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Identification of Generator Active Power Oscillations Stability Measure

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***Abstract*—The paper presents various strategies for the identification of the active power frequency response with respect to a measure used to evaluate the oscillations of active power in power microgrids. First, the estimation based on the voltage step response data is considered. Alternatively, the data corresponding to chosen voltage disturbances are used for such estimation. A specific dedicated method for frequency response estimation is designed for each type of experiment and experiment conditions. The synchronous generator of a cogeneration unit, which is a part of a power microgrid, is used within the case study presented in the paper. The simulation results show the usability of the estimated power frequency response in a similar manner as the conventional measurement based on the series of active experiments.**

***Index Terms*—frequency response, Fourier transform, passive experiment, step response, active power, microgrid, smart energy**

I. INTRODUCTION

Increasing environmental awareness to reduce the carbon footprint of humanity has put power systems under intense pressure [1]. Renewable energy is being integrated into the distribution level, and conventional power grids are evolving towards smart grids. In such transition, the concept of microgrid plays a crucial role [2].

One of the main concerns regarding the broad application of microgrids is stability and quality [3]. Different approaches have been developed to enhance the stability of microgrids so far [3, 4, 5]. For a more comprehensive literature review in this field, see [2, 6] and the references therein.

In general, the stability performance of microgrids is often assessed from the damping of the local mode, i.e. the generator swinging against the rest of the microgrid system [7]. The microgrid has to be designed to provide acceptable performance under a wide range of system conditions [8]. Thus, the ability to precisely determine the frequency response of the generator in a microgrid is crucial for both controller design and performance evaluation [2].

It is often not technically feasible or economically admissible to perform regular experiments to obtain a generator's frequency response in the microgrid. To this end, the paper proposes novel strategies for frequency response estimation based on data from step response experiments, using parametric and non-parametric model identification, and an approach based on the voltage disturbance data measured during a passive experiment.

II. PRELIMINARIES AND PROBLEM FORMULATION

Assume the following continuous-time transfer function model of the generated active power to be modelled during the active experiment:

$$F_a(s) = \frac{\Delta P_{eo}(s)}{\Delta V_{ref}(s)} = \frac{B_a(s)}{A_a(s)} \tag{1}$$

where $\Delta P_{eo}(s)$ is the Laplace transform of the deviation of the active power from its steady-state value and $\Delta V_{ref}(s)$ represents the deviation of the reference stator voltage from the corresponding nominal value (usually 1 p.u.). This experiment allows to excite the system with a proper input signal to measure the system response and then use it to estimate the frequency response. Typically, two distinct types of signal can be applied within the active experiments, namely, the sine signal and the step signal.

Likewise, a transfer function model $F_p(s)$ can be defined for the passive experiment. The model input stands for the

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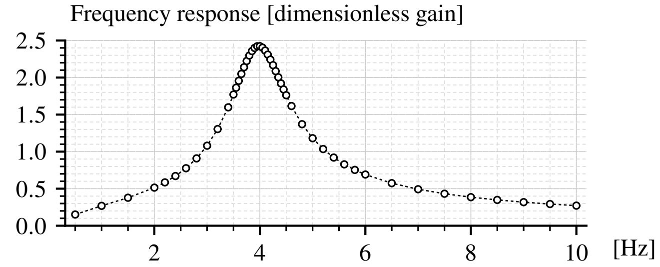

Fig. 1. Frequency response obtained by the means of the regular experiment and simulating the same procedure as in the case of actual measurement.

stator voltage, which is typically subject to disturbances, so the input is not independent:

$$F_p(s) = \frac{\Delta P_{eo}(s)}{\Delta V(s)} = \frac{B_p(s)}{A_p(s)} \tag{2}$$

where $\Delta V(s)$ is the Laplace image of the deviation of the stator voltage from the corresponding steady-state value.

