Sudden Short Circuits in a Doubly Fed Synchronous Machine (DFSM) with a Cyclo-Converter feeding the rotor

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Abstract – **Sudden short circuits in a Doubly Fed Synchronous machine (DFSM) with excitation from a cyclo-converter are described. The machines main features are outlined and simulation as well as experimental results on the short circuit currents and voltages are reported and discussed. The simulation of the transient phenomena is achieved with a SPICE simulator.**

Keywords: Sudden Short circuit, Doubly Fed Synchronous Machine, Cyclo-Converter

I. INTRODUCTION

The Doubly Fed Synchronous Machine (DFSM) is used as a variable speed generator in pumped storage water power plants. The intended application of the machine makes necessary a rotating excitation equalling the difference between synchronous speed as given from the grid and the speed of the prime mover. This is accomplished with a three phase winding fed by a cyclo-converter with low frequency. The power for excitation is transferred onto the rotor via slip rings. The star-connection of the three phase rotor winding is also accessible via slip ring which is unalterable due to the cyclo-converter used. After a brief look onto the steady state operation of the DFSM connected to the grid the transient occurrences in the machine and further in the cyclo-converter are discussed. Therefore a simulation model including all kinds of unbalanced load cases (especially zero sequence load cases) is developed. The results of the simulation as well as experimental results will be presented, compared and discussed.

II. THE DOUBLY FED SYNCHRONOUS MACHINE IN STEADY STATE OPERATION

The essential parts of a Doubly Fed Synchronous Machine are the stator winding which is the same as the stator winding of an ordinary synchronous machine and the multiphase excitation winding in the rotor. The stator winding is connected to the grid, while the rotor winding is fed by a converter. In high power applications i.e. water power generators cyclo-converters are required. The rotor winding is star-connected. The terminals of the windings as well as the star-point are connected to slip rings. A principal wiring of a complete application of the Doubly Fed Synchronous Machine is shown in Fig.1. For the design of the slip rings and the cyclo-converter the balance of the active and the reactive power in the rotor is of interest. It should be noticed, that active as well as reactive power in the rotor is governed by the slip of the machine. That means, the power which has to be supplied or consumed by the cyclo-converter is proportional to the deviation of the rotor speed from the synchronous speed.

The balance of active and reactive power is outlined in Fig.2 and Fig.3.

