

Advantages for the Electric Grid using a Doubly Fed Asynchronous Machine - Numerical simulations

Daniel Schafer
R&D Manager
ABB Power Generation Ltd.
Dept. KWHT
5242 Birr/Switzerland

Prof. Jean-Jacques Simond
Electrical Machines Department
Swiss Federal Institute of Technology
DE-LEME
1015 Lausanne/Switzerland

Introduction

Since a long time, it is known that hydraulic machines can work with an increased efficiency at partial load when the speed can be adapted to this partial load. In a standard configuration when the hydraulic machine is coupled to a synchronous machine which is directly connected to the electric grid this speed variation is not possible at all.

The use of a static frequency converter which is inserted between the grid and the stator is a well known solution to achieve an adjustable speed machine. Adjustable speed drive systems have already been applied in the past to hydro power plants. Up to now they have mainly been used for start-up purposes of pumps or pump-turbines. The used converters were therefore rather small in respect of converter power output (< 30 MVA).

When a static frequency converter is used in the stator, this converter has to be sized for the full electrical machine power. The solution is therefore not applicable in an economical way to very big unit outputs (>250 MVA).

In the last few years, considerable work has been done in order to develop a system which does not use a big converter and which presents considerable advantages also on the grid's side. A pilot power plant according to the new ABB-technology has been built and successfully commissioned in Spain.

This paper contains a description of the doubly fed asynchronous machine with a cyclo-converter in the rotor circuit. This configuration allows adjustable speed operation within a certain speed range. The size of the converter needed is much smaller than for a comparable solution with a synchronous machine. The maximum unit power output which may be realized with this system is limited to 450 MVA.

The advantage of an increased system efficiency at partial load is well known and may easily be calculated; it will therefore only be presented briefly. The main part of the paper is dedicated to the behaviour of this adjustable speed generator system in respect of grid stability and grid transients.

In a first step the general principles of this adjustable speed solution (called "VARSPPEED" at ABB) will be shown. The use of the VARSPPEED solution has several advantages which are not only limited to an increased overall efficiency at partial load operation but also:

- Possibility of active power control in pumping mode.
- Possibility of reactive power control at the interconnection point to the grid.
- Possibility of instantaneous power injection into the grid by using the energy stored in the rotating mass.
- Reduced abrasion of turbine runners at very silty water conditions.

The features mentioned above will be illustrated by an illustrating example.

In a second step, the advantages for the electric power grid will be presented by means of a simulation software. The simulations will show the currents, voltages, torques and speed as well as relevant harmonics of a VARSPPEED installation in the grid during transient and steady state operation.

Different kinds of short circuits as well as different load variations in the grid will be applied to the system and its advantageous behaviour will be presented.

The contents of harmonics injected into the grid during steady state operation may also be determined. One load point in generator mode will be shown and a comparison between a 6-pulse cycloconverter and a 12-pulse cycloconverter will be made

1. Variable speed for large motor-generators

As briefly explained, the Varspeed concept of electrical machines is the optimum solution in the case of large variation in the turbine and pumping heads, enables load control in pumping mode, results in the best overall

efficiency and improves the stability in the power system. The reason for these advantages comes from the ability to run the group at the optimum speed (in a given speed range) of the hydraulic machine for all hydraulic conditions. In the case of silt, using Varspeed strongly reduces the abrasion of the turbine runner.

ABB as a supplier for hydro generators has two different systems available:

- The system with synchronous machine and static frequency converter (SFC) of the LCI (Load Commutated Inverter)-type.[5]
- The system with a doubly fed wound rotor asynchronous machine fed on the rotor side either by a cycloconverter (DASM-solution) or by a GTO-converter. The last solution offers best dynamics and a big speed range.

In the following we will consider only the DASM-solution which is perfectly suitable for the application we are looking at. A single line diagram of this configuration is given below:

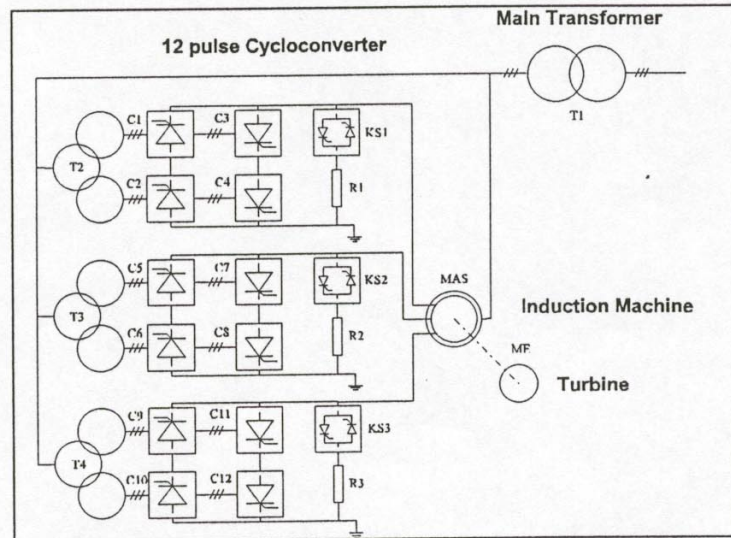


Figure 1. Single line diagram of a VARSPEED installation

This adjustable speed system, also known as sub and supersynchronous cascade uses a doubly fed slip ring rotor asynchronous machine (DASM). In this application the stator of the DASM is directly connected to the network, while the rotor is fed by a three-phase, sinusoidal current of slip frequency, which enables to run the unit in a given speed range around the synchronous speed.

For large Varspeed units, the asynchronous machine is the critical component and therefore we will mainly focus on it.

