TIME-DOMAIN IDENTIFICATION OF THE TRANSFER FUNCTIONS OF PARK'S DQ-AXIS SYNCHRONOUS GENERATOR MODEL FROM STANDSTILL DATA‡

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ABSTRACT: The design of a robust frequency converter controller for fatigue load reduction in variable speed wind turbines requires an accurate dynamic model of the electromagnetic part of the synchronous generator under investigation. In this paper a new procedure for identifying the transfer functions of Park's dq-axis model of a synchronous generator has been developed. It will be shown that the parameters of this model can be easily identified from standstill time-domain data obtained from the modified step-response test. The validity of the theoretical model has been verified by comparing time-domain simulations with measurements taken from the Lagerwey LW-50/750 direct-drive synchronous generator. It can be concluded that a consistent model estimate of the electromagnetic part of the LW-50/750 generator has been obtained. Ultimate validation, however, will follow after the implementation of the designed frequency converter controller in this wind turbine.
Keywords: Generators, Parameter identification, Standstill time-domain data, Models (mathematical)

1 INTRODUCTION

The design of robust frequency converter controller for fatigue load reduction in variable speed wind turbines requires that the (synchronous) generator model parameters are known accurately. In principle, synchronous machine parameters may be determined either from design calculations or from measurements acquired at the factory or on site. For high dynamic performance control, however, the former approach is inadequate. A primary goal of this paper is to address the latter issue.

Many papers have been published on synchronous machine parameter identification (*see e.g.* [1, 5, 7, 12, 14, 15] and references therein). Most papers address standstill frequency response (SSFR) methods following the protocols of IEEE Standard 115-1995 [4]. This standard focuses on identifying equivalent circuit parameters rather than on transfer functions. A few papers address methods of identifying the parameters from time-domain data. In both cases, the parameter estimation process generally consists of two parts. First, the time constants are extracted by applying a curve-fitting procedure to measured data. Next, the equivalent circuit parameters are determined by solving a set of non-linear equations through numerical optimisation. The weakness of this approach is that the order of the model must be known before the parameters can be determined and that numerical optimisation is a process fraught with numerical difficulties [3].

In this paper a new procedure is developed (using ideas from [14]) for identifying the transfer functions of Park's dq-axis model of a synchronous generator from time-domain standstill step-response data. The contribution of this paper is that Park's dq-axis model equations are rewritten such that a model structure arises that can be easily translated into a simulation scheme. The order of the rational transfer functions is not fixed but is determined by the data. The combination of identifying rational transfer functions and a high signal-to-noise ratio resulting from a standstill test offers the possibility to analytically determine the model parameters. That is, the identification procedure does not require good initial parameter values.

The resulting model is intended to be used for the design of a (robust) frequency converter controller that maximises the energy capture while minimising the fatigue loads of a wind turbine. The newly developed identification procedure will be applied to a 750 kW direct-drive synchronous generator implemented in the Lagerwey LW-50/750 wind turbine. This paper does not address the problem of saturation because the generator under investigation does not exhibit saturation under normal operating conditions.

2 SYNCHRONOUS GENERATOR MODEL

The aim of this section is to set up a theoretical model of a synchronous generator suited for both time-domain simulation, and model based control design. In essence, there are two aspects of a synchronous generator that need to be modeled, *viz.* the (electro)mechanical and the electromagnetic part. The mechanical part can be modeled using the techniques outlined in Molenaar [9]. In the present paper we will restrict ourselves to the dynamic modeling of the electromagnetic part.

From a modeling point of view all synchronous generators have similar representations. They differ only with respect to some model parameters. Because the round-rotor synchronous generator is a special case of the salient-pole rotor synchronous generator, we will treat only the latter for an arbitrary number of pole-pairs p. The LW-50/750 synchronous generator has the usual three stator windings, each 120 (electrical) degrees apart. The stator windings are star connected. The rotor has one accessible circuit, the field or excitation winding, and two sets of inaccessible circuits, called damper windings. Damper windings are real or fictitious windings that can be used to represent for ex-

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ample the damping effects of eddy currents in the machine.

