ARCHIVES OF ELECTRICAL ENGINEERING VOL. 62(3), pp. 401-415 (2013)

DOI 10.2478/aee-2013-0032

Applicability of Park transformation for the analysis of transient performance during subsynchronous resonances*

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(Received: 26.06.2012, revised: 26.11.2012)

Abstract: Long transmission lines have to be compensated to enhance the transport of active power. But a wrong design of the compensation may lead to subsynchronous resonances (SSR). For studies often park equivalent circuits are used. The parameters of the models are often determined analytically or by a three-phase short-circuit test. Models with this parameters give good results for frequencies of 50 Hz and 100 Hz resp. 60 Hz and 120 Hz. But SSR occurs at lower frequencies what arises the question of the reliability of the used models. Therefore in this publication a novel method for the determination of Park equivalent circuit parameters is presented. Herein the parameters are determined form time functions of the currents and the electromagnetic moment of the machine calculated by transient finite-element simulations. This parameters are used for network simulations and compared with the finite-element calculations. Compared to the parameters derived by a three-phase short-circuit a significant better accuracy of simulation results can be achieved by the presented method.

Key words: subsynchronous resonances, parameter identification, equivalent circuit, standstill frequency response test, three phase short circuit test, evolutionary strategy

1. Introduction

Since years the Park-equivalent circuit is used to model the behavior of synchronous machines. The parameters of this equivalent circuit normally are determined by a three-phase short-circuit test. During a short-circuit especially frequencies of 50 Hz and 100 Hz rep. 60 Hz and 120 Hz occur. Therefore, the determined parameters are appropriate for simulations of short-circuits and similar grid faults. But it has not been proven yet, whether the determined parameters of the Park-equivalent circuit represent the correct dynamic behavior in the case of subsynchronous resonances (SSR). In this case currents of low frequencies between 10 Hz and

* This is extended version of a paper which was presented at the 22th *Symposium on Electromagnetic Phenomena in Nonlinear Circuits*, Pula, Croatia, 26.06-29.06 2012.

45 Hz occur and lead to a significantly different physical behavior of the machine in comparison to the short-circuit case. Over 100 subsynchronous resonance studies were done in the past and all of them based on the equivalent circuit representation of the machine. Therefore, the applicability of this model, the correct parameter identification and the eventual need for a parameter adaption are important questions which will be worked out in this paper for the first time.

Two standard measurement methods, the three-phase short-circuit test and the standstill frequency response test, are presented and compared with each other concerning the quality of the determined parameter sets.

Since low-frequency oscillations cannot be measured entirely, a third novel method is presented which bases on a Park-parameter optimization from finite-element simulation results. The finite-element model has to consider the skin effect and saturation effects especially in the band of subsynchronous frequencies. The parameters of the equivalent circuit are varied until the time functions of currents and electromagnetic torque of both simulations are in good agreement.

The used optimization is based on an evolutionary strategy. For the validation of the optimized parameter set a three-phase short-circuit lasting for 100 ms and a following subsynchronous resonance is simulated with the finite-element model and compared with results from a network simulation using optimized parameters.

2. Determination of the electrical Park-equivalent circuit parameters

Three-phase short-circuit test

The three-phase short-circuit test is applied in practice as a standard method for determining the transient and sub-transient reactances and time constants of synchronous machines and is a standardized method defined in IEC [4].

At no-load operation the stator windings are shorted simultaneously and the currents of the three phases and the excitation current are recorded up to steady state (continuous short-circuit). If one phase current is zero at the time of the switching, the maximum peak current due to the three-phase short-circuit occurs at this phase.

The short-circuit current i_k of one phase following a no-load operation can be described analytically [4]:

$$i_k = \sqrt{2}U_N \left\{ \begin{array}{l} \left[\dfrac{1}{x_d} + \left(\dfrac{1}{x'_d} - \dfrac{1}{x_d} \right) \cdot e^{-\frac{1}{T'_d}} + \left(\dfrac{1}{x''_d} - \dfrac{1}{x'_d} \right) \cdot e^{-\frac{1}{T''_d}} \right] \cdot \cos(\omega_n t + \varphi_0) \\ -\dfrac{1}{2} \left(\dfrac{1}{x''_d} - \dfrac{1}{x''_q} \right) \cdot e^{-\frac{1}{T_a}} \cos(\varphi_0) + \left(\dfrac{1}{x''_d} - \dfrac{1}{x''_q} \right) \cdot e^{-\frac{1}{T_a}} \cos(2\omega_n t + \varphi_0) \end{array} \right\}. \tag{1}$$

With the parameters: x_d – synchronous reactance d-axis, x_q – synchronous reactance q-axis, x'_d – transient reactance d-axis, x'_q – transient reactance q-axis, x''_d – sub-transient reactance d-axis, x''_q – sub-transient reactance q-axis, T'_a – transient time constant, T''_a – sub-transient time constant, T_a – direct current time constant, U_N – rated voltage, φ_0 – start angle of rotation, ω_n – angular frequency of grid.