1.1 Design of a Doubly Fed Asynchronous Machine for Varspeed

The structural design of the wound rotor asynchronous machines compared to a conventional salient pole synchronous machine is different only on the rotor side. All the static components such as stator core, stator frame, stator winding, bearings, bearing bracket etc. are for both of the same design concept. Due to the small air gap of asynchronous machines, ABB's structural design concept with oblique elements is of great advantage especially with respect to ensuring roundness and concentricity of stator and rotor.

The rotor is equipped with a conventional 3-phase winding which is fed via 3 slip-rings by a 3-phase current system at the actual slip frequency. The design has to fulfill the following requirements.

- The rotor rim with the 3-phase winding must be designed to meet minimum iron losses considering the slip frequency, and must be in accordance with the specified limits such as temperature rise and mechanical stress.
- The rim must be equipped with radial air ducts for the cooling air.
- The overhang of the rotor winding must be supported properly for all mechanical and thermal conditions.

For asynchronous machines, up to a bore diameter of about 3 m the rotor winding overhang is normally supported by a prestressed bandage of stainless steel wire. The fitting of this bandage is very difficult due to the required thermo-mechanical process and in case of a break-down of bars in the rotor winding the whole bandage must be removed. Furthermore the cooling of the overhang is strongly reduced.

For bigger machines, a new end winding support concept based on retaining bolts is applied.

To minimize the iron losses, the rotor rim consists of high strength steel sheets or electric sheets with a thickness of less than 1 mm, which are stacked to form the rotor rim. The laminated ring has radial air ducts and is fixed onto the hub by means of special wedges.

The wedges are arranged around the circumference in such a way that concentric radial movements of the rotor rim, resulting from the centrifugal force, are possible. On the outer periphery of the rim there are slots into which a 3-phase winding is placed, which in turn is secured against forces acting in the radial direction by non magnetic slot wedges.

Press fingers which are secured against the centrifugal force by means of bolts fastened to the end plates of the rim provide an even axial pressure distribution exerted on the rotor rim and the teeth between the slots. The pressure on the press fingers is applied by pressing rings which act directly on the press fingers. These rings are positioned on each side of the rotor rim and are locked by prestressed axial bolts.

For electrical reasons (circulating currents) these axial bolts must be placed at the inner edge of the rim and are arranged to allow radial air circulation. The following figure shows the supporting and pressing system for the rotor end winding.

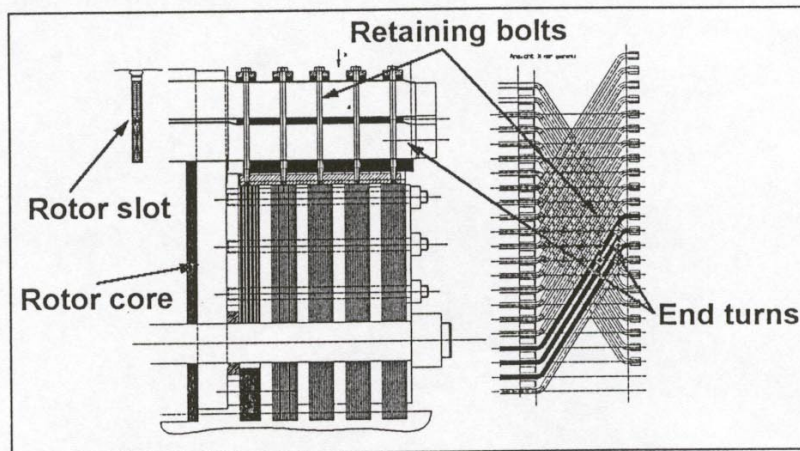


Figure 2. Supporting and pressing system of the end winding

The supporting ring is assembled by stacking 2 to 6 mm thick sheet steel segments to form single rings which are pressed together using prestressed shear-pressing bolts, resulting in a homogeneous ring. The single rings are separated from each other by the use of specially designed spacers. The cooling air flows between the individual rings to the winding overhang. Around the outer circumference, threaded templates are slid into axial T-shaped slots.

Radial bolts are passed through the spaces between the upper and lower winding bars and screwed into the threaded templates. Insulating pads under the bolt heads guarantee an even pressure distribution in the bars in the region of the winding overhang.

By advanced calculation tools, the rotor rim and the supporting and pressing ring are designed such that they expand equally in the radial direction.

This new design concept to support the overhang of the 3-phase rotor winding is very simple concerning mounting and dismantling of the rotor winding or of individual bars.

1.2 Converter Cascade for a Doubly Fed Asynchronous Machine

The machine which is coupled to the turbine is connected to the 50 Hz network on the stator side and is fed via a cycloconverter on the rotor side. Speed, active and reactive power are controlled via the corresponding control equipment of the three-phase cycloconverter, which supplies the rotor three-phase winding current of the machine via slip rings. The cycloconverter provides a three-phase, almost sinusoidal current source whose amplitude and phase position can be freely set. The network-commutated cycloconverter consists of two antiparallel three-phase current bridges per phase, which are operated free of circulating current and are supplied from the 50 Hz network using converter transformers. The converter is operated with controlled phases. The firing pulses are controlled such that an output voltage results which is sinusoidal and of slip frequency in its fundamental mode, and its amplitude and phase position may be set as desired. The resulting magnetic flux due to the impressed rotor currents, rotates with the slip frequency referred to the rotor and with

the network frequency referred to the stator; whereby it generates the corresponding counter magnetic flux within the stator.

The amplitude and phase position of the stator current and thereby the active and reactive power consumption of the machine is determined by control of the rotor current; and these parameters can be set in all four quadrants for any value desired.

At supersynchronous speed the cycloconverter supplies energy to the rotor; at subsynchronous speed energy is withdrawn from the rotor and returned to the network.

