SIMULATION OF POWER ELECTRICAL CIRCUITS OF AUTOMOTIVE

by
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Abstract. In this paper, a procedure for identifying the transfer functions of Park's dq-axis model of a synchronous generator has been developed for analyzing automotive charging systems. This application note focuses on one particular aspect of charging system design: alternator/regulator performance. This voltage regulated power system must operate satisfactorily under extreme transient conditions.
Two of these transients, a load-dump condition (heavy electrical load switching with a disconnected battery), and an engine rapid crankshaft speed-up, are examined.
It will be shown that the parameters of this model can be easily identified from standstill time-domain data. The validity of the theoretical model has been verified by comparing time-domain simulations with measurements taken from the direct-drive synchronous generator.

Key Words. Transfer functions, synchronous generator, automotive

1. Introduction

Recent advances in power electronics applied to alternators. Constant speed operation has not been the choice of alternators designers, but rather a necessity brought about by the fixed relationship between the speed of the DC generators and the fixed utility grid frequency. The two main advantages of variable speed operation over constant speed operation are additional energy capture at partial load and potential reduction of fatigue loads.
Fatigue load reduction is the most important and underestimated advantage of variable rotational speed operation. Obviously, it requires high bandwidth control. The bandwidth of the active blade pitch system is, in general, too small to achieve fatigue load reduction.
The design of such a robust frequency converter controller for high dynamic performance 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. Many papers have been published on synchronous machine parameter identification [1–6]. Most papers address standstill frequency response (SSFR) methods following the protocols of IEEE Standard 115-1995 [7]. 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 nonlinear equations through numerical optimization. The weakness of this approach is that the order of the model must be known before the parameters can be determined and that numerical optimization is a process fraught with numerical difficulties [8].
In this paper, a procedure is developed [5] for identifying the transfer functions of Park's *d*q-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.

2. Modeling the alternator (when operating like Synchronous Generator)

The aim of this section is to set up a theoretical model of alternator operating like synchronous generator suited for both time-domain simulation and model based control design. In essence, there are two aspects that need to be modeled: the 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 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. Figure 1 depicts a salient-rotor synchronous generator with only one pole-pair (p=1). The machine 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 example, the damping effects of eddy currents in the machine. In Fig. 1, one damper winding is located along the direct-axis, and one along the quadrature-axis (represented by P_{1d} and P_{1q} in Fig. 1). When the DC excitation of the field winding is provided by permanent magnets, the field windings can be replaced by fictitious ones carrying constant field currents.

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

$$u_d = -R_s i_d - \omega_e \psi_q - \frac{d}{dt}\psi_d$$

$$u_q = -R_s i_q + \omega_e \psi_d - \frac{d}{dt}\psi_q \qquad \textbf{(1)}$$

$$-u_f = -R_f i_f - \frac{d}{dt}\psi_f$$

with u_d the direct-axis voltage [V], R_s the stator-winding resistance [Σ], i_d the direct-axis current [A], $T_e = d2_e / dt$ the electrical angular frequency [rad/s], P_q the quadrature -axis winding flux [V_s], t time [s], P_d the direct-axis winding flux [V_s], 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[Σ], i_f the field-winding current [A], and P_f the field-winding flux [V_s].
A few observations can be made. The most important one is that (1) are coupled via the fluxes. In addition, they depend on the electrical angular frequency T_e, thereby introducing non-linearity's. The fluxes are given by

$$\psi_d(s) = L_{do}(s) I_d(s) + L_{dfo}(s) I_f(s)$$

$$\psi_q(s) = L_q(s) I_q(s) \qquad \textbf{(2)}$$

$$\psi_f(s) = L_{fdo}(s) I_d(s) + L_{fo}(s) I_f(s)$$

with s the Laplace operator, $\boldsymbol{P_{d,q,f}}$ the Laplace transformed fluxes, $\boldsymbol{I_{d,q,f}}$ the Laplace transformed currents, and L_{do} (s), L_{fdo}(s)= L_{dfo}(s), L_q(s), L_{fo}(s)
proper transfer functions. L(s) when s is infinite is a finite zero (or non-zero constant) which depend on the design of the generator.

