Adjustable speed Asynchronous Machine in Hydro Power Plants and its Advantages for the Electric Grid Stability

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Summary

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 œconomical 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 sucessfully commissioned in Spain.

This paper contains a description of the doubly fed asynchronous machine with a cylco-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 about 450 MVA.

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 "VARSPEED" at ABB) will be shown. The use of the VARSPEED 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.

Some of 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 of a VARSPEED 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.

## 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.[4]
- 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:
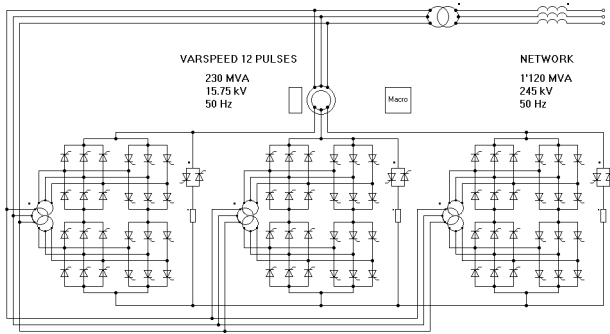
Figure 1. Diagram of a VARSPEED installation

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

- The rotor rim with the 3phase 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 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.

The following figure shows the supporting and pressing system for the rotor end winding.
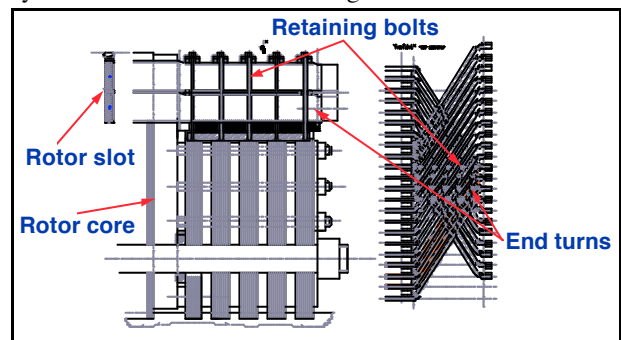
Figure 2. Supporting and pressing system of the end winding

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, at the slip frequency, 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 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.

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 converter systems of this kind have been 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 the cases mentioned above, 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 ± 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 ± 10 % of the synchronous speed. This speed variation corresponds to a power variation of ± 30 %. This feature allows the utility to pump with variable load or to generate with partial load but optimum efficiency.
* 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 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.

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 appendix of this paper. The program is in use at ABB Power Generation for more than 3 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.
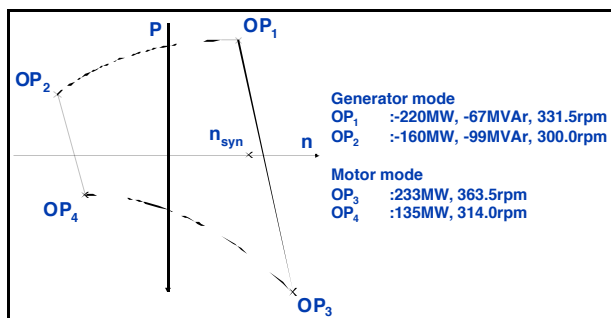
Figure 3. Limit operating points of the simulated VARSPEED installation

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.) 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 simulation results show the stator and rotor currents, the electromagnetical torque and the speed of the asynchronous machine:
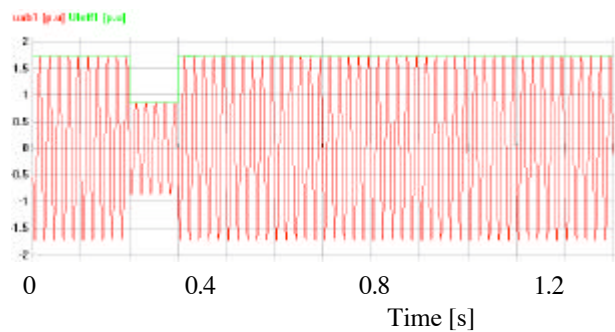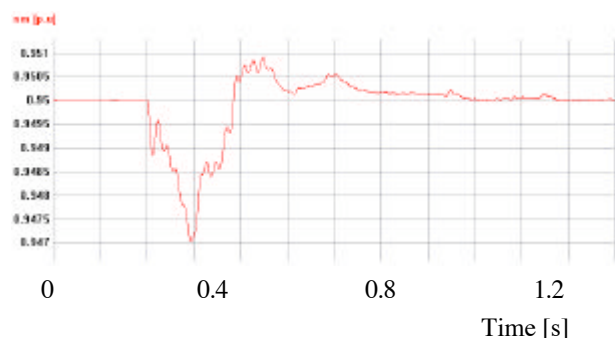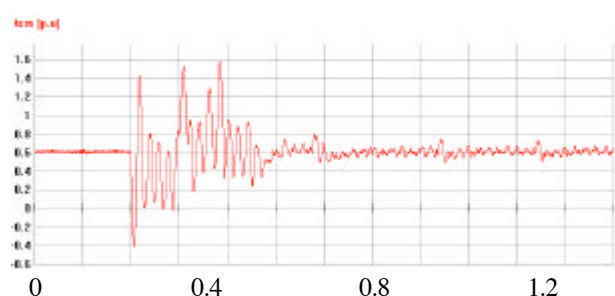
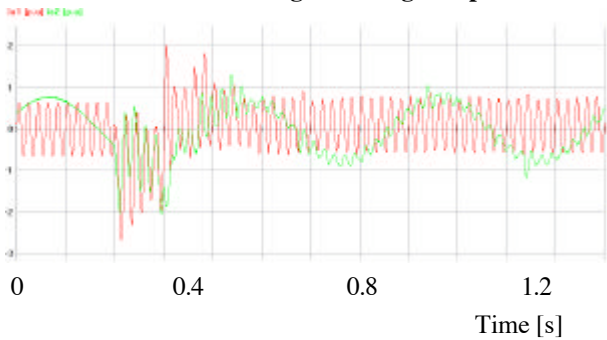**Figure 4a: 50% voltage drop on grid's side (100 ms)**