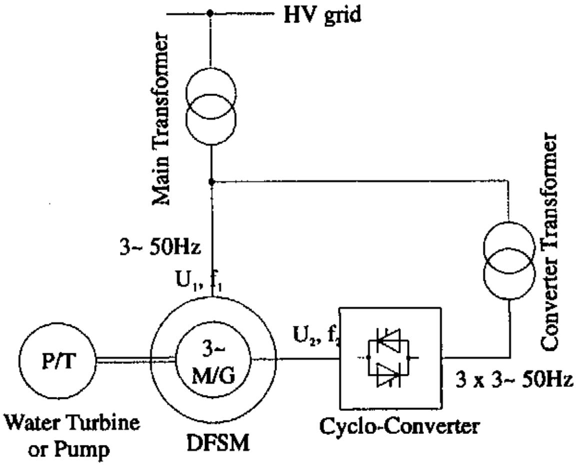


Fig. 1: Wiring of the DFSM on the HV-grid

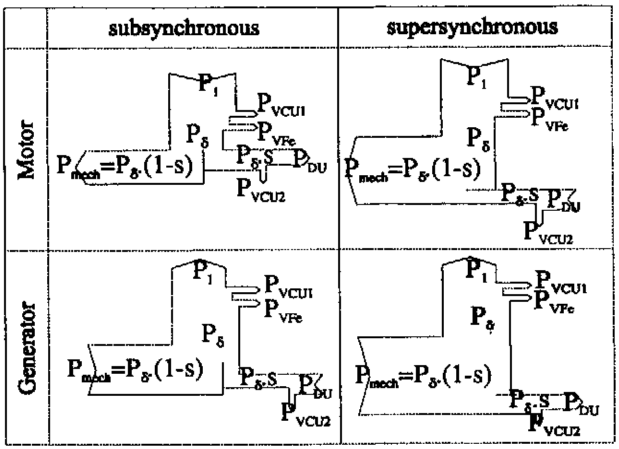


Fig. 2: Balance of active power

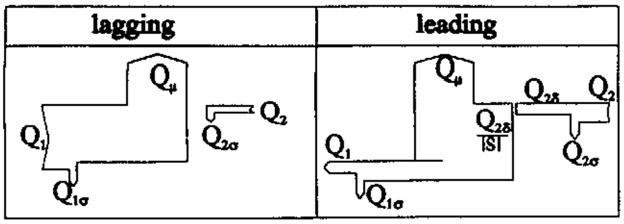


Fig.3 Balance of reactive power

To calculate the total balance of reactive power the reactive power due to displacement in the cyclo-converter has to be considered. Depending on the voltage of the cyclo-converter compared with the voltage of the rotor winding, the reactive power of displacement might be very high.

A cyclo-converter can be operated in 'circulating-current-free mode' or in 'controlled-circulating-current mode'. Due to the higher efficiency of the 'circulating-current-free mode' in steady state operation it was decided to build up an experimental test set up with a 'circulating–current–free–cyclo-converter'. The description of the experimental test set up is given later.

III. MATHEMATICAL MODEL OF THE DFSM FOR TRANSIENT ANALYSIS

To investigate the dynamic behaviour of the Doubly Fed Synchronous Machine a mathematical model is derived. The mathematical model describes the DFSM with space vectors. The system of differential equations and linear equations is solved in stator reference frame. Therefore the three-phase system is transformed into a xy0-system.

$$u_X = \tfrac{2}{3}\cdot u_{L1} - \tfrac{1}{3}\cdot(u_{L2} + u_{L3}) \tag{1}$$

$$u_Y = \tfrac{1}{\sqrt{3}}\cdot(u_{L2} - u_{L3}) \tag{2}$$

$$u_0 = \tfrac{1}{3}\cdot(u_{L1} + u_{L2} + u_{L3}) \tag{3}$$

Rotor currents and voltages have to be transformed into the stator reference frame. The transformation of voltages is given with (4) and (5). Currents have to be transformed similarly.

$$u_{2X}'^{S} = u_{2X}'^{R}\cdot\cos\gamma + u_{2Y}'^{R}\cdot\sin\gamma \tag{4}$$

$$u_{2Y}'^{S} = -u_{2X}'^{R}\cdot\sin\gamma + u_{2Y}'^{R}\cdot\cos\gamma \tag{5}$$

The relation between the coordinate systems of the rotor and the stator is shown in Fig. 4. The angle γ is given by multiplying the number of pole-pairs with the time-integration of the mechanical angular frequency of the rotor with respect to the stator.

$$\gamma = n_P\cdot\int_0^T \omega_{mech}\cdot dt \tag{6}$$

After transforming the voltages and currents into the stator reference frame the system of differential equations can be solved. Then the solution is transformed back into the original coordinate system.

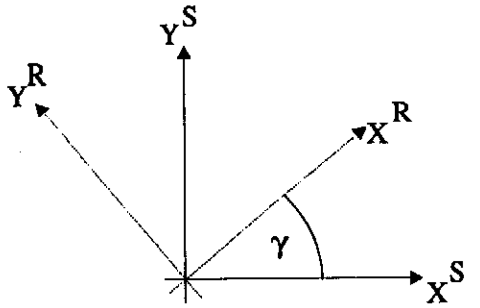


Fig.4: Rotor and stator coordinates and their relation

The voltage equations for stator and rotor result in xy0-coordinates (7) – (10).

$$u_{1X}^{S} = i_{1X}^{S}\cdot R_1 + \frac{d\psi_{1X}^{S}}{dt} \tag{7}$$

$$u_{1Y}^{S} = i_{1Y}^{S}\cdot R_1 + \frac{d\psi_{1Y}^{S}}{dt} \tag{8}$$

$$u_{2X}'^{S} = i_{2X}'^{S}\cdot R_2' + \frac{d\psi_{2X}'^{S}}{dt} - \omega_{mech}\cdot\psi_{2Y}'^{S} \tag{9}$$

$$u_{2Y}'^{S} = i_{2Y}'^{S}\cdot R_2' + \frac{d\psi_{2Y}'^{S}}{dt} + \omega_{mech}\cdot\psi_{2X}'^{S} \tag{10}$$

