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# Virtual Synchronous Machine

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**Demands in the area of electrical energy generation and distribution, as a result of energy policies, are leading to far reaching changes in the structure of the energy supply, which is characterised, on the one hand, by the substitution of conventional power stations by renewable energy generation, a decision which has already been made, and, on the other hand, by the changeover from centralised to decentralised energy generation. From an electrical engineering point of view, a new situation will arise for consumers concerning security of supply and power quality, which calls for further technical measures by the grid operators to ensure that the increasingly stringent supply criteria can be met. This article describes a new power electronics based approach which allows a grid compatible integration of predominantly renewable electricity generators even in weak grids making them appear to be electromechanical synchronous machines. As a consequence, all the proven properties of this type of machine which have so far defined the grid continue to do so, even when integrating photovoltaic or wind energy. These properties include, for instance, interaction between grid and generator as in a remote power dispatch, reaction to transients as well as the full electrical effects of a rotating mass. In addition, this new development can be operated in such a way that it provides primary reserve allowing, from a grid point of view, electricity generators such as wind and PV to be regarded as conventional power stations.**

## I. INTRODUCTION

The changes in the grid structure can be described as a transition from the proven vertical structure of generation to consumption with a few, but powerful generators (figure 1, left), to a distributed, increasingly amorphous and strongly meshed structure with numerous renewable energy generators which have very different feed-in characteristics (fig. 1 right). Consequently, depending on the local distribution of generators and local grid capacity, there can be an increased line impedance and reduction in short circuit power, which may cause or promote the appearance and mitigation of various disturbances.

The integration of electricity generators today is carried out using conventional converters and inverters, whose properties are the result of the implemented control principles. Frequently output voltage controlled inverters with subharmonic [1] or space-vector modulators [2, 3, 4] are used to locally stabilise the grid and supply the active and reactive power required by the grid depending on the local system management. The disadvantages of this operating principle lie in the large differences in grid behaviour between the grid coupled inverters and converters and conventional synchronous machines used for coupling traditional prime movers to the grid.

Up to now the layout, properties and operating strategy of electrical grids, the potential for automatically balancing a power deficit between grid areas as well as the dynamic behaviour of the grid have been closely connected to the static and dynamic properties of the electromechanical synchronous machines.

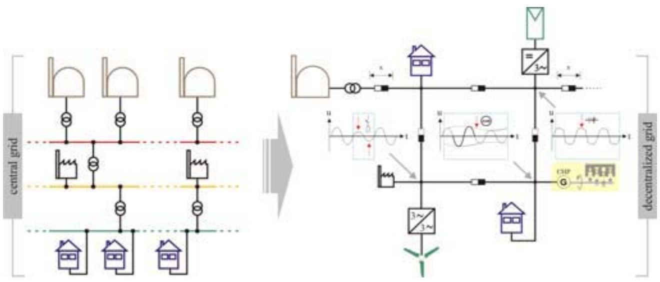


Figure 1. Change in structure of generation and distribution of electrical energy

It therefore seems necessary to develop a process by which inverters are able to connect any type of electrical generator to the grid in such a manner that the combination of inverter and generator behaves identically to an electromechanical synchronous generator.

## II. Solution Approach

The VISMA principle is based on combining the advantages of today's dynamic inverter technology with those of the static and dynamic operating properties of electromechanical synchronous machines. As shown in fig. 2, it is possible to specify the properties of an inverter in such a way that it acts like a synchronous machine between any direct voltage generator or storage system and the grid.

As a result of the storage connected to the direct voltage side of the VISMA, it can be operated in a full four quadrant mode and its alternating voltage side thus corresponds to the stator output of an electromechanical synchronous machine.

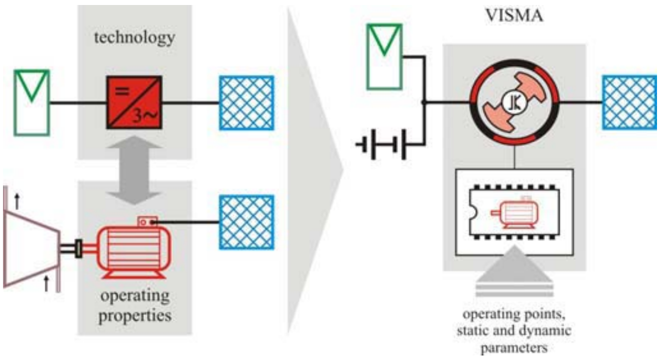


Figure 2. Basic concept of the Virtual Synchronous Machine (VISMA)

The mechanical system of an electromechanical machine with its shaft provides the second energy coupling point of this energy conversion machine. The mechanical component of a VISMA only exists as a logical concept. However, it is electrically fully effective from a grid point of view because it is modelled mathematically in real time by the control system, respectively process computer of the VISMA, and physically by means of the direct voltage supply circuit of the VISMA inverter. In this way a virtual rotating mass is created which is electrically effective in relation to the grid but can in addition be parameterised freely just as any of the other machine parameters.