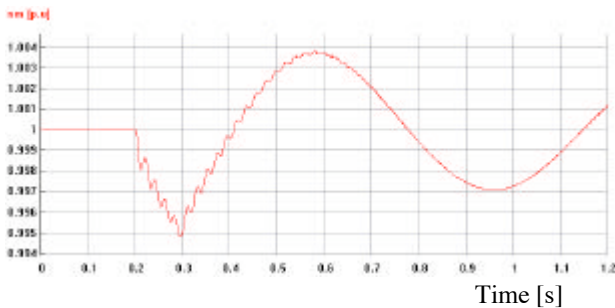**Figure 4b: Speed of the asynchronous machine during the voltage drop**

Figure 4c: Electromagnetic torque of the asynchronous machine during the voltage drop


Time [s]

Figure 4d: Stator and rotor currents of the asynchronous machine during the voltage drop

It may easily been 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 follwing 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.

Time [s]

Figure 5a: Speed of a conventional synchronous machine during a 50% voltage drop on grid's side (100 ms)


Time [s]
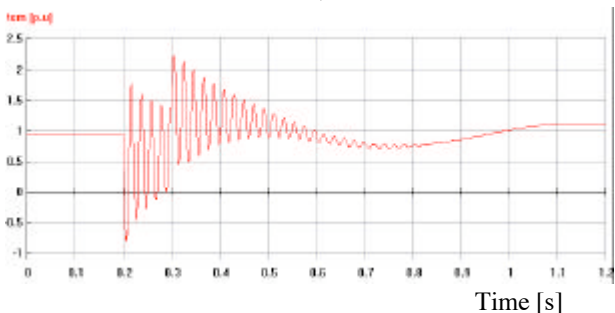
Figure 5b: Electromagnetical torque of conventional synchronous machine during a 50% voltage drop on grid's side (100 ms)

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.

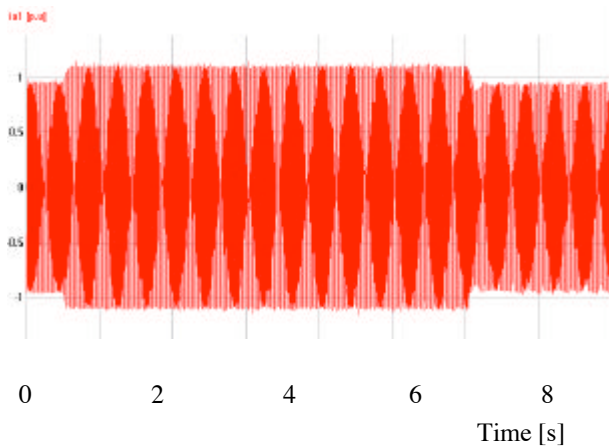### 2.2.2 Instantaneous power injection into the grid

Before the instantaneous power injection into the grid, the machine is operating with an active power output of 0.91 p.u. and speed 0.95 p.u. The speed set value is then decreased to 0.85 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 0.85 p.u.. The stator current is limited to 1.15 p.u. during this power injection. Depending on this limit, more or less power may be injected during a selected time.
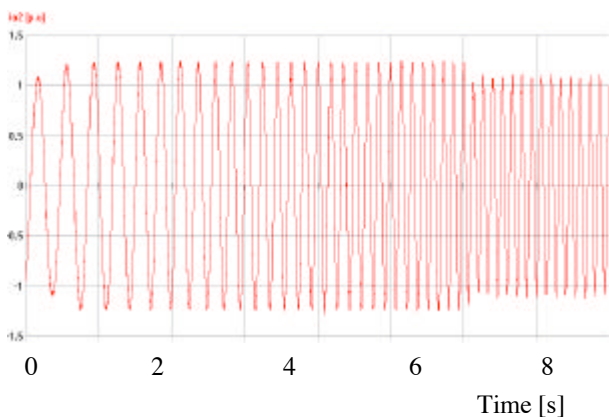