The numerator $B(s)$ and the denominator $A(s)$ polynomials of models (1), (2) are in the form:

$$B(s) = b_0 + b_1 s + \ldots + b_{n_B} s^{n_B} \tag{3}$$

$$A(s) = 1 + a_1 s + \ldots + a_{n_A} s^{n_A} \tag{4}$$

Where n_B is the number of model zeros and n_A is the number of model poles (model order). The choice of n_B and n_A will be the subject of further investigation.

III. CASE STUDY

We will examine the system frequency response for a finite set of N frequencies forming the vector $\bar{\omega} = \begin{bmatrix}\omega_1 & \omega_2 & \omega_3 & \cdots & \omega_N\end{bmatrix}^T$. The corresponding vector of estimated magnitudes of the system frequency response $F(j\omega)$ can be defined as follows:

$$|\hat{F}| = \begin{bmatrix}|\hat{F}(j\omega_1)| & |\hat{F}(j\omega_2)| & |\hat{F}(j\omega_2)| & \cdots & |\hat{F}(j\omega_N)|\end{bmatrix}^T \tag{5}$$

First, an active experiment is considered to obtain frequency response, i.e. direct measurement of the oscillation amplitudes as a response to feeding the system input with a harmonic signal of various frequencies. For each frequency, the excitation signal $u(t)$ with offset u_0 and amplitude a_i holds $u(t) = u_0 + a_i \sin(\omega_i t)$.

In this case study, the frequency response plotted in Figure 1 represents the correct and reference result to be compared with other proposed methods. These reference measurements form the vector $|F|$ as follows:

$$|F| = \begin{bmatrix}|F(j\omega_1)| & |F(j\omega_2)| & |F(j\omega_2)| & \cdots & |F(j\omega_N)|\end{bmatrix}^T \tag{6}$$

The results were obtained by means of simulation, so the same procedure is performed as in the case of the actual experiment. However, such a procedure may not be feasible for the generators used in the smart microgrids applications.

Another example of an active experiment using the reference voltage step response is also presented in section IV.

The simulation model of power microgrid considered in this work consists mainly of a synchronous generator (nominal power 75 [kVA], 400 [V]), which is part of a cogeneration unit, a three-phase transformer that allows connection to a distribution network (22 [kV]) and the asynchronous motors posing main loads in the microgrid.

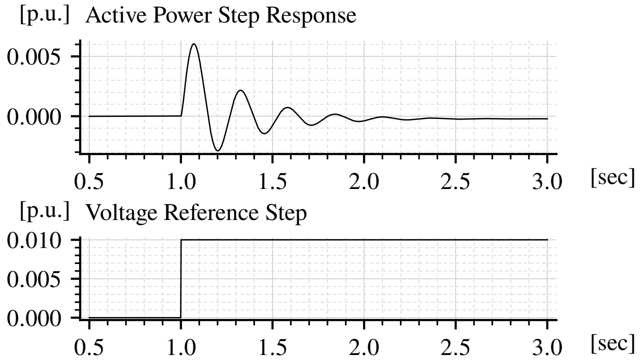

Fig. 2. Voltage response step data (deviations from steady-state).

IV. ESTIMATION BASED ON THE VOLTAGE STEP RESPONSE

The simplest, yet full-featured form of an active experiment is the step response. In contrast to the active frequency response experiment, where the input signal is harmonic and must be carried out for all examined frequencies separately, the step response experiment is evaluated only once, while the measured output response should contain the full information about the system frequency response.

An example of the voltage response step data is presented in Figure 2, where the deviation of the active power from its steady-state value and the deviation of the reference stator voltage from the corresponding nominal value are shown.

A. Parametric Model Identification

This strategy represents an interesting way to indirectly estimate the frequency response by the means of traditional parametric system identification methods based on the regular time domain data and analytically expressing the frequency response of thus identified transfer function model.