According to Park [10, 11] the voltage equations of an ideal synchronous generator (*i.e.* linear magnetic circuit and stator windings are sinusoidally distributed along the stator circumference) in the dq reference frame are given by (using generator sign convention for the stator circuits):

$$\begin{aligned} u_d &= -R_s i_d - \omega_e \psi_q - \frac{d}{dt}\psi_d \\ u_q &= -R_s i_q + \omega_e \psi_d - \frac{d}{dt}\psi_q \\ -u_f &= -R_f i_f - \frac{d}{dt}\psi_f \end{aligned} \tag{1}$$

with u_d the direct-axis voltage [V], R_s the stator-winding resistance [Ω], i_d the direct-axis current [A], $\omega_e = \frac{d\theta_e}{dt}$ the electrical angular frequency [rad/s], ψ_q the quadrature-axis winding flux [Vs], t time [s], ψ_d the direct-axis winding flux [Vs], u_q the quadrature-axis voltage [V], i_q the quadrature-axis current [A], u_f the field-winding voltage [V], R_f the field-winding resistance [Ω], i_f the field-winding current [A], and ψ_f the field-winding flux [Vs].

A few observations can be made. The most important one is that equations (1) are coupled via the fluxes. In addition, they depend on the electrical angular frequency ω_e, thereby introducing non-linearities. The fluxes are given by

$$\begin{aligned} \Psi_d(s) &= L_{do}(s)I_d(s) + L_{dfo}(s)I_f(s) \\ \Psi_q(s) &= L_q(s)I_q(s) \\ \Psi_f(s) &= L_{fdo}(s)I_d(s) + L_{fo}(s)I_f(s) \end{aligned} \tag{2}$$

with s is the Laplace operator and $L_{do}(s)$, $L_{fdo}(s) = L_{dfo}(s)$, $L_q(s)$, $L_{fo}(s)$ proper transfer functions (*i.e.* $\lim_{s\to\infty} L(s)$ is a finite (zero or non-zero) constant) which depend on the design of the generator. The aforementioned transfer functions are in literature often referred to as "operational inductances".

A few comments have to be made. For a finite number of damper windings the aforementioned transfer functions can be expressed as a ratio of polynomials in s [6]. Furthermore, in his original paper R.H. Park used the non-power invariant transformation to transform the stator quantities onto the dq reference frame that is fixed to the rotor. In the above derivation we have used the power-invariant version in order to ensure that in both reference frames the same power expressions are obtained. In addition, he used motor sign convention for the stator circuits.

The dynamic behaviour of an ideal synchronous generator is thus fully described by the sets of equations (1) and (2) expressed in the dq reference frame. The resulting block diagram is depicted in Fig. 1 for the standstill case (*i.e.* $\omega_e = 0$). Observe that we need the inverse of the aforementioned rotor flux equations which is given by

$$\begin{bmatrix} I_d \\ I_f \end{bmatrix} = \frac{\begin{bmatrix} L_{fo}(s) & -L_{fdo}(s) \\ -L_{fdo}(s) & L_{do}(s) \end{bmatrix}}{L_{do}(s)\cdot L_{fo}(s) - L_{fdo}^2(s)} \cdot \begin{bmatrix} \Psi_d \\ \Psi_f \end{bmatrix} \tag{3}$$

It can be shown that the denominators of $L_{do}(s)$, $L_{dfo}(s)$, $L_{fdo}(s)$, and $L_{fo}(s)$ are identical. Consequently, the denominators in the above matrix equation are identical.

Obviously, for simulation as well as control design purposes, accurate information about the transfer functions $L_{do}(s)$, $L_{fdo}(s)$, $L_q(s)$ and $L_{fo}(s)$ as well as the resistances R_s and R_f is required. In the next sections, the aforementioned quantities will determined using parameter identification techniques.