Time [s]
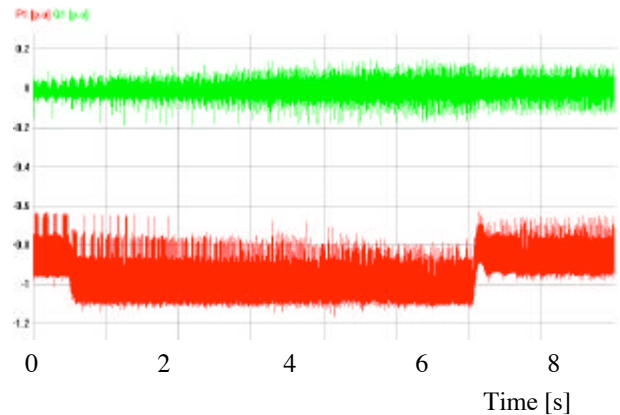
Figure 6a: Instantaneous power injection into the grid; stator active and reactive power of the machine

Time [s]
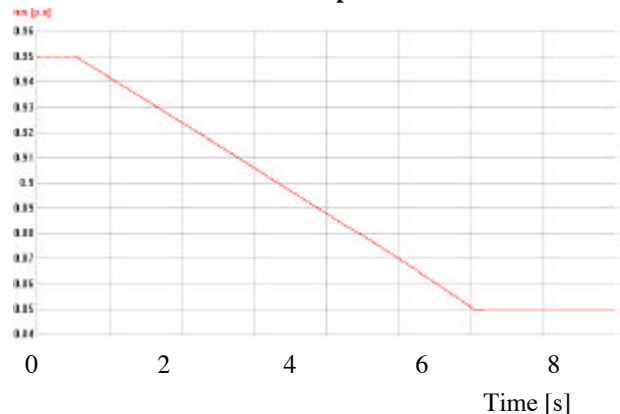
Figure 6b: Instantaneous power injection into the grid; mechanical speed of the machine

Figure 6c: Instantaneous power injection into the grid; stator current (1 phase only) of the machine

Figure 6d: Instantaneous power injection into the grid; Rotor current (1 phase only) of the machine

The following features may be seen in the simulation results represented in figure 6:

- A power of 0.12 p.u (28 MW) may be injected into the grid during 5.5 seconds
- The reactive power production of the VARSPEED system remains unchanged at the transformer LV side.
- The mechancial torque produced by the turbine is assumed to remain constant 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 feld 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 electromagnetical 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 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 advantatgeous for grid control.
- In addition to these advantages we would like to mention also the "classical" advantages, i.e. reduced abraision 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 developped 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 adequatly 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.

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.
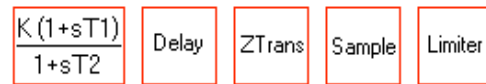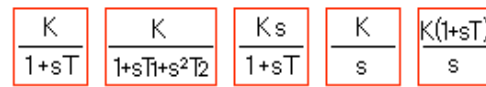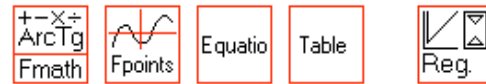
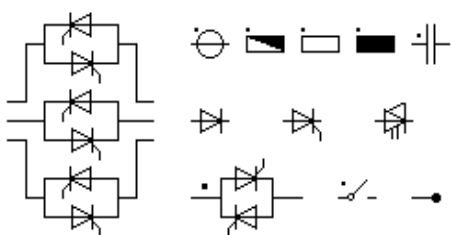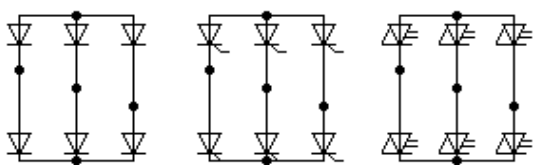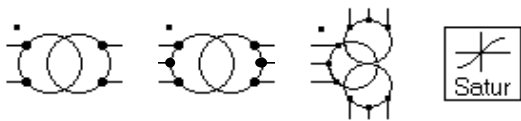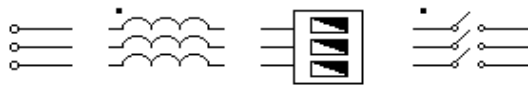

Figure A. Non exhaustive list of SIMSEN units

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).

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