvement of the damping of interarea modes through a controller with the reference frequency obtained through filtering of the local frequency

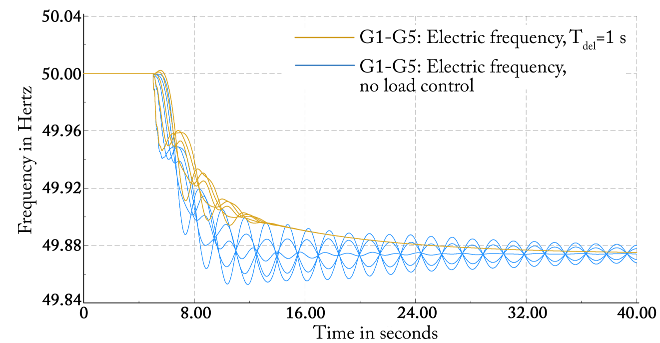

Fig. 9. Improvement of the damping of interarea modes through a controller with the reference frequency obtained through filtering of the local frequency

of one region would look like. In reality this would include a great number of loads that all may have very different looking load profiles.

The ordinate of the graph also shows negative values for the controller output. This does indicate generative power but simply a reduction of the load power compared to the value before the disturbance.

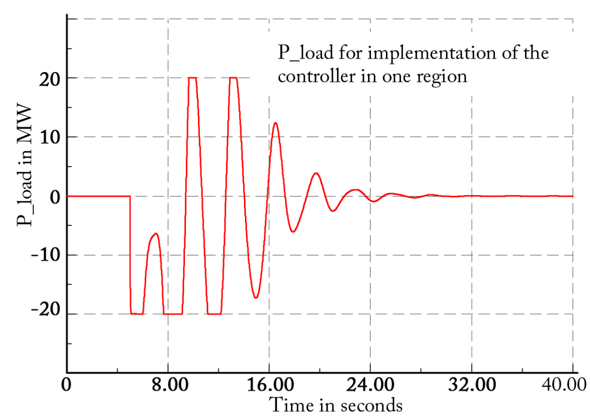

Fig. 10. Output signal of the load controller with filtered reference frequency

A direct comparison of the results with the implementation in one region shows that there are only minor differences in the effects of the controllers. The significant differences are much rather found in the design iteself. Both controllers exhibit a delay in their reaction on a disturbance of the frequency – one through the time delay of the distant frequency measurement, the other through the phase shift of the low-pass filters. However, the time delay of the measurement is likely to vary uncontrollably due to transmission disruptions whereas the phase shift of the low-pass filters will always remain the same. This makes the first approach with the distant measurement as reference frequency less robust. In addition, for this solution a far more sophisticated and expensive information infrastructure would be required.

V. Conclusion

The attempt to use additional load control for the damping of frequency oscillations across a large power grid were successful. The best results were achieved for controllers spread all over the grid. Also, the larger the controlled load was, the better the oscillations were damped.

Despite the promising results, currently there is obviously no realistic use of the principle. Neither the infrastructure for the transmission of measurements nor a sufficient amount of loads with a controller that could easily be upgraded with an additional control scheme are available. The future development will provide answers to the questions that will eventually decide over the usability of a load control for damping interarea oscillations. This will include answers to the questions whether or not consumers should be included in the control of power grids or if distributed control schemes offer enough advantages to centralized control approaches like FACTS or other conventional protections devices.

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