The joint vector of estimated parameters of model (2) is $\hat{\theta} = \begin{bmatrix}b_0 & b_1 & \cdots & b_{n_B} & a_1 & a_2 & \cdots & a_{n_A}\end{bmatrix}^T$. The following quadratic cost function is typically minimized to estimate the parameter vector $\hat{\theta}$:

$$J(\hat{\theta}) = \sum_{i=0}^{N_s} \left[\hat{y}(i,\hat{\theta}) - y(i)\right]^2 \tag{7}$$

where $y(t)$ stands for the system output measured during the step response experiment, $\hat{y}(t)$ is the simulated model output and N_s is the number of samples. The nonlinear least-squares problem (7) can be solved numerically.

In order to derive the frequency response $F(j\omega)$ of the identified parametric model (2), the Laplace operator s has to be replaced by $j\omega$ and the magnitude $|F(j\omega)|$ can be expressed as:

$$|F(j\omega)| = \left|\frac{B(j\omega)}{A(j\omega)}\right| \tag{8}$$

TABLE I
SIMPLE FIT METRIC (SFM) RESULTS [%]

n_A/n_B	0	1	2	3	4	5
2	-95.069	69.589	83.465	-	-	-
3	-99.422	88.030	92.390	94.924	-	-
4	-42.512	-62.017	95.099	95.102	95.095	-
5	-35.734	31.079	**95.104**	95.002	95.017	95.024

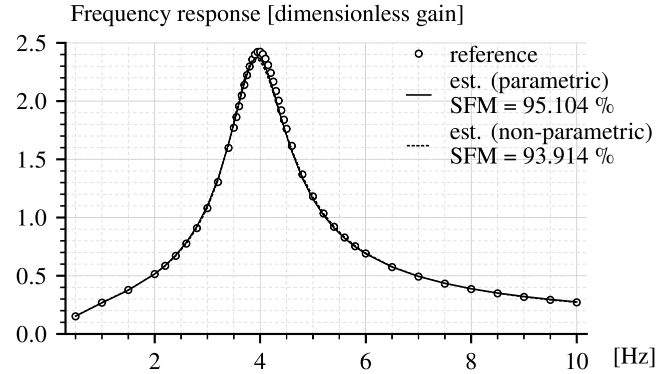

Fig. 3. Graphical comparison of the reference with the frequency response obtained using the parametric model (transfer function) and the non-parametric approach (spectral analysis).

The main advantage of the proposed approach is that the single step response experiment is sufficient to fully estimate the frequency response without the need to carry out multiple experiments for each of the investigated frequencies separately.

The accuracy of the estimated frequency responses was quantified by the Simple fit metric (SFM), which is defined as follows:

$$\text{SFM} = \left(1 - \frac{\sqrt{\left(|F| - |\hat{F}|\right)^{\mathsf{T}} \left(|F| - |\hat{F}|\right)}}{\sqrt{\left(|F| - |\bar{F}|\right)^{\mathsf{T}} \left(|F| - |\bar{F}|\right)}}\right) \times 100\% \quad (9)$$

where $|F|$ is the vector of magnitudes of the measured frequency responses and $|\hat{F}|$ is the vector of estimated magnitudes of the frequency responses.

The results of Simple fit metric evaluated for different combinations of model orders n_B and n_A are summarized in Table I. It can be concluded that the best fit value $\text{SFM} = 95.104$ [%] corresponds to model orders $n_A = 5$ and $n_B = 2$. The graphical comparison of the estimated frequency responses with the reference frequency response can be seen in Figure 3.

B. Non-parametric Model Identification

Assume the frequency transfer function of the model (1) in the following form:

$$F(j\omega) = \frac{y(j\omega)}{u(j\omega)} \quad (10)$$

where $y(j\omega)$ represents the Fourier transform of the system output $y(t)$ and $u(j\omega)$ is the Fourier transform of the input $u(t)$.