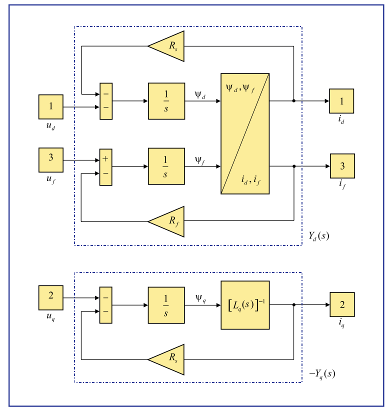

fig. 1: *Block diagram of an ideal synchronous machine.*

3 SYNCHRONOUS GENERATOR PARAMETER IDENTIFICATION

Synchronous machine identification and parameter determination can be performed either during normal operation (*i.e.* on-line), or during off-line running machine or standstill tests. Off-line standstill tests (*e.g.* DC-decay or Modified Step-Response (MSR) test) are preferred over on-line and off-line running machine tests, because:

- Off-line test results in signals with good signal-to-noise ratio due to absence of disturbance signals (electromagnetic interference);
- At standstill ($\omega_e = 0$) there is no coupling between d-axis and q-axis as illustrated in Fig. 1. In practice, zero generator speed can be enforced by mechanically locking the rotor during the experiments.

Step-response tests are proposed by *e.g.* Boije *et al.* [1], by Keyhani *et al.* [5] and by Vleeshouwers [16]. The measurement set-up as well as the experimental procedures are similar in the aforementioned step-response tests. In all cases, a sudden DC voltage is applied across two of the stator terminals with the rotor positioned in the d or q axis. On the contrary, the way the parameters are identified is quite distinct. For example, Keyhani *et al.* obtain initial values for the maximum-likelihood (ML) estimation by first applying a curve-fitting procedure to measured data. Subsequently, the ML estimation algorithm is used to identify the d and q axis transfer function model parameters. Vleeshouwers, on the other hand, transforms the measured time-domain data first to the frequency domain and after that identifies the transfer function model parameters using a ML estimator. We have decided to follow the well-documented procedures of Vleeshouwers' MSR test to generate the time-domain data. The main reason for this is the compactness of the measurement equipment. For identifying the transfer functions, however, we developed a new, procedure using the time-domain MSR data.

4 MSR TEST APPLIED TO LAGERWEY LW-50/750 GENERATOR

In this section the MSR-test will be used to identify the transfer function $Y_q(s)$, and $Y_d(s)$ as well as the resistances R_s and R_f of the Lagerwey LW-50/750 generator.

4.1 Measurement set-up

The measurement equipment consists mainly of a data-acquisition system, a low power DC voltage source (*i.e.* a $12\ V$ battery) to generate the step-like excitation signal, and sensors to measure the voltages and currents. The battery is connected to the b and c stator terminals. For the switching a thyristor is applied which eliminates the problem of bouncing [16].

The data-acquisition system consists of three main parts, *viz.* an input-output (I/O) board, a digital signal processor board from dSPACE® [2] with a TMS320C40 processor from Texas Instruments®, and a personal computer (PC) connected to the processor board. The automated data-acquisition process is started by switching on the (mechanical) switch and subsequently triggering the thyristor.