With the short-circuit test only the parameters of the *d*-axis can be determined directly. For the determination of the *q*-axis parameters further experiments have to be performed (for example the measurement with a small slip to get the value of x_q). The evaluation of the currents by the use of the evolutionary strategy now arises the possibility to determine the values of the *q*-axis from the 3-phase short-circuit experiment. The choice of starting values has a great influence on the result and thus the quality of optimization, but with the determined parameters of the *d*-axis suitable initial values are available.

Standstill frequency response test (SSFR)

The big advantage of a standstill frequency response test (SSFR) is the determination of the electrical parameters of *d*- and *q*-axis without having to make major changes in the test setup. In addition, the measurements are performed at stand still condition of the machine and with low currents and voltages. Hence, the risk of damaging the machine while measuring is very small.

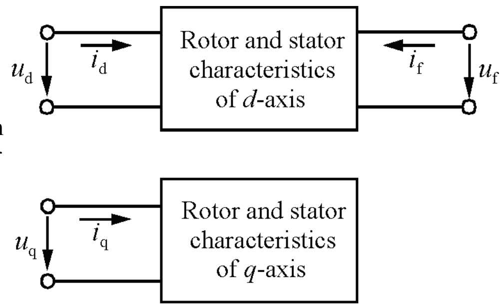

Fig. 1. Two-port representation of a synchronous machine for the *d*-and *q*-axis

The SSFR provides the input and transmission behavior of the studied machine depending on the frequency. In the *d*-axis the machine can be treated as a reciprocal two-port (Fig. 1). For its fully description the input- respectively transfer functions $\underline{Z}_{\mathrm{d}}(j\omega_e)$, $\underline{Z}_{\mathrm{df}}(j\omega_e)$ and $\underline{T}_{\mathrm{fd}}(j\omega_e)$ have to be determined [5]. The *q*-axis is completely described by the input function $\underline{Z}_{\mathrm{q}}(j\omega_e)$.

Analogous to the impedance of the d-axis the transmission impedance $\underline{Z}_{\mathrm{df}}$, the impedance of the *q*-axis $\underline{Z}_q$ and their corresponding inductivities $\underline{L}_{\mathrm{df}}$ and $\underline{L}_{\mathrm{q}}$ can be defined. By an appropriate wiring of the stator windings and by an positioning of the rotor to the fed windings of the stator it can be ensured that the d- and q-axis are stimulated separately and measured frequency curves are scaled with the proper conversion factors to the two-axis values.

In Figure 2 the test arrangements of the SSFR for the *d*- and *q*-axis are shown. Before running the test, it has to be ensured that all electrical connections to the stator terminals and the field winding are disconnected. In addition, it must be possible to rotate the rotor of the machine to a specific position. The feeding of the stator windings is done via a variable frequency AC power source. The frequency range of this source is from f_{e} = 0.001 Hz up to 1000 Hz.

An integrated power amplifier provides the required high current, so that a sufficiently large magnetic flux is achieved within the machine.

In all frequency responses the injected current $\underline{i}_a$ is generally measured as the first signal, while the second signal depends on the searched quantity (voltage or current). Thus, for example, the impedance $\underline{Z}_d(j\omega_e)$ of the d-axis and the power transmission function $\underline{T}_{fd}(j\omega_e)$ can be measured in a single test run.

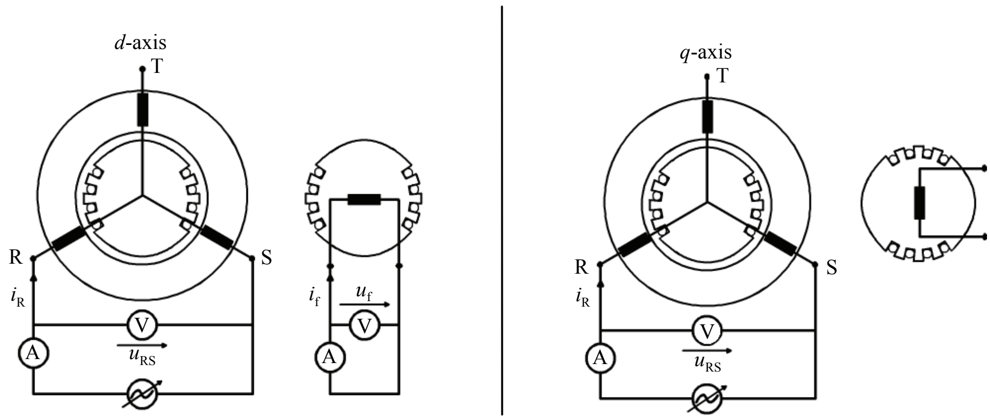

Fig. 2. Interconnection, measurement taps and the rotor position to determine the frequency response of the input- and transmission functions

To determine the d-axis parameters, the rotor is oriented in such way that the flux produced by the windings R and S is fully covered. The alignment is done by a current supply of the windings with a constant frequency (e.g. 100 Hz) and a measurement of the induced voltage at the exciter winding. The rotor is then rotated until the induced voltage in the exciter winding reaches the maximum value. According to the measurements in the q-axis the rotor is turned until the voltage reaches the minimum value of zero.

Finite-element simulations

In the following a novel method of parameter determination is recommended by the authors. This method is very effective. If precise measurements are not practicable, they can be replaced by transient finite-element simulations. The finite-element model has to include the skin effect and saturation effects. For the simulation of subsynchronous resonances the finite-element model of the machine has to be connected to a network consisting of a transformer, a long transmission line, a series capacitance for compensation and a grid (Fig. 3). Furthermore a torsional model of the shaft has to be implemented.