The voltage equations for the zero sequence machine are given with (11) and (12).

$$u_{01} = i_{01}\cdot R_{01} + \frac{d\psi_{01}}{dt} \tag{11}$$

$$u_{02}' = i_{02}'\cdot R_{02}' + \frac{d\psi_{02}'}{dt} \tag{12}$$

The stator and rotor flux linkages are also transformed into the xy0-system.

$$\psi_{1X}^{S} = i_{1X}^{S}\cdot(L_{\sigma1} + L_h) + i_{2X}'^{S}\cdot L_h \tag{13}$$

$$\psi_{1Y}^{S} = i_{1Y}^{S}\cdot(L_{\sigma1} + L_h) + i_{2Y}'^{S}\cdot L_h \tag{14}$$

$$\psi_{2X}'^{S} = i_{2X}'^{S}\cdot(L_{\sigma2}' + L_h) + i_{1X}^{S}\cdot L_h \tag{15}$$

$$\psi_{2Y}'^{S} = i_{2Y}'^{S}\cdot(L_{\sigma2}' + L_h) + i_{1Y}^{S}\cdot L_h \tag{16}$$

This machine described by space vectors does not contain the zero sequence components of the flux linkages in the machine. The so called zero sequence machine has three times the poles of the fundamental. As can be shown, the zero sequence machine acts like a single phase transformer where the mutually inductance changes with the rotation of the rotor. Now the equation for the flux linkage of the zero sequence become:

$$\psi_{01} = i_{01}\cdot(L_{\sigma01} + L_{h0}) + i_{02}'\cdot L_{h0}\cdot\cos(3\cdot\gamma) \tag{17}$$

$$\psi_{02}' = i_{02}'\cdot(L_{\sigma02}' + L_{h0}) + i_{01}\cdot L_{h0}\cdot\cos(3\cdot\gamma) \tag{18}$$

The developed electromagnetic torque can be derived from the change of the energy stored in the mutually coupled inductive circuits.

$$t_i = \tfrac{3}{2}\cdot n_P\cdot\left[i_{2X}\cdot\psi_{2Y} - i_{2Y}\cdot\psi_{2X}\right] \tag{19}$$

With the electromagnetic torque and the load-torque the equation of rotating motion can be written as:

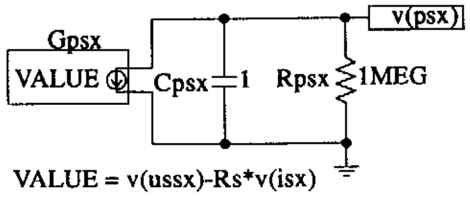
$$t_i - t_{load} = \Theta \cdot \frac{d\omega_{mech}}{dt} \tag{20}$$

IV. SIMULATION MODELS

A. *Doubly Fed Synchronous Machine*

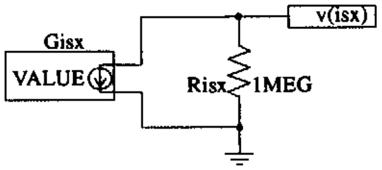
The Spice simulator allows to achieve a very easy implementation of the differential equations into a Spice model. The algorithm to solve the system of equations is quite similar to the solution process done by an analog computer. Each differential equation can be solved with an easy to build integrator which consists of a controlled current source feeding a capacitor. To achieve fast converging of the Spice solution algorithm a high ohmic resistor is in parallel to the capacitor. Fig. 5 shows the easy to build integrator representing the differential equation (7).
A system of linear equations is solved with controlled current sources feeding high ohmic resistors. In Fig. 6 one can see the implementation of (13).

The complete model of the Doubly Fed Synchronous Machine is implemented in a so called subcircuit that can be placed in any electric circuit diagram. The graphical design representing the subcircuit of the DFSM is shown in Fig. 7.