4.2 Data-acquisition and identification procedure

The MSR test consists of the following measurements:

1. **R_f-measurement**. One possible way to determine the field winding resistance R_f is by a stepwise excitation of u_f (field winding voltage) and measuring i_f (field winding current). Subsequently, dividing the steady-state values gives R_f;
2. **Q-measurement**. The dynamic behaviour of the quadrature-axis is fully described by the transfer function
$$Y_q(s) = -\frac{I_q(s)}{U_q(s)} = \frac{1}{R_s + s \cdot L_q(s)} \qquad (4)$$
in Fig. 1. For the identification of $Y_q(s)$ knowledge of the quadrature-axis voltage $u_q(t)$ and current $i_q(t)$ is thus both necessary and sufficient. These quantities can be easily derived from the following two measured variables: $u_{bc}(t)$ (stator voltage), and $i_c(t)$ (stator current). An appropriate rotor position for quadrature-axis identification is the one when the field winding axis is parallel to the a-phase winding (*i.e.* $\theta_e = 0$);
3. **D-measurement**. The dynamic behaviour of the direct-axis is fully described by the transfer function matrix $Y_d(s)$ between u_d, u_f and i_d, i_f. In this case, an appropriate rotor position is the one when the field winding axis is perpendicular to the a-phase winding (*i.e.* $\theta_e = \frac{1}{2}\pi$). In principle, the elements of Eq. (3), *viz.* $L_{fo}(s)$, $L_{fdo}(s)$ and $L_{do}(s)$, can be identified using data acquired from two independent measurements, namely one with excitation of the quadrature-axis voltage while the field winding is left open and one when the field winding is short-circuited [16]. Combining the resulting transfer functions gives the required 2×2 transfer function matrix. Due to the finite-precision arithmetic of a computer, however, this will result in an ill-conditioned matrix.

   One way to overcome this problem is to identify the MIMO (multiple-input-multiple-output) transfer function between the fluxes ψ_d, ψ_f and the currents i_d, i_f assuming that both R_s and R_f are already determined.

   Both the direct-axis winding flux ψ_d, and the field winding flux ψ_f, however, can not be measured in practice. Conversely, these variables can be generated by integration of Eq. (1) with the u_d, u_f, i_d, and i_f acting as input. Analogous to the quadrature-axis identification, the latter variables can be deduced from the two measured variables: $u_{bc}(t)$, and $i_c(t)$.

The "D" and "Q"- measurements have been preceded by remagnetising the system by either a large negative or positive current depending of the direction of the step in order to fix the initial magnetic state on the low boundary of the hysteresis loop. It should be noted that none of the measurements incorporated anti-aliasing filters. The "Q"-measurement data were collected with a sample rate of 5 kHz and have a 3.1 second measurement period. Both the "D" and "R_f"-measurement data were collected with a sample rate of 1 kHz and a 10.1 second measurement period. Each measurement is repeated at least three times.

The synchronous generator parameter identification procedure consists of three successive steps:

- **Step 1: Pretreatment of data**. The necessary pretreatment of the time-domain data is limited since the MSR-test results in relatively clean signals. The only pretreatment of the data that is required is compensating for the (slight) static non-linearity of the sensors, and removal of the offset;
- **Step 2: Model structure and order selection**. The measured input-output data is imported into the System Identification Toolbox [13]. First, an initial model order estimate is made by estimating 1100 ARX-models using the prediction-error method (*i.e.* minimizing the difference between the model's (predicted) output and the measured output) [8]. If the resulting model, however, produces an unsatisfactory simulation error and/or if the input is correlated with the residual, the model is rejected. Next, another model structure (or order) is selected until the model produces a satisfactory simulation error as well as results in zero cross-covariance between residual and past inputs. In that case it can be concluded that a consistent model estimate has been obtained;
- **Step 3: Model validation**. Model validation is highly important when applying system identification. The parameter estimation procedure picks out the "best" model within the chosen model structure. The crucial question is whether this "best" model is "good enough" for the intended application. To this end, the outputs of the identified model are compared to the measured ones on a data set that was not used for the fit (the so-called "validation data set").

4.3 Model validation criterion

As mentioned above, the outputs of the identified model are compared to the measured ones from a validation data set to validate the model. The percentage of the output variations that is reproduced by the model is chosen as measure of the goodness of fit. The precise definition is:

$$M_{gof} = \left[1 - \frac{\sqrt{\sum_{t=-0.1}^{10} \left(y(t) - y_{sim}(t)\right)^2}}{\sqrt{\sum_{t=-0.1}^{10} |y(t) - \bar{y}|^2}} \right] \cdot 100$$

with y is the measured output, y_{sim} is the simulated model output, and $\bar{y}$ the average value.