For the control of the rotor current, a three-phase sinusoidal signal is generated with the aid of a rotor position indicator mounted on the shaft. The frequency of this signal corresponds to the speed and its phase position corresponds to the rotor position of the asynchronous machine. From this signal, together with the corresponding three-phase sinusoidal network signal, a new three-phase sinusoidal signal is generated by the slip frequency calculator. The amplitude and the phase position of this signal may be varied and in this manner the set-point for the rotor current can be preset.

During both subsynchronous and supersynchronous operation, independent of the speed, the active and reactive power of the stator side of the machine is controlled via the resulting rotor current, the phase position and amplitude of which may be varied.

In addition to the control of the active and reactive power, cascade control systems allow the control of other parameters, depending on the particular application, as, e.g.,

- power / frequency control
- network voltage control
- speed control

The doubly-fed asynchronous machine with a cycloconverter has been in use for many years for the purpose of power control in converter systems which provide the 16.7 Hz traction current network from the 50 Hz network. The ABB group has gained many years of operational experience in this area .

In total, six such converter systems have been newly installed and converters and control equipment are being supplied for other plants. The two largest of these facilities are Seebach in Switzerland and the converter power plant at the Neckar II Community Power Station, at Neckarwestheim in Germany. The Seebach plant which has two 80 MVA machine units has been in successful operation for more than 15 years; the Neckarwestheim plant which has two machine units of 82.5 MVA has been operating successfully for 8 years.[1]

In these cases mentioned, a 16.7 Hz single-phase synchronous generator running on the traction current network, is driven by a doubly fed asynchronous machine which is running on the 50 Hz network. The frequency of the traction current network varies up to $\pm 5\%$ of the nominal frequency and therefore it is necessary that the synchronous machine can be operated at variable speeds, according to the changes in frequency. The transmission of power in both directions takes place via this elastic frequency coupling between the 50 Hz grid and the 16.7 Hz traction current network.

At the *Compuerto* hydroelectric power plant in Spain, ABB has converted one of the two 10 MW synchronous machine units into a machine unit for variable speeds.[2]

For this purpose the salient pole rotor has been replaced by a new rotor with a three-phase winding. This rotor is supplied with an alternating current of slip frequency via a sub and supersynchronous static converter cascade system. With this pilot plant, it is possible to gain experience concerning the operational qualities and the interaction of the asynchronous machine control with the turbine control and with the superior control system, and to use this experience profitably for future applicable cases.

1.3 Reasons to use a Doubly Fed Asynchronous Machine for Hydro Power Generation

- The speed can be altered within a sufficiently large range of normally $\pm 10\%$ of the synchronous speed. This speed variation corresponds to a power variation of $\pm 30\%$. This feature allows the utility to pump with variable load or to generate with partial load but optimum efficiency. Figure 3 shows a typical efficiency chart for a turbine.
- The converter has to be sized according to the slip power. The greater the required speed adjustment range is in relation to the synchronous speed, the greater the slip power is and therefore the required converter size will increase. The cycloconverter has to be sized for the considered power and speed range. The power limit in the rotor circuit is given by the thermal stresses on the rotor. The mechanical load acting on the three-phase rotor winding must be considered as well.
- The active and reactive power of the network can be controlled as desired and independent of each other, according to the demands of the network. Even if a VARSPEED installation will not primarily be built to deliver reactive power to the grid, this feature may be interesting.

- Due to the fact that the speed may be altered in a certain speed range, the machine may also be used for instantaneous power injection to the grid. This feature will allow to reduce the spinning reserve in an existing grid. Figure 3 shows the basic principle. Assuming an inertia of 1500 tm² and a speed reduction from n_s+10% to n_s-10% a power of 12 MW may be injected into the grid during 30 seconds.

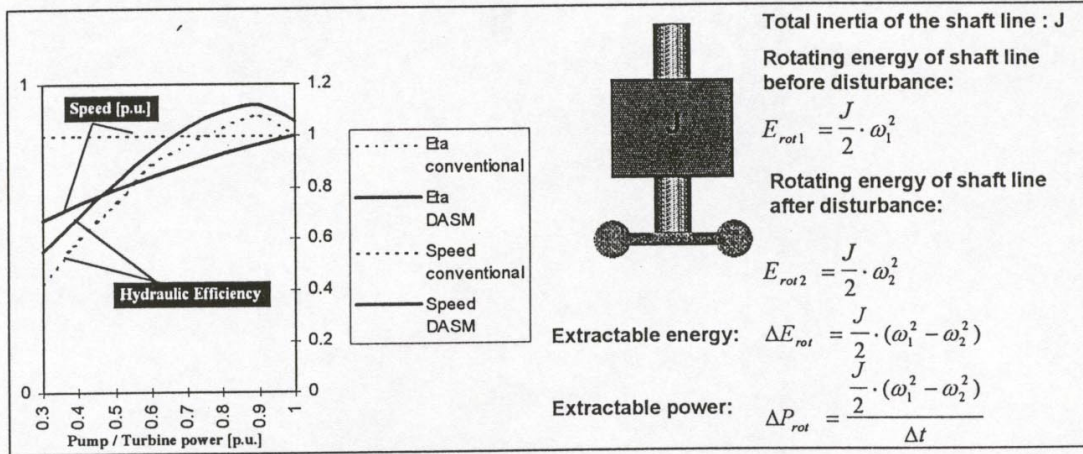


Figure 3. Efficiency and speed of a pump-turbine at partial load and extractable energy at speed variation

2. Simulations of a VARSPEED installation with a Doubly Fed Asynchronous Machine and a 12-pulse Cycloconverter

For the simulations of the following examples the following machine and grid parameters have been taken into account:

Rated apparent power:	MVA	230
Synchronous speed:	rpm	333.33
Speed range:	rpm	300 .. 366
Rated machine voltage:	kV	15.75
Grid voltage:	kV	245
Grid short circuit power:	MVA	1120
Frequency:	Hz	50
Shaft line inertia:	tm ²	1410

The simulations have been carried out with the simulation program SIMSEN developed at the Swiss Federal Institute of Technology in Lausanne. A brief description of this program is given in the annex of this paper. The program is in use at ABB Power Generation for more than 2 years now.