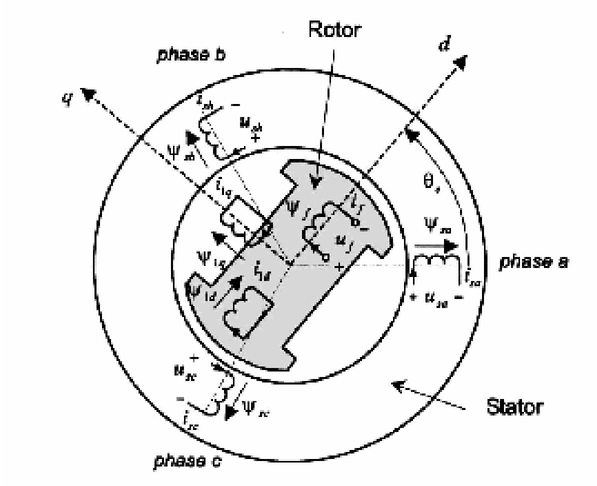


Fig. 1 Schematic representation of an elementary three-phase, synchronous generator

For a finite number of damper windings, the aforementioned transfer functions can be expressed as a ratio of polynomials in s [12]. 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 behavior of an ideal synchronous generator is thus fully described by the sets (1) and (2) expressed in the *dq* reference frame. For time-domain simulation purposes, it is convenient to rewrite the first set of equations in the following form

$$\psi_d = -\int (u_d + R_s i_d + \omega_e \psi_q) dt$$

$$\psi_q = -\int (u_q + R_s i_q + -_e \psi_d) dt \qquad \textbf{(3)}$$

$$\psi_f = \int (u_f - R_f i_f) dt$$

with the fluxes as state variables. The rotor flux equations can be conveniently expressed in matrix form

$$\begin{bmatrix} \psi_d \\ \psi_f \end{bmatrix} = \begin{bmatrix} L_{do}(s) & L_{fdo}(s) \\ L_{fdo}(s) & L_{fo}(s) \end{bmatrix} \begin{bmatrix} I_d \\ I_f \end{bmatrix} \qquad \textbf{(4)}$$

It can be easily shown that the inverse transformation is given by

$$\begin{bmatrix} I_d \\ I_f \end{bmatrix} = \frac{\begin{bmatrix} L_{fo}(s) & -L_{fdo}(s) \\ -L_{fdo}(s) & L_{do}(s) \end{bmatrix}}{L_{do}(s)L_{fo}(s) - L^2{}_{fdo}(s)} \begin{bmatrix} \psi_d \\ \psi_f \end{bmatrix} \qquad \textbf{(5)}$$

From those equations we can conclude blocks diagrams

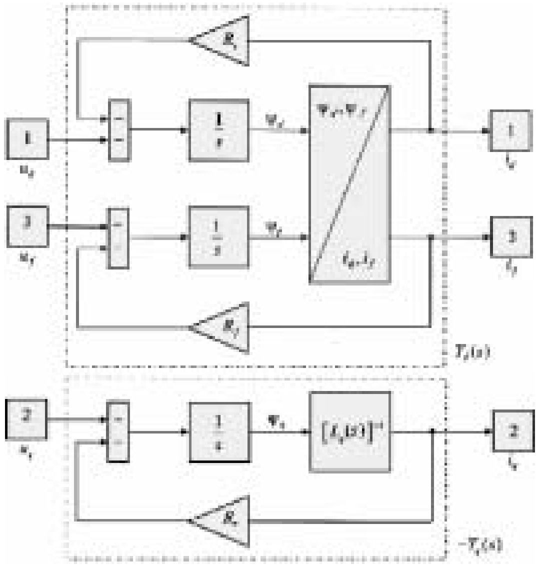


Fig. 2 Block diagram of an ideal synchronous machine

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

3. Identification of parameters

Synchronous machine identification and parameter determination can be performed either during normal operation (on-line), or during specially designed identification experiments (off-line). A disadvantage is that it is not possible to manipulate the input signals arbitrarily in order to obtain the best identification results. This implies that the influence of the operating conditions on the (accuracy of) identified parameters has to be careful analyzed.

Off-line identification experiments have been used for decades to identify electrical machine parameters. Two concepts are commonly used: running machine or standstill. Standstill tests are very attractive from a practical viewpoint: if it is permissible to take the machine out of operation, because driving the machine often creates serious complications of the measurement set-up [13].

Furthermore, the measured signals will have good signal-to-noise ratios due to the absence of disturbance signals (electromagnetic Interference). All standstill tests reported in literature are variations on the same concept, they mainly differ in the kind of excitation signal applied (i.e., step, ramp, sinusoidal, or random excitation).

The standstill test concept is preferred because there is no interaction between the direct and the quadrature axis. Using this observation, it can be concluded that the parameter identification for both axes may be carried out separately. In practice, zero generator speed can be enforced by mechanically locking the rotor during the experiments.