VALUE = v(ussx)-Rs*v(isx)

Fig. 5: Integrator function solved with a Spice model



VALUE = Lss*v(isx)+Lh3*(v(isx)+v(irx))-v(psx)

Fig. 6: Linear equation solved with a Spice model

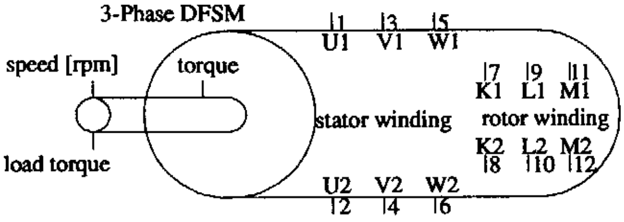


Fig. 7: Graphical design of the DFSM-model

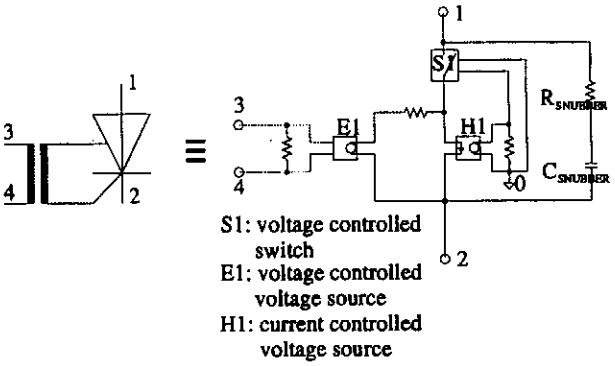


Fig. 8: Simulation model of a thyristor

B. *Thyristor Model*

To minimise the CPU-time for calculation the model for the thyristor is as simple as possible. As it can be seen in Fig. 8 the model for the thyristor with the impulse-transformer is built up with voltage- and current-controlled sources and a voltage controlled switch. The model also comprises the snubber circuit.

C. *Simulation Circuit*

A typical application of the DFSM connected the grid is being simulated. The models of the DFSM and the cyclo-converter are put together to the required configuration. To simulate the transient phenomena a short circuiter is connected to the terminals of the DFSM. The short-circuiter is realised with time controlled switches.

The complete model of the cyclo-converter consists of anti-parallel thyristors and support devices (firing circuits, controller,..). The models for firing circuits and current control algorithms as well as control algorithms for the cyclo-converter i.e. thyristor-bank selection are build with so called analog behavioural models and will not be addressed in this paper.

The circuit simulated is shown in Fig. 9.

V. SIMULATION RESULTS

Some characteristic failures were investigated. All cases simulated start from the same steady state operation (no load point; slip = 0,1)

A. *Three phase sudden-short circuit on the terminals of the stator and rotor*

This case will appear, if there is a three phase sudden short-circuit on the terminals of the stator winding and due to this fault the overvoltage-protection device in the rotor circuit immediately short-circuits the terminals of the rotor winding. After short-circuiting all terminals the flux linkage in the machine decreases. Hence the induced voltages in the stator windings as well as in the