2.1 Steady state behaviour

For the steady state evaluations, 4 different operating points in the operating range of the asynchronous machine have to be considered. These points are defined by the maximum apparent stator power and the maximum converter power output. The following figure shows these 4 points considering as well the power output/input of the pump-turbine corresponding to its speed.

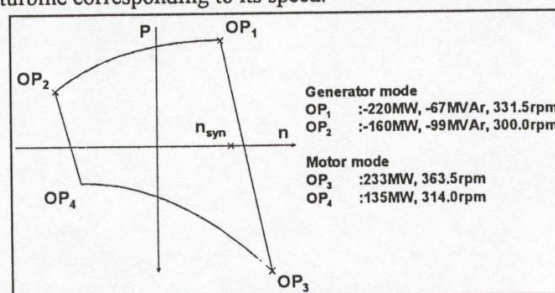


Figure 4. Limit operating points of the simulated VARSPEED installation

The following figure shows the simulation results for one of the specified steady state operating points. In the diagram we can see stator voltage, stator active and reactive power, stator currents and rotor currents. Due to the fact, that the operating point has been selected close to the synchronous speed the rotor currents are at very low frequency:

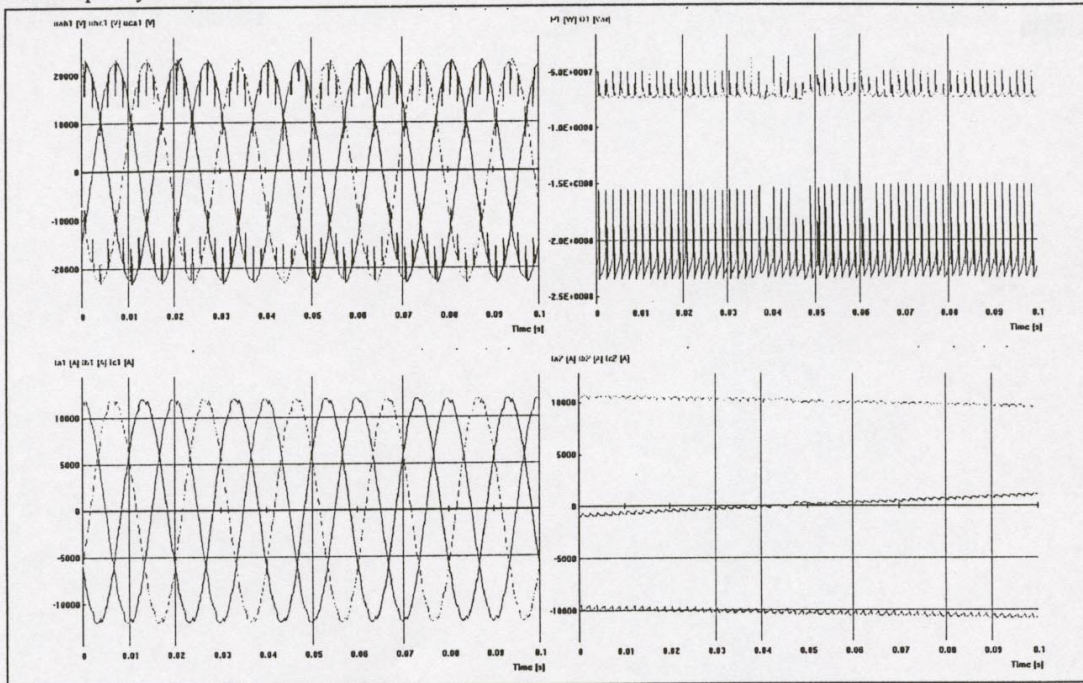


Figure 5: Simulation results of operating point 1 corresponding to Generator mode, 331.5 rpm, -220 MW, -67 MVar

On the following figure we can see the voltages on the grid side and a Fourier analysis of the currents and voltages on the grid side showing that due to the 12-pulse arrangement of the cycloconverter the amount of harmonics on the grid side is very low even without using any filter. The y-axis of the Fourier Analysis plot has been selected in order to show the low amplitudes of the 11th and the 13th harmonic.