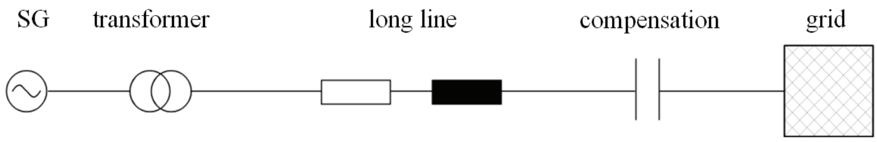

Fig. 3. Network model for SSR-simulations [7]

Then, a network simulation program with a Park-equivalent circuit representation of the generator is used to simulate the same case as done with the finite-element model. Therefore, the parameters of the Park-equivalent circuit are varied by the use of an evolutionary strategy until the time functions of the currents and the electromagnetic torque of the machine are in good agreement between both simulations.

With this method even grid failures with oscillations below the operation frequency, which occur also during subsynchronous resonances, can be simulated and compared accurately.

3. Use of the evolutionary strategy to determine the equivalent circuit parameters

The evolutionary strategy simulates the principle of biological selection. Some terms used in this context are therefore biological names and listed in the table below.

Table1. Terms from the context of evolutionary strategies

Biological term	Technical meaning
Parent	initial value set as basis for the variation
Offspring	by variation achieved new set of parameters
Mutation	variation of the parameter set

The main idea of this method is to vary the parameters of an existing model (e.g. from estimates of a similar generator of the same power class) and to calculate the short circuit currents and frequency responses for each variation by solving the model equations. The calculated curves are then compared with the measurement results. Only the variations with the best result are used again to form new variations. This procedure is repeated until the two curves coincide up to a pre-defined error. Depending on the accuracy and quality requirements of the starting values, different approaches for changing the parameters can be chosen. The process of evolutionary strategies is illustrated in the following flowchart (Fig. 4).

The mutation, which is the creation of a new offspring, in this case depends on the quality of the results, which is described by the sum of the square errors. The smaller the error is, the narrower are the limits for the mutation of new offspring (step size of the mutation). The advantage of this step size adaptation is the optimization with a small mutation step size in the near of the optimum. A fixed mutation range, however, might lead to the optimization at a local minimum or is not convergent.

The parents are subject to the same evaluation criteria as the offspring and therefore can survive as well. The survival of the parents may lead to a better convergence of the optimization but also has the disadvantage that, in the worst case, immortal parents can be generated, which will stop the progress of optimization. The described method was programmed in MATLAB® and the determination of equivalent circuit parameters from the three-phase short-circuit test for various electrical machines was successfully tested [1]. For the determination of parameters from the standstill frequency response tests, the present program has been modified, so that it uses the frequency responses of input- and transfer functions instead of the short-circuit current curves to derive the model parameters. Therefore, measured and calculated frequency responses are compared.

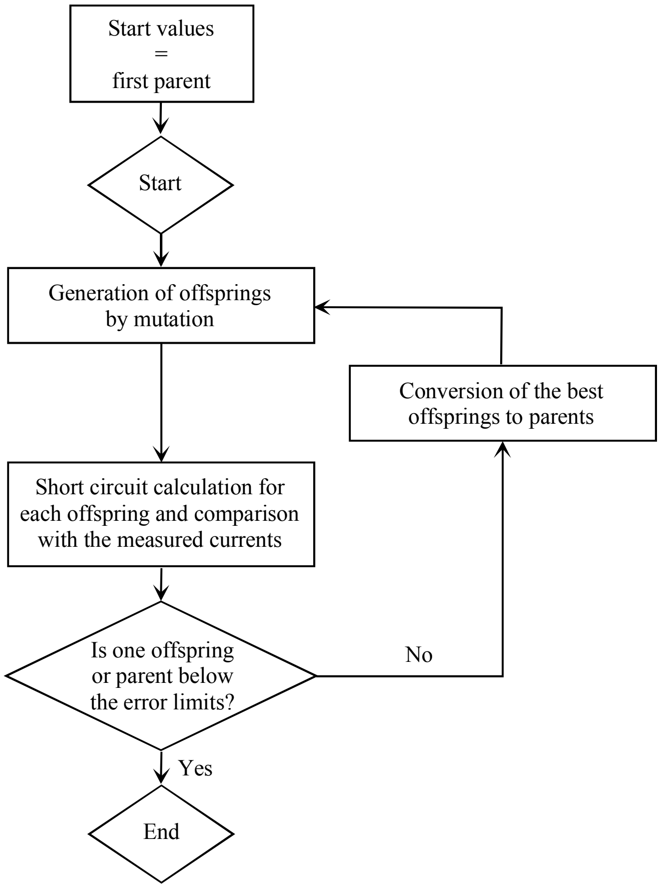

Fig. 4. Flowchart of evolutionary strategies

4. Determination of the Park-parameters by the use of the evolutionary strategy

In principle, the parameters of each adequate equivalent circuit can be determined with this optimization process. In practice, in most simulation programs for the analysis of electromechanical systems, the Park-equivalent circuit as a model for the integrated synchronous generator is used. The simulation program NETOMAC [6] is used in this paper. It is based on the standard model shown in (Fig. 5). For this type of model the parameters can be calculated from the geometry of the machine.