Before selecting the most appropriate standstill test, we will first highlight the most important aspects of both the quadrature-axis and the direct-axis identification.

A. Quadrature-Axis Identification. The dynamic behavior of the quadrature-axis of an ideal synchronous generator is fully described by the transfer function Y_q(s) in Fig. 2. From the block diagram it directly follows that

$$Y_q(s) = -\frac{I_q(s)}{U_q(s)} = \frac{1}{R_s + sL_q(s)} \quad \textbf{(6)}$$

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. It will be shown below that these quantities can be easily derived from three measurable variables, the stator voltages of the *b* and *c* phase (u_b(t) and u_c(t)), and the stator current i_c(t).

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.,2_e =0, see Fig. 1). In addition, if in this position the stator $b - c$ terminals are excited while the a-terminal remains open i_a(t)=0, it follows that i_b(t) = - i_c(t) . Furthermore, it can be concluded from symmetry considerations that

u_a(t)=1/2(u_b(t)+ u_c(t)).

Substituting the above results in the equations for the transformed stator voltages and currents

$$u_{0dq} = T_{0dq} u_s$$

$$i_{0dq} = T_{0dq} i_s$$

where

$$u_{0dq} = \begin{bmatrix} u_0 & u_d & u_q \end{bmatrix}^T$$

$$u_s = \begin{bmatrix} u_a & u_b & u_c \end{bmatrix}^T$$

$$i_{0dq} = \begin{bmatrix} i_0 & i_d & i_q \end{bmatrix}^T$$

and $\boldsymbol{T_{0dq}}$ the Park's power-invariant transformation matrix,

$$T_{0dq} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \cos(\theta_e) & \cos(\theta_e - \frac{2}{3}\pi) & \cos(\theta_e + \frac{2}{3}\pi) \\ \sin(\theta_e) & \sin(\theta_e - \frac{2}{3}\pi) & \sin(\theta_e + \frac{2}{3}\pi) \end{bmatrix}$$

gives

$$u_q = \frac{1}{2}\sqrt{2}(u_c - u_b) \qquad u_d = 0 \quad i_q = \sqrt{2} i_c \qquad i_d = 0 \tag{7}$$

Finally, the q-axis parameters (L_q(s) and R_s are deduced algebraically from the transfer function Y_q(s).

B Direct-Axis Identification. The dynamic behavior of the direct-axis of an ideal synchronous generator is fully described by the transfer function matrix Y_d(s) between u_d, u_f and i_d , if in Fig. 2. In this case, an appropriate rotor position is the one when the field winding axis is perpendicular to the ***a***-phase winding (i.e.,2_e =π/2, see Fig. 1). After all, it can be easily shown that for 2_e =π/2 it follows that:

$$u_d = \frac{1}{2}\sqrt{2}(u_c - u_b) \qquad u_q = 0 \qquad i_d = \sqrt{2}i_c \qquad i_q = 0 \qquad \textbf{(8)}$$

In principle, the elements of (5) 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 [13]. Combining the resulting transfer functions gives the required 2x2 transfer function matrix.
One way to overcome this problem is to identify the transfer function between the fluxes P_d , P_f and the currents i_d , i_f and assuming that both R_s and R_f are known. Recall that the stator winding resistance is known from the quadrature-axis identification. One possible way to determine the field winding resistance is by a stepwise excitation of u_f and measuring i_f .
Neither the direct-axis winding flux P_d, or the field winding flux P_f , however, can be measured in practice. Conversely, these variables can be generated by integration of (3) 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 three measurable variables u_b, u_c, and i_c.

C Testing and Selection of Excitation Signal. It is straightforward to understand that the character of the input signal that is applied during the experiment highly determines the amount of relevant information that is present in the data. For example, applying a constant input signal u(t)=c to the generator will not result in an output signal that contains any information on the dynamics of the system. Observe that in this case only static behavior can be uniquely determined. Consequently, in order to extract sufficient information from measured data concerning the dynamics, conditions have to be imposed on the character of the input signal.
Generally step-response testing may be more practical for obtaining parameters for installed synchronous machines. Summarizing, based on both the excitation requirements and the practical demands, a step-response test seems the most appropriate test among the standstill tests for the identification and parameter determination of alternator.

4. Measurement Set-Up
Fig. 3 shows an automotive charging system, which includes a complete electro-mechanical alternator model. This model includes all of the internal flux coupling factors that vary with the shaft rotation angle.