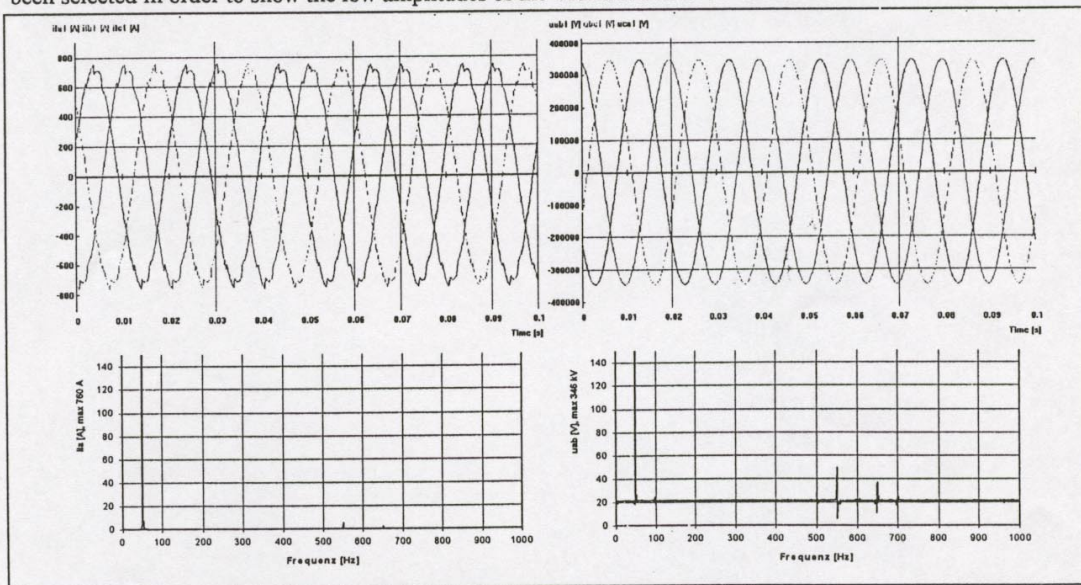


Figure 6: Analysis of voltages and currents on transformer HV-side for operating point 1 according to figure 4

A comparison between the simulated 12-pulse converter and the more simple 6-pulse converter shows that in both cases the 11th and 13th current harmonic is roughly 0.5 % of the fundamental amplitude. The 5th and 7th current harmonic are roughly 4% of the fundamental amplitude for the 6-pulse converter whereas the 12-pulse converter doesn't produce any 5th or 7th harmonic on the grid side.

2.2 Simulations of transient behaviour

In the following paragraph, the transient behaviour of the VARSPEED installation is shown. The technical parameters are the same as for the machine simulated in steady state condition in chapter 2.1. Before the disturbance the machine is in steady state condition and then the following disturbances are applied:

- 1.) 50 % voltage drop on the grid side
- 2.) Instantaneous, permanent short circuit on the grid side
- 3.) Power injection into the grid by slowing down the unit to a new steady state speed.

2.2.1 50 % Voltage drop on the grid side

The grid voltage is reduced to 50% of its rated value during 100 ms on all 3 phases. After this voltage drop the voltage rises again to its rated value. The plot of the grid voltage is represented in the following figure.

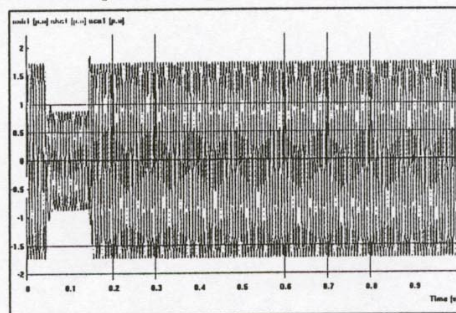


Figure 7: Voltages on transformer HV side during disturbance and voltage recovery after 100 ms

The simulation results show the stator and rotor currents, the electromagnetic torque and the speed of the asynchronous machine:

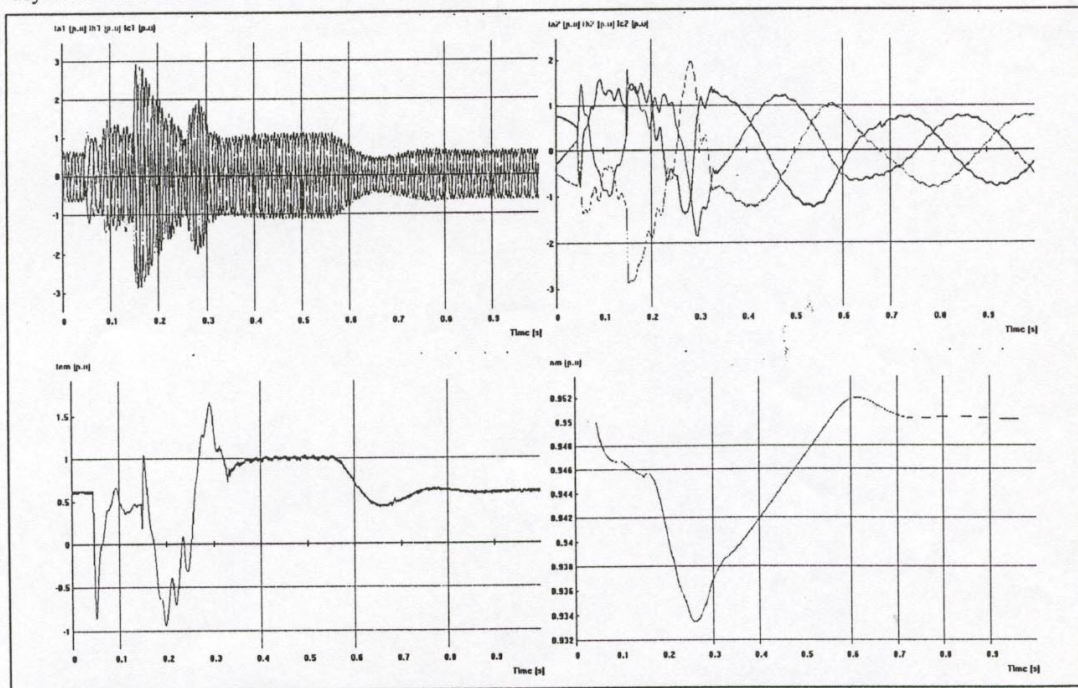


Figure 8: Stator currents, Rotor currents, Electromagnetical torque and mechanical speed of the DASM during a 50% voltage drop on grid's side (100 ms)

It may easily be seen that the VARSPEED machine has a stabilizing effect on the grid. After a very short period, the machine is again working at the operating point it had before the disturbance and the grid is not disturbed by an oscillation of the machine as this would be the case with a classical synchronous machine.

For comparison purposes, the following figure shows the behaviour of a classical synchronous machine operating at the same operating point before the disturbance. The inertia of the machine has been selected equally to the one of the doubly fed asynchronous machine simulated above.