The Fourier transform operator $\mathscr{F}\left\{f(t)\right\}$ is given by the following integral transform applied to a general continuous function $f(t)$:

$$\mathscr{F}\left\{f(t)\right\} = \int_{-\infty}^{\infty} f(t)\cos(\omega t)\mathrm{d}t - j\int_{-\infty}^{\infty} f(t)\sin(\omega t)\mathrm{d}t \quad (11)$$

The real part of the complex function $\mathscr{F}\left\{f(t)\right\}$ can be seen as the correlation function with the cosine whereas, the imaginary part can be interpreted as the correlation with the sine function.

These frequency-dependent correlation functions can be separated as:

$$R_{fc}(\omega) = \int_{-\infty}^{\infty} f(t)\cos(\omega t)\mathrm{d}t \quad (12)$$

$$R_{fs}(\omega) = \int_{-\infty}^{\infty} f(t)\sin(\omega t)\mathrm{d}t \quad (13)$$

Accordingly, the frequency response (10) can be written as:

$$F(j\omega) = \frac{R_{yc}(\omega) - jR_{ys}(\omega)}{R_{uc}(\omega) - jR_{us}(\omega)} \quad (14)$$

For data-based estimation, the integrals of the correlation functions $R_{yc}(\omega_k)$, $R_{ys}(\omega_k)$ defined by (12), (13) have to be solved as finite summations assuming that the infinitesimal element $\mathrm{d}t$ will be replaced by the sample time $T_s > 0$ and the truncated experiment duration t_f:

$$\hat{R}_{fc}(\omega_k) = T_s \sum_{i=0}^{\frac{t_f}{T_s}} f(T_s i)\cos(\omega_k T_s i) \quad (15)$$

$$\hat{R}_{fs}(\omega_k) = T_s \sum_{i=0}^{\frac{t_f}{T_s}} f(T_s i)\sin(\omega_k T_s i) \quad (16)$$

The input excitation signal in this experiment is the Heaviside step function with the step size a_s:

$$u(t) = \begin{cases} -\frac{a_s}{2} & t < 0 \\ +\frac{a_s}{2} & t > 0 \end{cases} \quad (17)$$

The Fourier transform of the input signal $\mathscr{F}\left\{u(t)\right\}$ can be derived analytically for the above step function. Substituting $u(t)$ from equation (17) to (12) and (13) yields the following correlation functions:

$$\begin{aligned} R_{uc}(\omega) &= -\frac{a_s}{2}\int_{-\infty}^{0}\cos(\omega t)\mathrm{d}t + \frac{a_s}{2}\int_{0}^{\infty}\cos(\omega t)\mathrm{d}t \\ &= -\frac{a_s}{2}\frac{1}{\omega}\left[\sin(t)\right]_{-\infty}^{0} + \frac{a_s}{2}\frac{1}{\omega}\left[\sin(t)\right]_{0}^{\infty} = 0 \end{aligned} \quad (18)$$

$$\begin{aligned} R_{us}(\omega) &= -\frac{a_s}{2}\int_{-\infty}^{0}\sin(\omega t)\mathrm{d}t + \frac{a_s}{2}\int_{0}^{\infty}\sin(\omega t)\mathrm{d}t \\ &= \frac{a_s}{2}\frac{1}{\omega}\left[\cos(t)\right]_{-\infty}^{0} - \frac{a_s}{2}\frac{1}{\omega}\left[\cos(t)\right]_{0}^{\infty} = \frac{a_s}{\omega} \end{aligned} \quad (19)$$

The resulting spectrum of the in input signal is $u(j\omega) = -j\frac{a_s}{\omega}$. The above equation implies that the step signal (17) comprises the whole frequency spectrum, while its magnitude is decreasing with frequency. The estimate of the frequency transfer