In practice, access to the virtual pole system and the virtual shaft is achieved by influencing the corresponding parameters of the software running on the process computer and can therefore be carried out locally or by remote dispatch. If the grid requires active power, a corresponding virtual torque on the virtual shaft must be provided. The energy necessary for this is taken from the direct voltage system of the VISMA inverter, respectively supplied to the direct voltage system by the electricity generation unit. If reactive power has to be supplied to the grid, then in analogy the process computer influences the value of the virtual excitation voltage. The capacitor of the VISMA in the intermediate circuit supplies the reactive current.

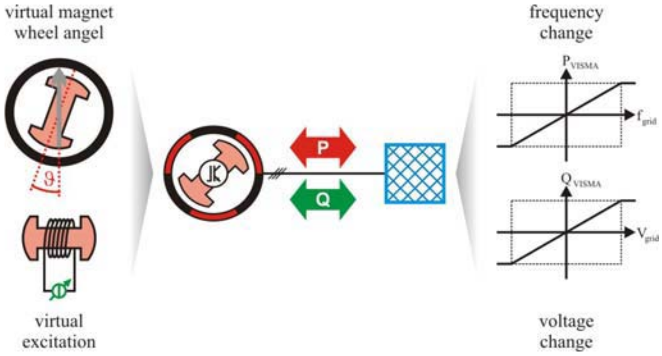


Figure 3. Transport of active or reactive power either locally induced (left) or due to voltage and frequency changes in the grid (right)

The full analogy with the electromechanical synchronous machine is established on the basis of the virtual values of torque and excitation voltage in combination with the intermediate circuit.

Similar to conventional machines, the transport of active and reactive power can be initiated by voltage and frequency changes in the grid by means of remote dispatch. This tried and proven mechanism requires no additional exchange of information and entire grid areas are able to balance their power deficit or surplus themselves.

The VISMA model is based on the complete two shaft model of an electrically excited synchronous machine as to be seen in fig 4 (left) which is fully described electrically by the d-q impedances of the stator Ld, Rd and Lq, Rq, the damper LD, RD and LQ, RQ as well as the exciter Le, Re, and magnetically by the coupling impedances and the mass inertia of the virtual rotor. As a consequence, the VISMA not only has static, but also dynamic properties, as the example shows in fig. 5 (right). The stator current reacts as a result of a decrease in the stator voltage and the rotor oscillates depending on the configuration of the damper after a change in the load.

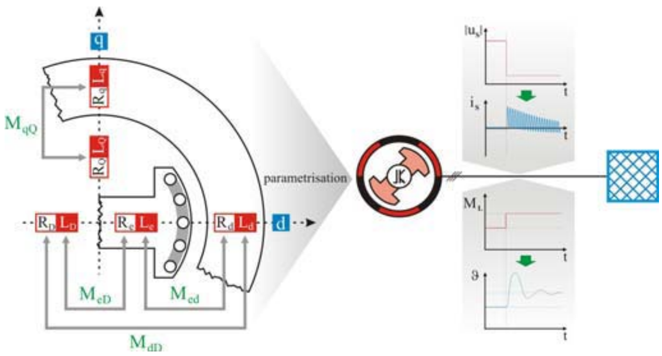


Figure 4. A model of the machine (left) and adjustability of the dynamic properties of the VISMA using the machine parameters (right)

## III. Technical Realisation

Modelling the synchronous machine requires the measurement of the voltage at the point of common coupling with the grid, the calculation of the machine current in real time and the feeding of the current into the grid.