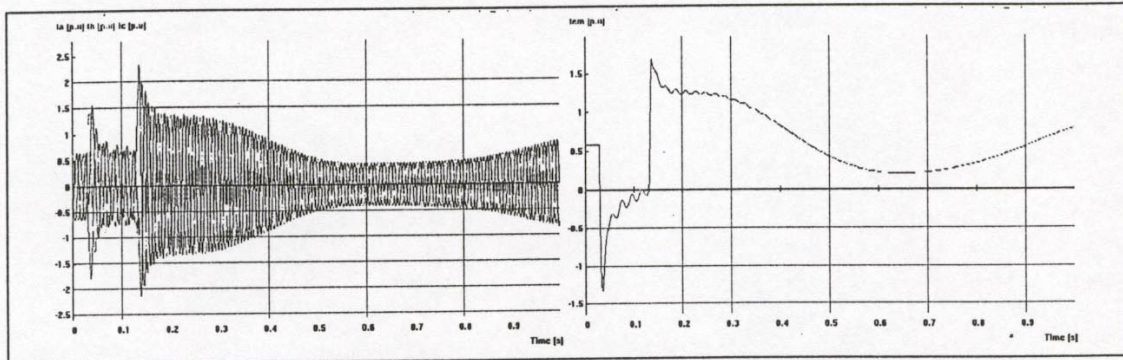


Figure 9: Stator current and electromagnetic torque of a conventional synchronous machine during a 50% voltage drop on grid's side (100 ms)

The simulation results show that the conventional synchronous machine needs more time to stabilize itself again after the disturbance. The oscillation of the pole wheel persists for several seconds. The machine has therefore a poor stabilizing effect on the grid compared to the solution with the doubly fed asynchronous machine.

2.2.2 Instantaneous, permanent short circuit on the grid side

The simulations in this chapter show the behaviour of the Varspeed-machine during an instantaneous, permanent short circuit on the grid side.

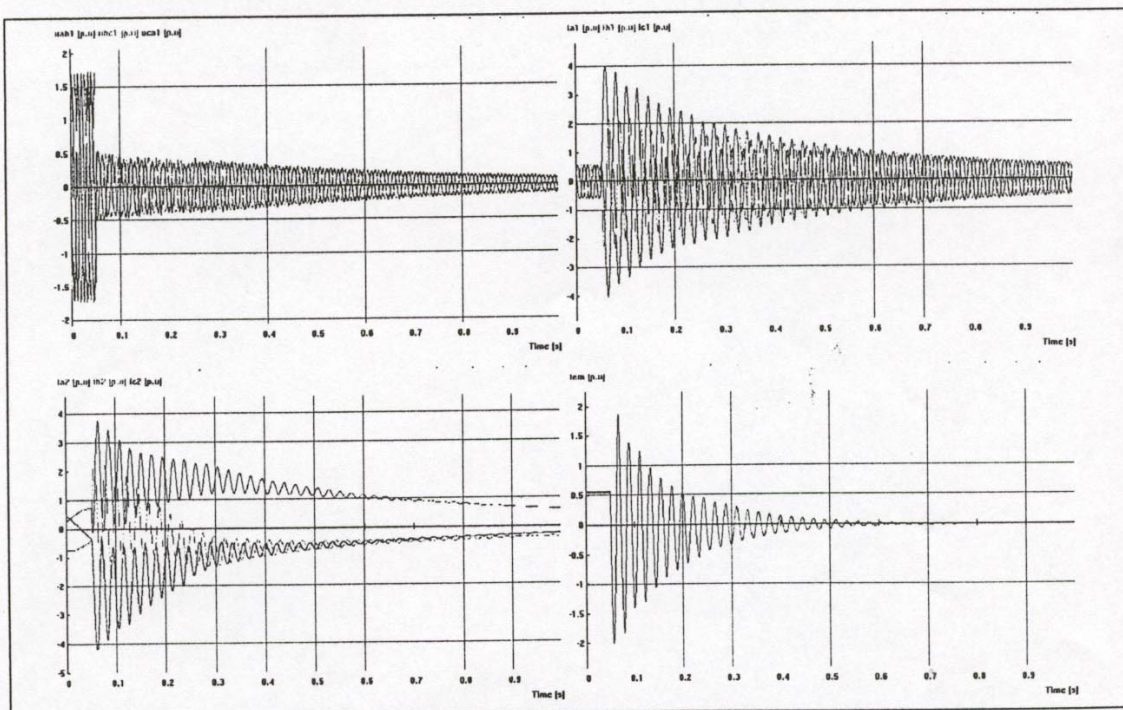


Figure 10: Stator voltage, stator current, rotor currents and electromagnetic torque of the DASM at a permanent short circuit on the transformer HV side

2.2.3 Instantaneous power injection into the grid

Before the instantaneous power injection into the grid, the machine is operating with an active power output of 0.95 p.u. close to synchronous speed. The speed is then decreased to 0.9 p.u and the rotating energy is extracted for instantaneous injection into the grid. After this operation the machine stabilizes at the new steady state speed of 0.9 p.u.. The stator current is limited to 1.1 p.u. during this power injection. Depending on this limit, more or less power may be injected during a selected time.