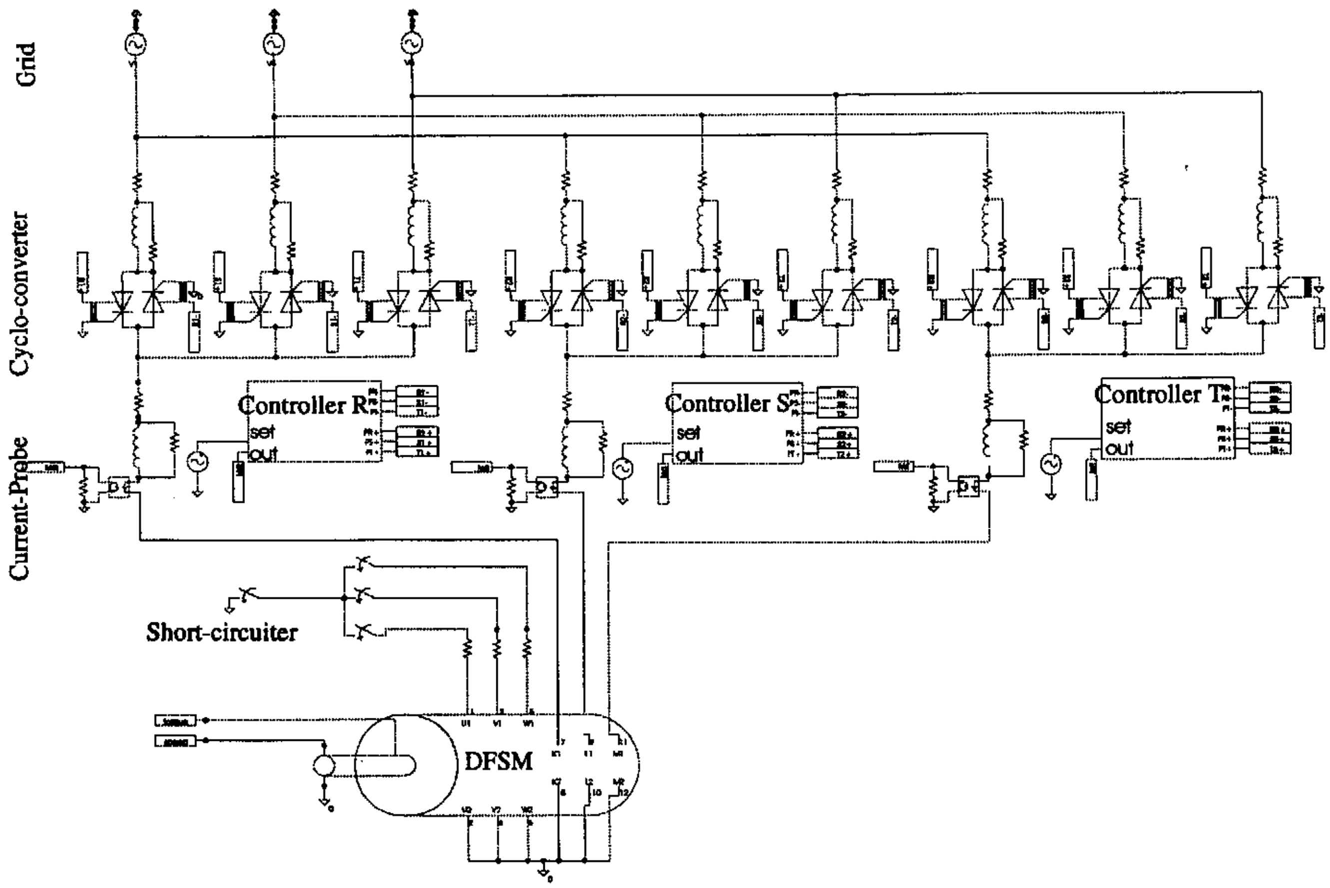


Fig. 9: Spice circuit for simulation

rotor winding yield into current peaks and high transient torque. Fig. 10 gives the transient currents and torque due to such faults.

The transient currents reach about eight times the rated current of the machine under test. The transient torque is about six times the rated torque.

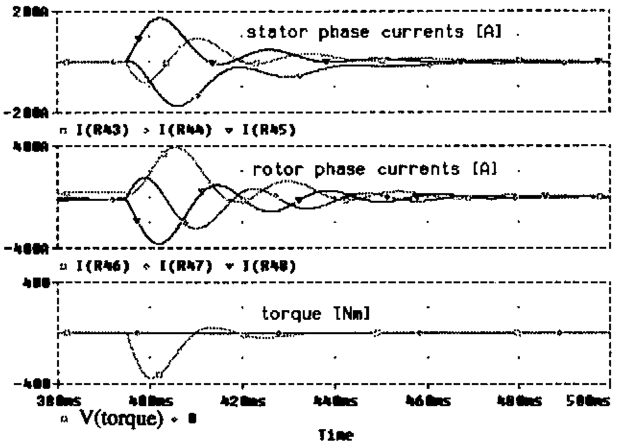


Fig.10: Calculated transient currents and torque due to a 3 phase sudden short-circuit on stator and rotor terminals

B. *Three phase sudden short-circuit on the terminals of the stator while the rotor is fed with the cyclo-converter*

This fault is simulated to show the transient overvoltages on the terminals of the DFSM which can occur during faults. The transient overvoltages origin in the limitation in direction of current and the discontinuity of current due to the 'circulating-current-free' cyclo-converter. Fig. 11 shows the discontinuity of rotor-current and hence the transient overvoltages on the terminals of the rotor winding. The ripple current in the three phases of the rotor winding causes a zero sequence current in the rotor.

Due to the inductance of the transformer used in the cyclo-converter the transient currents are reduced to about three times the rated current.

C. *Single phase sudden short-circuit of one stator phase while the rotor is fed with the cyclo-converter*

The single phase short-circuit is a kind of unbalanced load, which the generator has to deal with. The zero sequence current in the stator winding causes a high frequency zero sequence current in the rotor winding. The limitation in current direction in the rotor phases produces transient overvoltages.