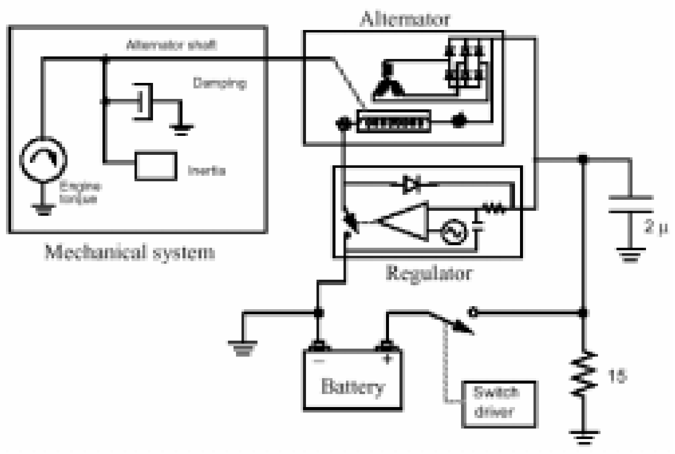


Fig. 3 Charghing system in automotive

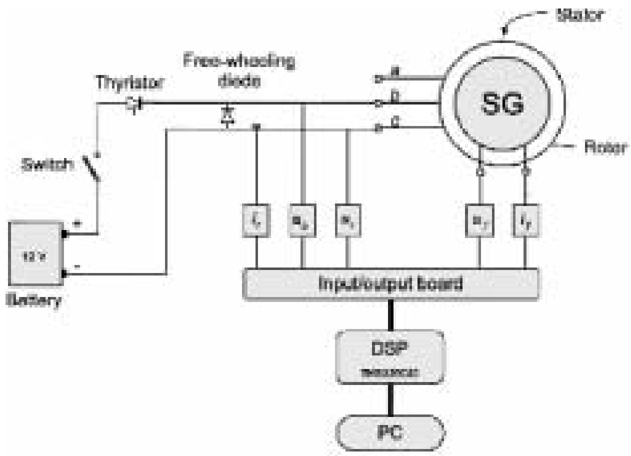


Fig. 4 Scheme of the measurement set-up of the modified step-response test as used for the identification of the machine parameters

Figure 4 shows a schematic of the measurement set-up. The step-like excitation signal is generated by switching on a low-power DC voltage source (i.e., a 12V battery). The battery is connected to the b and *c* stator terminals of the alternator. A thyristor is used for the switching. A thyristor is preferred over a mechanical switch because it eliminates the problem of bouncing [13].

Depending on the measurement type, a combination of the following signals is measured: i_c, (stator current), u_{bc} (stator voltage), u_f (field winding voltage), and i_f (field winding current).
The data-acquisition system consists of three main parts, an input-output I/O board, a digital signal processor board from 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.

A. Data-Acquisition and Identification Procedure. The modified step-response test consists of three successive measurements:
1. Q-measurement. Rotor positioned such that the quadrature axis is excited;
2. D-measurement. Rotor positioned such that the direct axis is excited, while the field winding is short-circuited;
3. R_f -measurement. Stepwise excitation of u_f and measu-ring i_f.

B. Parameter Estimation Procedure. System identify-cation or parameter estimation deals with constructing mathematical models of dynamical systems from experimental data. The parameter estimation procedure picks out the best model within the chosen model structure according to the measured input and output sequences and some identification criterion. A common and general method of estimating the parameters in system identification is the prediction error method [16]. In this method, the parameters of the model are chosen so that the difference between the model's (predicted) output and the measured output is minimized.

The developed identification procedure consists of next steps:

- ***Model structure and order selection.*** It is trivial that a bad model structure cannot offer a good, low order model, regardless the amount and quality of the available data. The measured input-output data is imported into graphical user interface. If the resulting model, however, produces an unsatisfactory simulation error and/or if the input is correlated with the residual, the model is rejected and another model structure (or order) is selected. This continues until the model produces a satisfactory simulation error and 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;

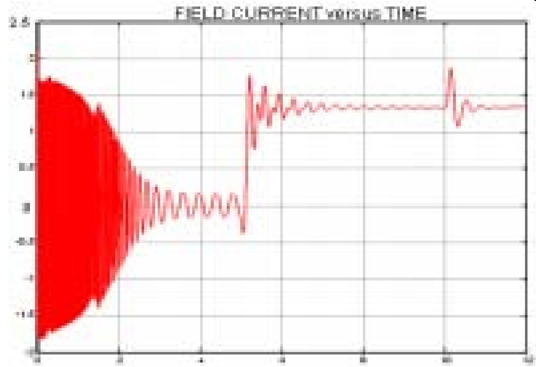
- ***Model validation.*** Model validation is highly important when applying system identification. The parameter estimation procedure picks out the best model within the chosen model structure. The crucial question is whether this *best* model is *good enough* for the intended application: time-domain simulation, analysis of dynamic loads, or control design purposes. To this end, the identified models should be confronted with as much information about the process as practical. Here, the outputs of the identified model are compared to the measured ones on a data set that was not used for the fit (called *validation data set*).