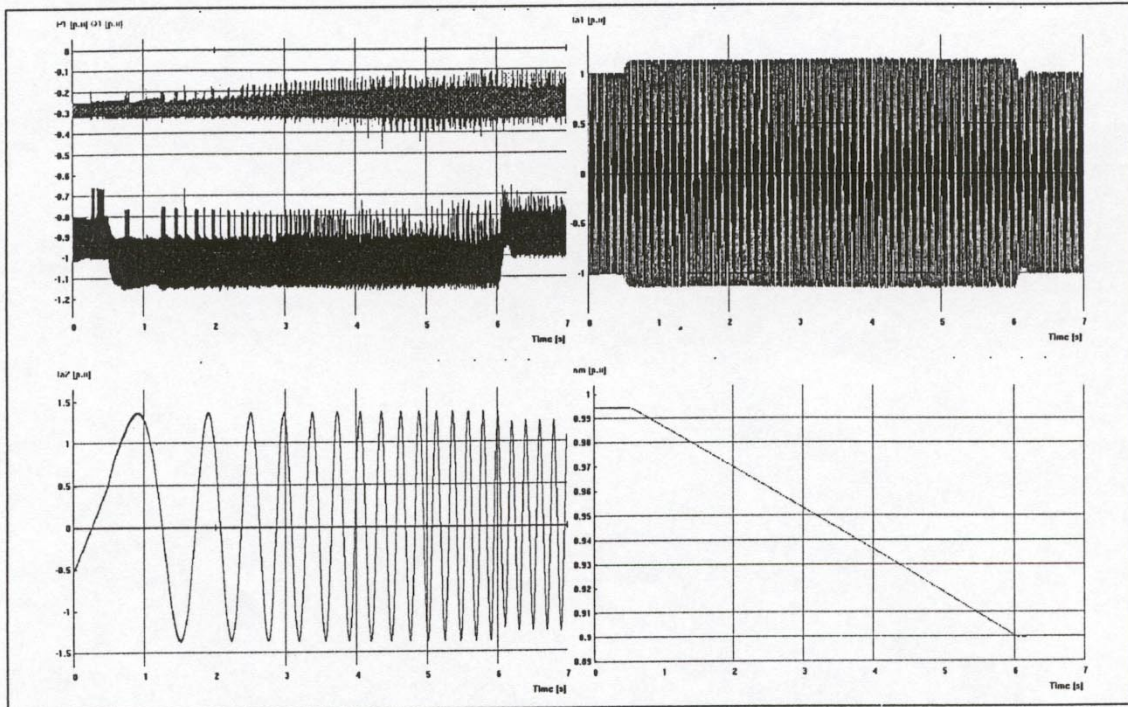


Figure 11: Instantaneous power injection into the grid; Stator active and reactive power, stator and rotor currents (1 phase only) and mechanical speed of the machine

The following features may be seen in the simulation results represented in figure 11:

- A power of 0.1 p.u (23 MW) may be injected into the grid during 6 seconds
- The reactive power production of the VARSPEED system remains unchanged at the transformer LV side.
- The mechanical power produced by the turbine remains unchanged during the whole sequence
- The current in the stator after the power extraction is approximately the same as before due to the fact that the stator has to deliver some more reactive power for the converter at the lower speed.

Due to these features, the machine set has a stabilizing effect on the grid if quick power changes occur and have to be covered. Nearby steam power plants don't need to be driven with accumulated steam and may therefore be used at a better efficiency. The task of grid control may partly be taken over by the Varspeed unit.

3. Conclusions

The general principles of the VARSPEED adjustable speed generator-motor for application in the field of hydro power generation have been presented.

The behaviour of a VARSPEED installation of 230 MVA has been simulated in steady state as well as transient operation. The transient simulations show the advantageous behaviour of the VARSPEED machine for the grid stability.

- After a voltage drop of 50% during 100 ms on all phases in the grid, the machine turns back to its original operating point after a very short period. No oscillations of stator current and electromagnetic torque are created. Due to its inherent control system and the possibility of speed variation the VARSPEED installation has very good self stabilizing properties.

- The behaviour of the machine during a short circuit is comparable to a conventional synchronous machine.
- The machine may be used to inject power instantaneously into the grid by slowing down from one steady state speed to a lower steady state speed. This feature may be used for grid control and has been demonstrated by an example.
- Due to the possibility of speed adjustment, the pump power may easily be adjusted. This feature is also advantageous for grid control.
- In addition to these advantages we would like to mention also the “classical” advantages, i.e. reduced abrasion of turbine runners and improved overall efficiency of the installation.
- It also has been demonstrated that the simulation tool SIMSEN may be easily used for the simulation of adjustable speed drives such as the simulated VARSPEED system in steady state and transient operation mode.

Considering the facts mentioned above it is easy to understand that a VARSPEED machine is an interesting alternative to a conventional synchronous pump-storage machine especially in countries where the grid stability has to be improved. The doubly fed asynchronous machine with its 12-pulse cycloconverter allows to achieve the advantages stated above for a fairly reasonable investment.

Appendix: SIMSEN - a new modular software package for the numerical simulation of power networks and variable speed drives.

The above described variable speed drives have been simulated with a new software package developed at the Federal Institute of Technology in CH-Lausanne. The main features of this simulation tool running on PC are the following.:

SIMSEN is based on a modular structure which enables the numerical simulation of the behaviour in transient or steady-state conditions of power networks or variable speed drives with an arbitrary topology.

The user builds its network directly on the screen by choosing and linking adequately the suitable units shown in table 1 in order to create the desired topology. Each unit represents a specific element in the network, it includes a set of differential equations based on the unit modelling.

An original algorithm generates automatically the main set of differential equations for all the system taking into account all the possible interactions between the different units.

A transient mode of operation may include several successive perturbations.