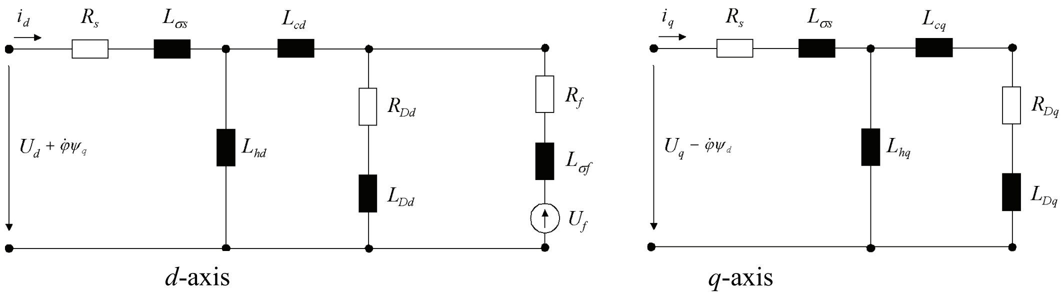

Fig. 5. Park-equivalent circuits of a synchronous machine with the extension by Canay

Determination of the Park-parameters from the short-circuit by the use of the evolutionary strategy

To determine the Park-parameters, the phase currents and the excitation current during a short-circuit from no-load operation have to be measured at the generator terminals. Since no measurements on the investigated 775 MVA generator can be done, the required currents are generated by a numerical field calculation with the finite-element program FELMEC.

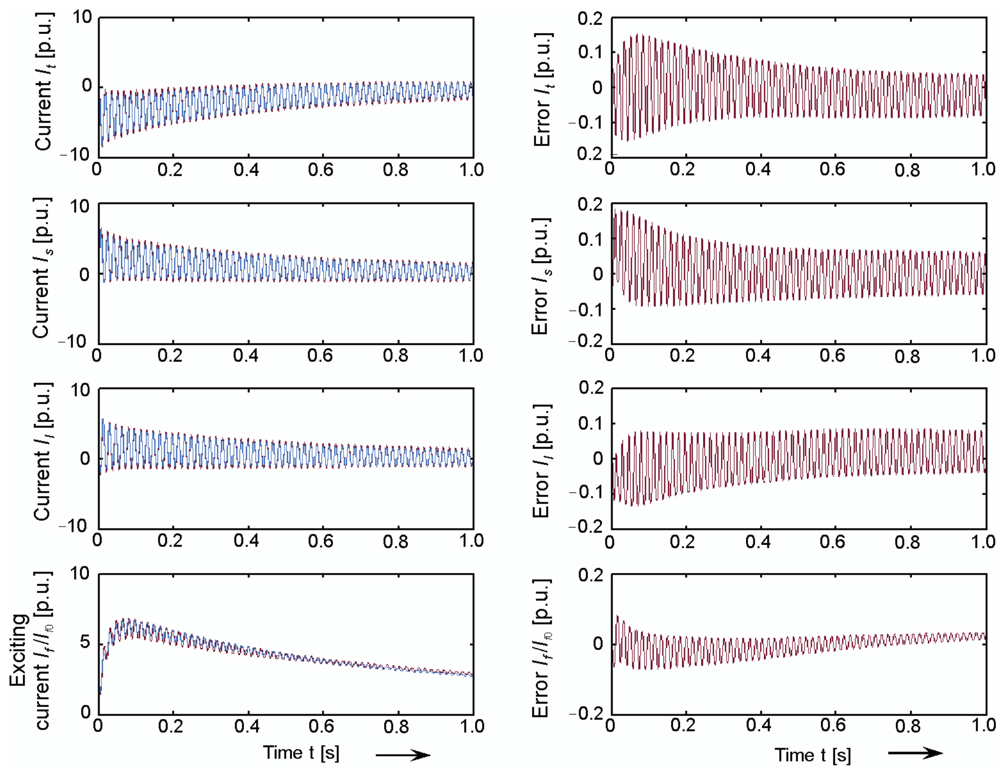

Fig. 6. Comparison of time curves of the stator- and excitation currents of a 775 MVA synchronous generator after the optimization

The transient simulation of one second takes about one hour computation time on a standard desktop computer. A description of the program FELMAC is given in [3]. These currents are used as a reference for the optimization. The parameters are varied during the optimization until the differences between the reference current curves and the current curves computed from the optimized parameters are minimal.

Figure 6 shows a comparison of the time curves of calculated currents with FELMEC (red) and the current characteristics, which were calculated with the optimized parameters (blue) in the left column. In the right column the related errors are illustrated. The comparison displays a good agreement between the current characteristics. The biggest error of the current I is less than 0.2 p.u. at a maximum current of 8.2 p.u.