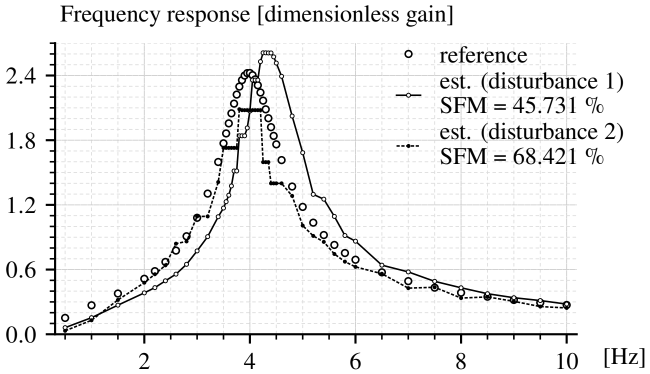

Fig. 4. Graphical comparison of the estimated frequency responses for the passive experiment.

function (14) can be derived by assuming the step input signal (17) with the frequency spectrum $u(j\omega)$.

$$F(j\omega) = \omega \frac{\hat{R}_{ys}(\omega) + j\hat{R}_{yc}(\omega)}{a_s} \tag{20}$$

The resulting estimated frequency response is shown in Figure 3 with SFM $= 93.914$ [%].

V. ESTIMATION BASED ON THE VOLTAGE DISTURBANCE

The passive experiments in the form of voltage disturbances are also considered, while the assumed data correspond to a regular microgrid operation of a synchronous generator. The voltage disturbance no. 1 is caused by a small step-vise change in voltage reference signal (set-point change). The disturbance no. 2 is caused by the asynchronous motor, which is connected to the microgrid. The step-vise change of the load torque causes the second disturbance.

Recall that the transfer function model considered for the passive experiments was defined in (1). To estimate the frequency response, we assume an arbitrary and independent input excitation signal $u(t)$. The general frequency response (14) is used, while the correlation functions can be replaced with their estimates $\hat{R}_{yc}(\omega_k)$, $\hat{R}_{ys}(\omega_k)$ and $\hat{R}_{uc}(\omega_k)$, $\hat{R}_{us}(\omega_k)$ calculated according to (15) and (16).

Multiplying the numerator and the denominator of $\hat{F}(j\omega_k)$ from (14) by the denominator complex conjugate yields:

$$\Re\left\{\hat{F}(j\omega_k)\right\} = \frac{\hat{R}_{yc}(\omega_k)\hat{R}_{uc}(\omega_k) + \hat{R}_{ys}(\omega_k)\hat{R}_{us}(\omega_k)}{\hat{R}^2_{uc}(\omega_k) + \hat{R}^2_{us}(\omega_k)} \tag{21}$$

$$\Im\left\{\hat{F}(j\omega_k)\right\} = \frac{\hat{R}_{yc}(\omega_k)\hat{R}_{us}(\omega_k) - \hat{R}_{ys}(\omega_k)\hat{R}_{uc}(\omega_k)}{\hat{R}^2_{uc}(\omega_k) + \hat{R}^2_{us}(\omega_k)} \tag{22}$$

The estimation results based on the voltage disturbance data are plotted in Figure 4. A graphical comparison shows that a reasonable estimate of the frequency response can be obtained even when the voltage itself, not the voltage reference, is considered as the input signal.

VI. CONCLUSION AND FUTURE WORK

The paper proposed methods to estimate the frequency response of the generator's active power based on the data from the step response experiment and even from the fully passive experiment data obtained under the operating conditions of the microgrid. The first method relies on the parametric transfer function model identification based on the time domain data and the least squares method. On the other hand, the second approach utilizes the Fourier transform and spectral analysis of the input and output signals to estimate the frequency response. The simulation results showed that both proposed methods are capable of providing estimates comparable to traditional measurements, while the need to repeatedly carry out the active experiment for each frequency separately could be fully avoided this way.

The results presented in this paper create a basis for our future work primarily aimed at the passive experiment of the voltage disturbance data. Such data are, in principle, available during the nominal operation of the power microgrid without the need to carry out specialized experiments. In addition, by estimating the frequency response of the active power, the stability and performance of power microgrids can be improved over a wide range of operating conditions by employing oscillation measures in a similar manner as in larger power grids.

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