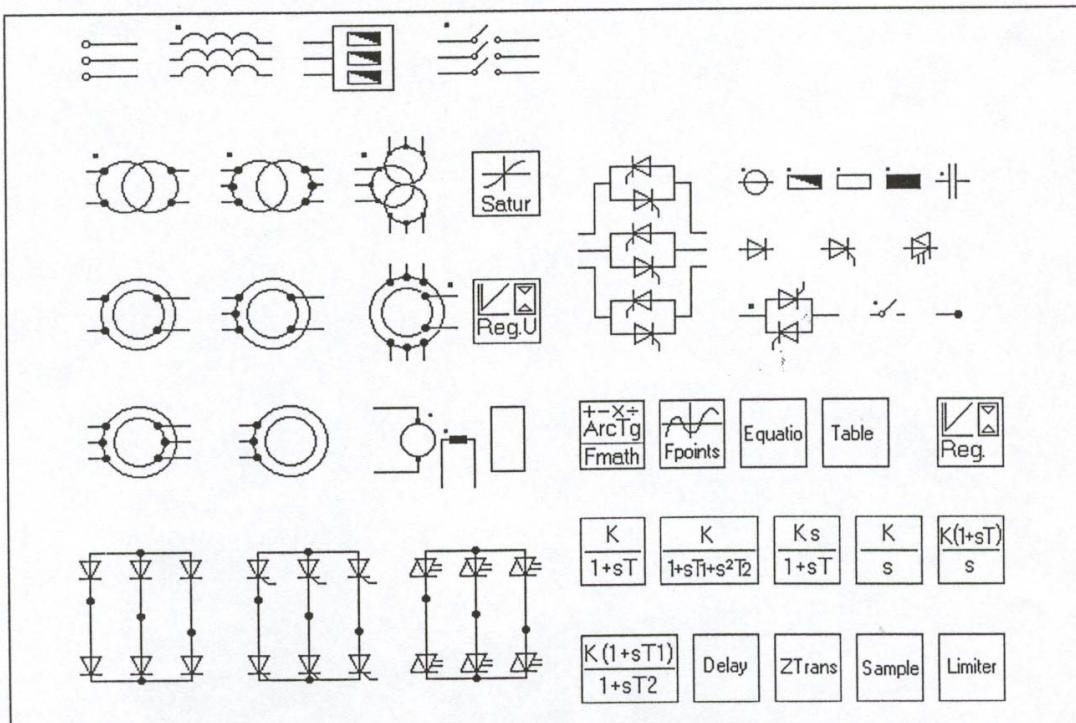


Figure A. Non exhaustive list of SIMSEN units

For applications without units having semi-conductors the initial conditions are obtained with a load-flow program.

The numerical integration works with a variable step size, it is therefore possible to detect exactly all the events in time as the on-off switching of a semi-conductor or of a circuit - breaker.

The open structure of SIMSEN allows newly developed units to be easily implemented. An existing unit can also be modified without difficulties. It is thus possible to widen the applications field furthermore in the future.

The only restriction on the size of the power network to simulate is prescribed by the available memory of the microcomputer. The dynamic administration of the memory makes possible the simulation of large networks (up to 1000 state variables).

References

1. W. L. Bruggisser: The largest rotating converters for interconnecting the railway power supply with the public electricity in Kerzers and Seebach, Switzerland, BBC Review 65 1978 (11) p. 707-715
2. J. M. Merino, A. Lopez: ABB Varspeed generator boosts efficiency and operating flexibility of hydropower plant, ABB Review 3/1996, p. 33-38
3. H. G. Herzog, R. Knäulein, R. Schäfer: Design and simulation of an optimised control unit for doubly fed induction machines, Stockholm, Power Technology 1995
4. L. Terens, R. Schäfer: Variable speed in hydro power generation utilizing static frequency converters, Nashville Tennessee, Waterpower 93
5. R. Bhatia, H. Krattiger, A. Bonanini, D. Schafer, J. Inge, G. Sydnor: Adjustable Speed Drive Using Single 135'000 HP Synchronous Motor, Milwaukee, International Electric Machines and Drives Conference 97
6. T. Yanagisawa, T. Kageyama, K. Okamura, K. Kusunoki, T. Taguchi, M. Abe, H. Kaneko: Transient Analysis of Converter-Fed Adjustable Speed Generator-Motor for the Pumped Storage Power Plant, Electrical Engineering in Japan, Vol 116. No. 2 1996, p. 63-76
7. M. Nose, N. Kondo: The Ohkawachi pumped storage scheme in Japan, Water Power & Dam Construction November 1988, p. 17-21
8. E. Kita, A. Bando, T. Kuwabara: 400 MW Adjustable-Speed Pumped Storage Hydraulic Power Plant, Hitachi Review Vol. 44 (1995), No. 1, p.55-62
9. K. Kudo: Japanese Experience with a converter-fed variable speed pumped storage system, Hydropower & Dams, March 1994
10. J. J. Simond, A. Sapin, B. Kawkabani, D. Schafer, M. Tu Xuan, B. Willy: Optimized Design of Variable Speed Drives based on Numerical Simulation, EPE Trondheim, 1997

Biographical details of the authors

Daniel Schafer graduated in Electrical Engineering from the Swiss Federal Institute of Technology in Lausanne in 1993. In 1993 he joined the Hydro Power Division at ABB Power Generation Switzerland. From 1993 to 1995 he was working as an electrical designer and he was in charge of special investigations in the field of conventional synchronous machines and Varspeed machines. From 1995 to 1996 he was the Manager of the Electrical Design group for hydro generators. Currently he is Manager of the Research and Development group for hydro generators. He also provides sales support for large adjustable speed machines and pump-storage machines.

Jean-Jacques Simond graduated in Electrical Engineering (1969) and Ph.D. in Technical Science and Engineering from the Swiss Federal Institute of Technology in Lausanne in 1976. In 1977 he joined BBC/ABB Switzerland first as research and development engineer in the field of large electrical machines and then as manager of the technical department for Hydro- and Dieselgenerators. Since 1990 he is professor for electrotechnics and electrical machines at the Swiss Federal institute of technology in Lausanne (EPFL). He is mainly working in the field of large machines and drives and in the development of a powerful, modular software-tool SIMSEN for system simulation.