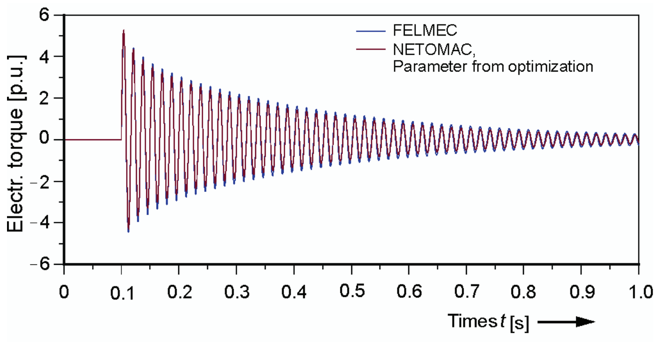

Fig. 7. Comparison of the electromagnetic torque of the reference calculation with FELMEC and NETOMAC with optimized parameters

Table 2. Comparison of the equivalent circuit parameters (Fig. 5) calculated from the geometry of a 775 MVA generator and evaluated from a 3-phase-SC

From geometry calculated equivalent circuit parameters								**Optimized by 3-phase SC**							
d-axis				*q*-axis				*d*-axis				*q*-axis			
R_S	=	0.0010	p.u.	R_S	=	0.0010	p.u.	R_S	=	0.0010	p.u.	R_S	=	0.0010	p.u.
$X_{\sigma s}$	=	0.1140	p.u.	$X_{\sigma s}$	=	0.1140	p.u.	$X_{\sigma s}$	=	0.1631	p.u.	$X_{\sigma s}$	=	0.1631	p.u.
X_{hd}	=	1.4580	p.u.	X_{hd}	=	1.3770	p.u.	X_{hd}	=	1.3059	p.u.	X_{hd}	=	1.3663	p.u.
R_{Dd}	=	0.0068	p.u.	R_{Dd}	=	0.0063	p.u.	R_{Dd}	=	0.0066	p.u.	R_{Dd}	=	0.0018	p.u.
X_{Dd}	=	0.0270	p.u.	X_{Dd}	=	0.0702	p.u.	X_{Dd}	=	0.0008	p.u.	X_{Dd}	=	0.0546	p.u.
X_{cd}	=	0.0243	p.u.	X_{cd}	=	0.0243	p.u.	X_{cd}	=	0.0250	p.u.	X_{cd}	=	0.0250	p.u.
R_f	=	0.0008	p.u.					R_f	=	0.0015	p.u.				
$X_{\sigma f}$	=	0.0891	p.u.					$X_{\sigma f}$	=	0.0787	p.u.				

In Table 2 the identified equivalent circuit parameters from the optimization are compared with the calculated parameters from the geometry of the machine. It can be noticed that the optimized parameters differ from the original data set. It is not necessary that the identified parameter sets match with calculated parameters from the geometry, as long as they represent the electrical behavior of the generator properly. For this purpose, an example of the electromagnetic torque calculated with the optimized equivalent circuit parameters and NETOMAC is shown in Figure 7 and compared with the reference calculation. Both curves show a good agreement. It can be noted that the optimization yields good results in terms of the dynamic behavior of the generator during a short-circuit fault.

Identification of Park-parameters using the standstill frequency response measurement and the evolutionary strategy

For the identification of the Park-parameters from the standstill frequency measurement, the input resp. transfer functions $\underline{Z}_d(j\omega_e)$, $\underline{Z}_q(j\omega_e)$ $\underline{Z}_{df}(j\omega_e)$ and $\underline{T}_{fd}(j\omega_e)$ of a 52 MVA turbine generator were measured. In order to determine appropriate equivalent circuit parameters describing the correct dynamic behavior of the generator, suitable initial values for the optimization have to be chosen. The DC resistance of the stator, for example, can be estimated from the measured course of the impedance $\underline{Z}_d(j\omega_e)$. For this, the curve has to be extrapolated to the frequency of 0 Hz, as in this point the impedance Z_d just equals to the resistance R_s.