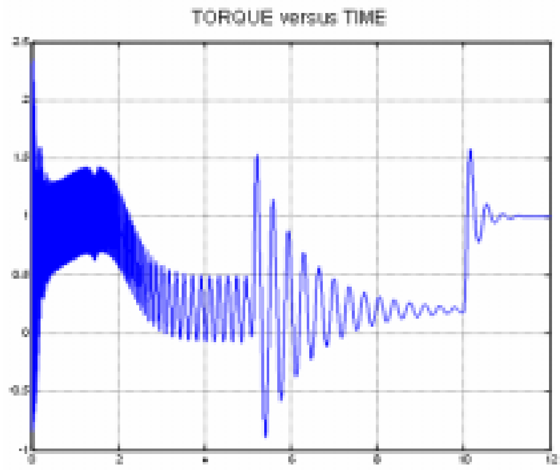
C. Model Validation. As mentioned above, the outputs of the identified model are compared to the measured ones from a validation data set to (in)validate the model. The percentage of the output variations that is reproduced by the model is chosen as measure of the goodness of fit.

D. Results. The q-axis transfer function Y_q(s) of the elec-tromagnetic part of the generator has been identified. A third order model turns out to be sufficient. The q-axis parameters are derived from Y_q(s) as outlined above.

The structure of the symmetric d-axis transfer function matrix and both inputs i_d and i_f ,the percentage of the variations in the fluxes P_d, P_f that is reproduced by the fourth order model is larger than 99.5%.

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. 2. The resulting inputs and outputs of the model are shown in Fig. 5 for a validation data set. Obviously, the simulated data matches the measured data very well.





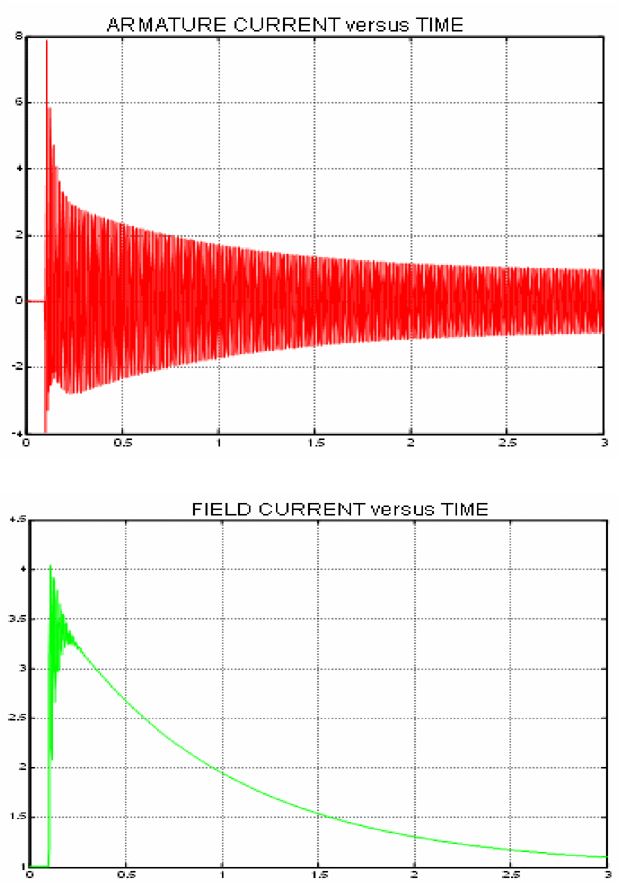


Fig. 5 Scheme of the measurement set-up of the modified step-response test as used for the identification of the machine parameters

Observe that i_f is not equal to zero because the short-circuit is not perfect due to the slip-rings 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 exists.

5. Conclusions

In this paper, a procedure for identifying the transfer func-tions of Park's dq-axis model of a synchronous generator has been developed. The following conclusions can be drawn:

- 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 favorable 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.
Combination of the aforementioned results leads to the conclusion that it is possible to identify an accurate model of the electromagnetic part of the generator on the basis of modified step-response data.

Future Work. The validated model will be used to develop a new , robust frequency converter controller for high dynamic performance in automotive industry.

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