The simulation results are given in Fig. 12.

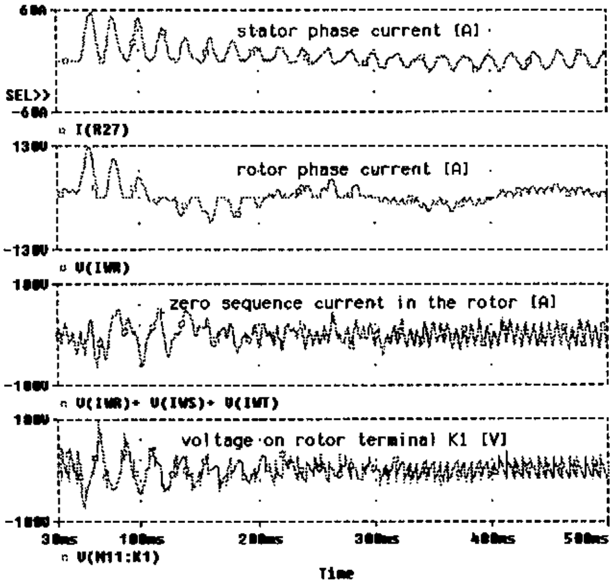


Fig. 11: Simulation results of transient voltages and currents due to a 3 phase sudden short circuit on the terminals of the stator

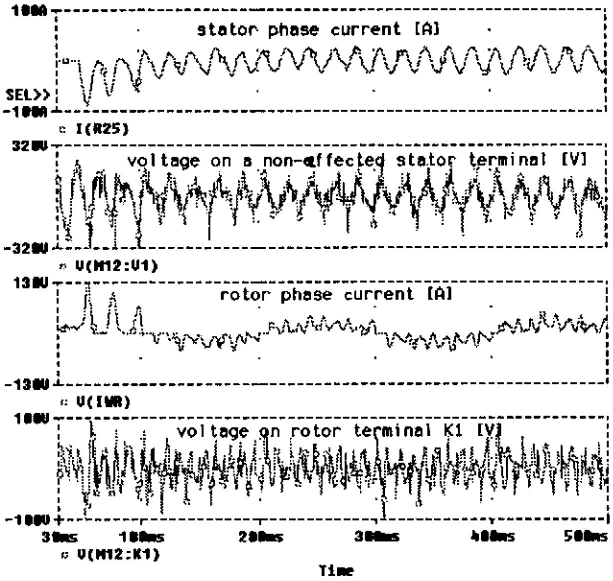


Fig. 12 Simulation results of transient voltages and currents due to a single phase sudden short-circuit on a stator terminal

In high voltage applications where the insulation level of the winding is near to rated voltage attention has to be paid to the transient overvoltages to avoid damage of the insulation. This becomes very important to the rotor winding of the Doubly Fed Synchronous Machine, where the insulation level is set to the slip fraction of the rotor voltage, if by accident the rotor is magnetised at standstill.

To simulate the transient behaviour of the Doubly Fed Synchronous Machine combined with a cyclo-converter over one second of real time it takes about two hours for a Pentium 166 processor with 64 MB RAM. The amount of data which result from the simulation is very large because of the small iteration steps necessary for the switch operations. If the simulation model of the DFSM is fed with plain ac voltage or current sources the CPU time for simulating the same period of time reduces to about five seconds. Hence the amount of data decreases too.

VI. EXPERIMENTAL VERIFICATION

To verify the results of the simulation an experimental test set up was built.

The machine for the test set up is a 15,9 kVA three phase Doubly Fed Synchronous Machine with four slip rings (three phases and star point). The parameters of the machine are summarised in the following table:

number of pole pairs n_P:	2
supply voltage:	3 ~ 380 V 50Hz
speed range:	1350 – 1650 U/min (converter frequency: 0 - ±5Hz)
stator/rotor turns ratio (fundamental):	2,17
stator resistance R_1:	0,272 Ω
rotor resistance R_2:	0,08 Ω
stator leakage inductance $L_{1\sigma}$:	3,42 mH
rotor leakage inductance $L_{2\sigma}$:	0,73 mH
magnetising inductance L_h:	66,8 mH
zero sequence stator/rotor turns ratio:	1,08
zero sequence magnetising inductance L_{h0}:	2,09 mH

The cyclo-converter is of a symmetrical three-pulse-mid-point-circuit type which is driven in the 'circulating-current-free mode'. For this purpose a controller was developed to make sure that during operation only one thyristor-bank (positive or negative current direction) per phase is fired while the other thyristor-bank is blocked.