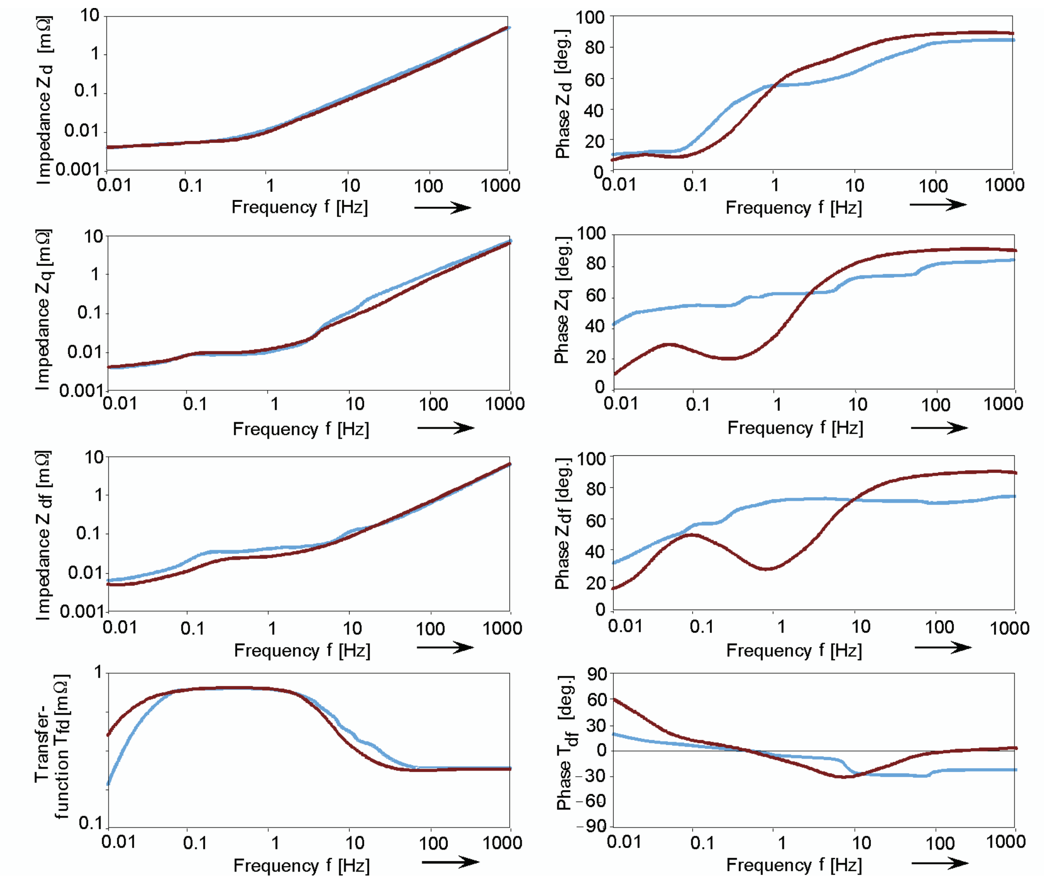

Fig. 8. Comparison of input respectively transfer functions of a 52 MVA synchronous generator after optimization

Another quantity, which can be determined during the measurement, is the resistance of the excitation winding R_f. Thus, two parameters of the equivalent circuit are known and can be treated as fix values during optimization. The other parameters are varied by the optimization until the differences between the measured frequency responses and the frequency responses calculated with the optimized parameters become minimal.

Figure 8 shows the comparison of the measured frequency responses (blue) with the frequency responses identified by the optimization of the parameters (red). The frequency responses are represented with 10 measurement points each decade.

It is striking that there are sometimes large discrepancies between the two curves, especially in the phase angles. The comparison of the equivalent circuit parameters from the datasheet of the studied generator with the optimized parameters (Tab. 3) shows the same result. Here, the deviations are much greater than for the optimization using the 3-phase-SC (see Tab. 2).

Table 3. Comparison of the equivalent circuit parameters (see Fig. 5)
calculated from the geometry and optimized (SSFR)

From geometry calculated equivalent circuit parameters								**Optimized by 3-phase SC**							
d-axis				*q*-axis				*d*-axis				*q*-axis			
R_S	=	0.0017	p.u.	R_S	=	0.0017	p.u.	R_S	=	0.0011	p.u.	R_S	=	0.0017	p.u.
$X_{\sigma s}$	=	0.1257	p.u.	$X_{\sigma s}$	=	0.1257	p.u.	$X_{\sigma s}$	=	0.1194	p.u.	$X_{\sigma s}$	=	0.1194	p.u.
X_{hd}	=	1.8400	p.u.	X_{hd}	=	1.7420	p.u.	X_{hd}	=	1.9284	p.u.	X_{hd}	=	1.5907	p.u.
R_{Dd}	=	0.0092	p.u.	R_{Dd}	=	0.0028	p.u.	R_{Dd}	=	0.1757	p.u.	R_{Dd}	=	0.2667	p.u.
X_{Dd}	=	0.0323	p.u.	X_{Dd}	=	0.0409	p.u.	X_{Dd}	=	0.0341	p.u.	X_{Dd}	=	0.0060	p.u.
X_{cd}	=	−0.0014	p.u.	X_{cd}	=	−0.0014	p.u.	X_{cd}	=	−0.0042	p.u.	X_{cd}	=	−0.0036	p.u.
R_f	=	0.0009	p.u.					R_f	=	0.0009	p.u.				
$X_{\sigma f}$	=	0.1152	p.u.					$X_{\sigma f}$	=	0.1215	p.u.				

The large differences in the frequency responses and the values of the parameters indicate that the identified parameters from the SSFR do not reflect the dynamic behavior of the generator accurately enough for an analysis of a complex electro-mechanical system [2]. The comparison of the electromagnetic torque curves calculated by the original parameters and calculated ones from the SSFR-optimization in Figure 9 confirms this thesis. The two curves show large differences in amplitude and frequency of the torque after a 3-phase short-circuit at the generator terminals.

At this point the question may be asked why the optimization of equivalent circuit parameters based on the standstill frequency response measurement does not yield a satisfactory result. To answer this question, a verification of the measurement and a validation of the parameter identification have to be done.