4.4 Results

The q-axis transfer function $Y_q(s)$ of the electromagnetic part of the Lagerwey LW-50/750 generator has been identified using an ARX model structure. A third order model turned out to be sufficient. The q-axis parameters (*i.e.* $L_q(s)$ and R_s) are deduced algebraically from the transfer function $Y_q(s)$ using Eq. (4).

The structure of the symmetric d-axis transfer function matrix (*i.e.* common denominator) and the high signal-to-noise ratio calls for a MIMO ARX model structure. For both inputs i_d and i_f, the percentage of the variations in the fluxes ψ_d, ψ_f that is reproduced by the (fourth order) model is larger than 99.5 % (identification data set).

The aforementioned q-axis parameters and d-axis transfer function matrix as well as the field-winding resistance are implemented in the block diagram shown in Fig. 1. The resulting inputs and outputs of the model are shown in Fig. 2 for a validation data set. Obviously, the simulated data matches the measured data very well. Observe that u_f is not equal to zero because the short-circuit is not perfect due to the slip-rings. The percentage of the output variations that is reproduced by the model is in case of the identification data set 99.74 %, 99.47 %, and 99.89 % for i_d, i_f, and i_q respectively. For the validation data set the percentages are 99.16 %, 92.78 %, and 99.76 % for i_d, i_f, and i_q respectively.

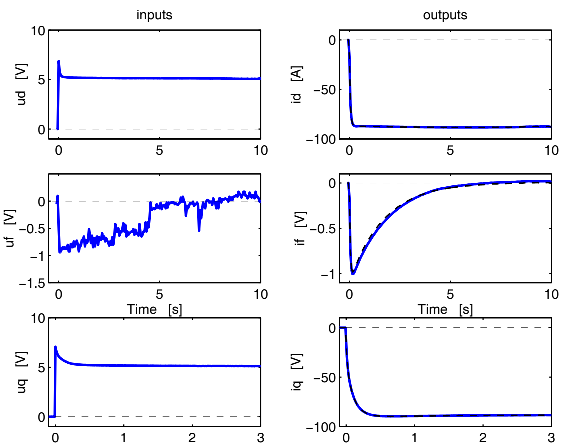

fig. 2: *Left figures: measured inputs u_d, u_f and u_q as function of time. Right figures: outputs i_d, i_f and i_q as function of time. Solid lines: measured data (validation data set), and dashed-lines: simulated data.*

In addition, the quality of the model is also checked by examining the cross correlation function between inputs and output residuals. In both cases an almost zero cross-covariance existed.

5 CONCLUSIONS AND FUTURE WORK

In this paper a new procedure for identifying the transfer functions of Park's dq-axis model has been developed. The following conclusions can be drawn.

5.1 Conclusions

A theoretical model of the electromagnetic part of a synchronous generator has been proposed. It has been shown that the parameters of this model can be easily identified following the developed procedure. The required input-output data is obtained from the modified step-response test. This test is the most favourable standstill test considering equipment costs and weight, measurement time and complexity.

The validity of the theoretical model has been verified by comparing time-domain simulations with measurements taken from the Lagerwey LW-50/750 generator.

It can be concluded that it is possible to identify an accurate model of the electromagnetic part of the Lagerwey LW-50/750 generator on the basis of modified step-response data. Ultimate validation, however, will follow after the implementation of the designed frequency converter controller in the Lagerwey LW-50/750 wind turbine.

5.2 Future work

The validated model will be used to develop a new, robust frequency converter controller for high dynamic performance of the Lagerwey LW-50/750 wind turbine direct-drive synchronous generator.

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