The short circuiter was built up with anti-parallel thyristors making possible exact timing of the sudden short circuits. The laboratory test set up allowed to measure repetitive sudden short-circuits with and without ground faults.

The verification of the calculated transient phenomena was done with various experiments. The following Figures relate to the 'Three phase sudden short-circuit on the terminals of the stator while the rotor is fed with the cyclo-converter'. A typical rotor current occurring during this fault is shown in Fig. 13. The first peak current reaches about three times the rated current then the natural oscillation of the rotor current is hampered by the thyristors, which causes transient overvoltages on the terminals of the rotor.

Fig. 14 shows the measured terminal voltage of the rotor during a three phase sudden short circuit on the stator terminals. The peak voltage on the terminals is about 2,5 times the rated voltage of the cyclo-converter used in the experimental set up.

Several short circuits have been investigated and the measured curves of current and voltage are nearly congruent with the computed ones.

VII. CONCLUSION

The Doubly Fed Synchronous Machine can be used as a variable speed generator in water power plants. Therefore the rotor winding has to be fed via slip rings with a cyclo-converter. The design of the converter requires knowledge

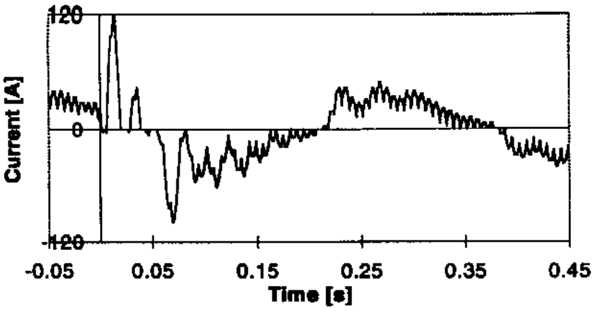


Fig. 13: Measured current in a rotor winding due to a three phase sudden short-circuit on the stator terminals

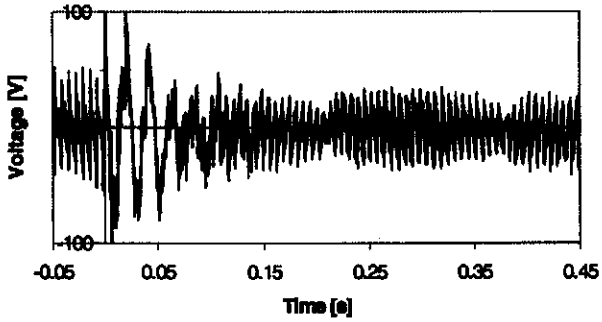


Fig. 14: Measured voltage on a rotor terminal due to a three phase sudden short-circuit on the stator terminals.

of the overvoltages and peak currents which occur due to transient failures.

A mathematical model of the DFSM is derived. This model can be easily implemented into a Spice-simulation algorithm and then placed as a component in a circuit editor. Additionally a simulation model of the cyclo-converter was developed. By means of these models it is possible to calculate the reaction of both (the DFSM and the cyclo-converter) on each other. Various transient load cases (three phase-, single phase sudden short circuits,...) were calculated and measured to verify the accuracy of the developed models. The Spice simulator proofed to be a useful program to simulate transient load cases of electrical machines combined with converters.

VIII. ACKNOWLEDGEMENTS

The authors are grateful to ELIN ENERGIEVERSORGUNG GmbH for technical support.

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APPENDIX :

List of Symbols:

u	voltage	i	current
t_i	torque	ψ	flux linkage
L_h	main inductance	L_σ	leakage inductance
Θ	moment of inertia	n_P	number of pole pairs
γ	angle between stator and rotor coordinate		
ω_{mech}	mechanical angular frequency of the rotor		
index 1/2	stator / rotor quantities		
index 0	zero sequence quantities		
superscript S/R	quantities with respect to the stator / rotor reference frame		