To verify the applied optimization method the equivalent circuit parameters from the datasheet of the machine (see Tab. 3, left side) were used to calculate the input resp. transfer functions which were used as reference characteristics for the optimization program. The result

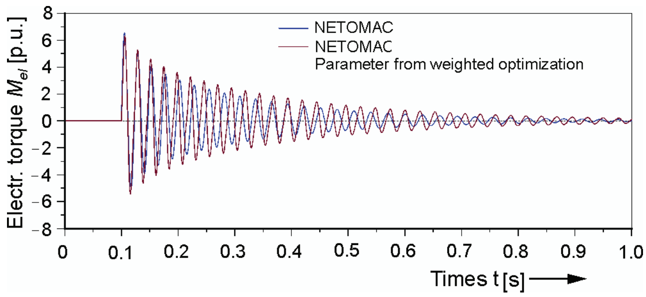

Fig. 9. Comparison of the electromagnetic torque of the reference calculation and the calculation with optimized parameters (SSFR) with NETOMAC

of this optimization is, that the identified parameters match with those from the datasheet and the calculated frequency responses are identical with the reference curves. If the optimization method provides accurate results for this case, but fails to reproduce the measured frequency response, so the SSFR method itself has to be the reason for the discrepant results.

A big advantage of the SSRT compared to the 3-phase-SC method, is the simple test setup of a machine in standstill condition. However, in this way no rotational effects are taken into account. Due to the low currents used in the SSFR, nonlinear effects in the measurement results do not occur either. The minimum frequency at which the measurement should be performed is 0.001 Hz. Hence, the measurement would take nearly 17 minutes, with the result of high winding temperatures. In addition, the requirement for a constant temperature throughout the measurement would be violated.

5. Comparison of NETOMAC calculation using optimized parameters and FELMAC calculation

For the determination of the Park-parameters the phase currents, the electromagnetic torque and the excitation current during a subsynchronous resonance caused by a three-phase fault clearing with clearing time of 100 ms has to be recorded. Since no measurement data is available for the investigated 775 MVA generator, the currents are calculated numerically with the finite-element program FELMAC. This currents are used as reference for the parameter optimization. The identified parameters are listed in Table 4.

These parameters replace the parameters derived from the geometry of the machine and are used for a new simulation of a three-phase short-circuit using NETOMAC®. The calculated time functions of currents and the electromagnetic torque are compared with the time functions of the numerical calculation.

The calculated torque reproduces the original function nearly exact (Fig. 10). The time function of the current *Ir* and its frequency spectrum are compared in Figure 11 and the electromagnetic torque is shown in Figure 12. These results underline the very good agreement of the NETOMAC® calculation with optimized equivalent circuit parameters.

Table 4. From a SSR (caused by a 3-phase short-circuit which is cleared after 100 ms) optimized equivalent circuit parameters of a 775 MVA generator

***d*-axis**				***q*-axis**			
R_s	=	0.0011	p.u.	R_s	=	0.0011	p.u.
$X_{\sigma s}$	=	0.1144	p.u.	$X_{\sigma s}$	=	0.1144	p.u.
X_{hd}	=	1.2446	p.u.	X_{hq}	=	1.2351	p.u.
R_{Dd}	=	0.0120	p.u.	R_{Dq}	=	0.0030	p.u.
X_{Dd}	=	0.0258	p.u.	X_{Dq}	=	0.0773	p.u.
X_{cd}	=	0.0255	p.u.	X_{cq}	=	0.0255	p.u.
R_f	=	0.0013	p.u.				
$X_{\sigma f}$	=	0.1259	p.u.				

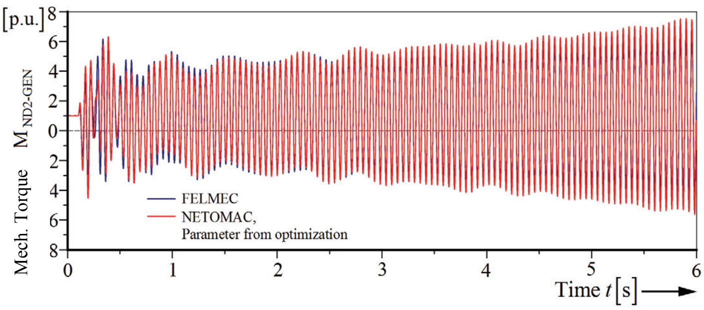

Fig. 10. Mechanical torque between low pressure turbine 2 (ND2) and generator (GEN) due to a SSR caused by a 3-phase short-circuit which is cleared after 100 ms (degree of compensation X_C = 69%)

6. Conclusion

Theoretically, the SSFR is a simple method to determine the parameters of the Park-equivalent circuit of a synchronous generator. But the measurement involves some sources of error, so that this method does not meet all requirements in practice.

SSR-studies which base in the Park-equivalent circuit and standard parameters determined by a three-phase short-circuit test or from the geometry of the machine lead to good but imprecise results which can be used as rough estimates.

Transient finite-element simulations with a coupled network are very time consuming and therefore not suitable for wide-ranging network studies.

A practicable solution is given by the presented method in which optimized Park-parameters are determined from one transient finite-element simulation. This parameter set then can be used for exhaustive network studies with a conventional network simulation program.

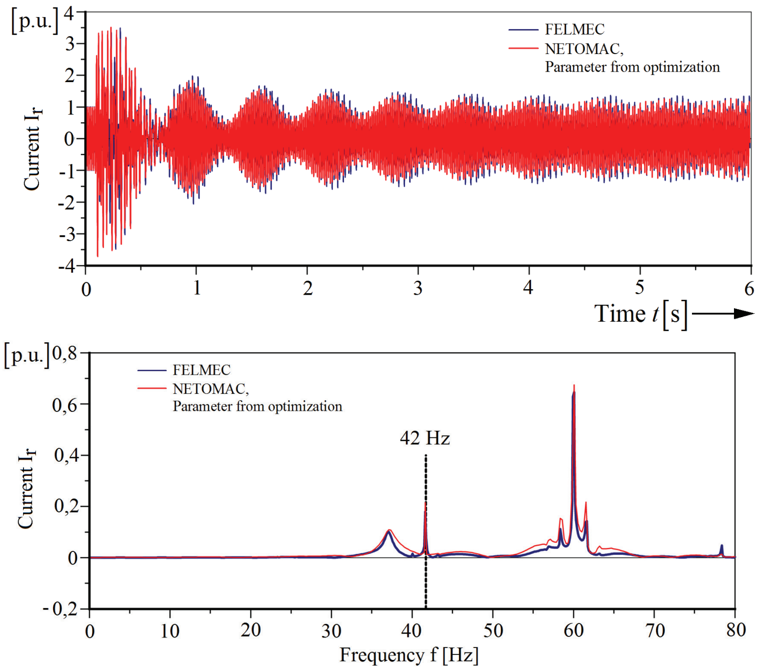

Fig. 11. Current I_r and frequency spectrum due to a SSR caused by a 3-phase short-circuit which is cleared after 100 ms (degree of compensation X_C = 69%)

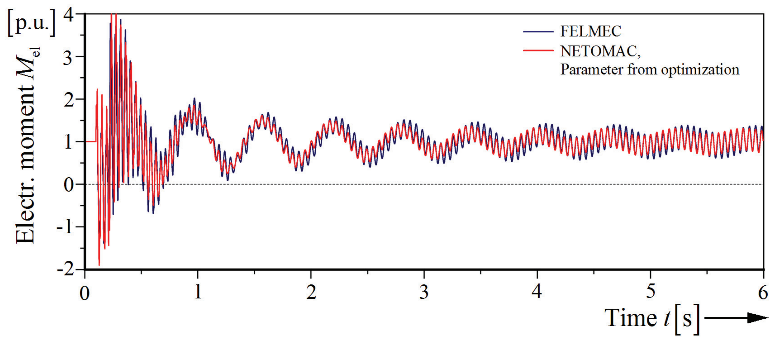

Fig. 12. Electromagnetic torque due to a SSR caused by a 3-phase short-circuit which is cleared after 100 ms (degree of compensation X_C = 69%)

The optimized parameters derived by a numerical finite-element calculation of a SSR yield good results in modeling the dynamic behavior of the machine by the use of a Park-equivalent circuit.

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Symbols

Symbol	Unit	Meaning
f	Hz	frequency
i	A	current
i_d	A	current of stator winding, *d*-axis
i_f	A	current of field winding
i_k	A	short-circuit current
i_q	A	current of stator winding, *q*-axis
L_{cd}	H	Canay-inductivity, *d*-axis
L_{cq}	H	Canay-inductivity, *q*-axis
L_{Dd}	H	inductivity of damping winding, *d*-axis
L_{Dq}	H	inductivity of damping winding, *q*-axis
L_h	H	main inductivity
L_{hd}	H	main inductivity, *d*-axis
L_{hq}	H	main inductivity, *q*-axis
L_σ	H	leakage inductivity
$L_{\sigma s}$	H	leakage inductivity of stator winding
$L_{\sigma f}$	H	leakage inductivity of field winding
R	Ω	resistance
R_{Dd}	Ω	resistance of damping winding, *d*-axis
R_{Dq}	Ω	resistance of damping winding, *q*-axis
R_f	Ω	resistance of field winding
R_S	Ω	resistance of stator winding
T_a	s	direct current time constant
T_a'	s	transient time constant
T_a''	s	sub-transient time constant
T_d'	s	transient short-circuit time constant
T_d''	s	sub-transient short-circuit time constant
T_{fd}	s	current transfer function
t	s	time
U_N	A	rated voltage
u_f	A	voltage of field winding
u_d	A	voltage of stator winding, *d*-axis
u_q	A	voltage of stator winding, *q*-axis
X	Ω	reactance
X_C	Ω	reactance of series compensation
X_{Dd}	Ω	reactance of damping winding, *d*-axis
X_{Dq}	Ω	reactance of damping winding, *q*-axis
X_d	Ω	reactance of stator winding

X_d'	Ω	transient short-circuit reactance of stator winding
X_d''	Ω	sub-transient short-circuit reactance of stator winding
X_h	Ω	main reactance
X_{hd}	Ω	main reactance, *d*-axis
X_{hq}	Ω	main reactance, *q*-axis
X_σ	Ω	leakage reactance
$X_{\sigma s}$	Ω	leakage reactance of stator winding
$X_{\sigma f}$	Ω	leakage reactance of field winding
Z_d	Ω	impedance of *d*-axis
Z_{df}	Ω	transfer impedance of *d*-axis
Z_q	Ω	impedance of *q*-axis
Ψ_d	Vs	flux of *d*-axis
Ψ_f	Vs	flux of field winding
Ψ_q	°	flux of *q*-axis
φ_0	rad/s	flux of field winding
ω_n		angular frequency of grid