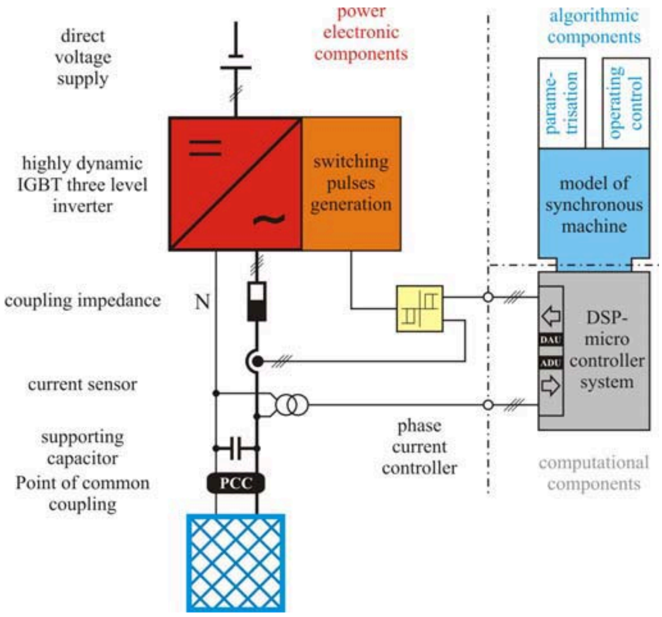


Figure 5. VISMA components

Figure 5 shows the components required for the VISMA including the highly dynamic three level inverter with phase current control.

This combination, regardless of the grid voltage but within design specific limitations, makes it possible to generate any current profile including direct current components which are, for instance, necessary for the exact modelling of the stator current of the machine in the case of a voltage drop in the grid.

The program interfaces for the machine parameters and the fundamental component management are addressed in each cycle of the algorithm. The on-going calculation of the machine model in real time as shown in fig. 6 allows a fast response to parameter changes so that newly calculated electrical properties of the machine become effective in the grid immediately.

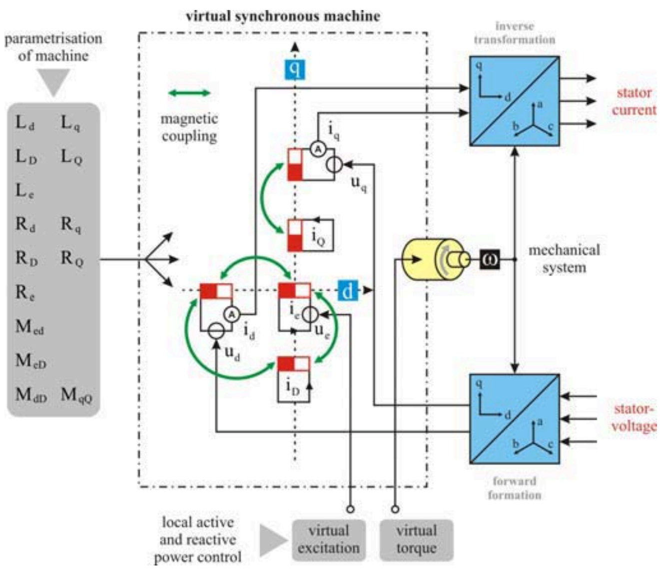


Figure 6. Synchronous machine model of the VISMA

The coefficients of the system of differential equations describing the VISMA can be parameterised freely and changed at any time during operation. The calculated machine currents are the reference values for the three phase current which the inverter feeds into the grid. It is important to note that the inverter must always be capable of feeding the current value calculated by the machine model into the grid. If not, the system loses it linear properties.

## IV. Measurements

The properties of the VISMA were investigated according to the experimental set-up shown in fig. 7. The characteristics of fundamental frequency and the contribution of the damper as regards the power flow to and from the grid, induced either locally or caused by the grid, were investigated as well as the response of reactive power during a drop in grid voltage and the transfer of power from the damper to the intermediate circuit of the VISMA.

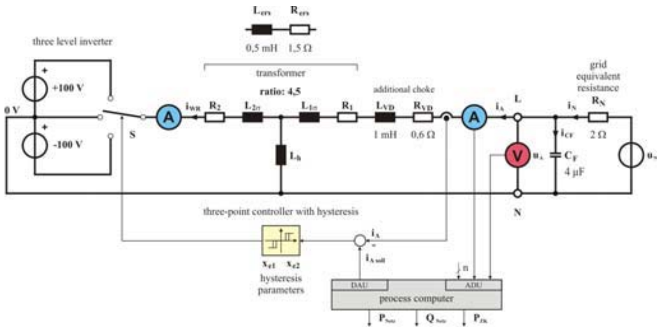


Figure 7. Single phase equivalent circuit diagram of the experimental set-up of the VISMA

The VISMA was supplied by a battery on the direct voltage side and connected to the grid using a three phase autotransformer with three magnetically decoupled systems with a transfer ratio of 4.5. The grid resistance shown in fig. 7 was used to achieve a reduction in short circuit power at the point of coupling to the grid.

Fig. 8. shows the fundamental frequency properties of the VISMA when using it together with the damper to decouple the grid from the connected electricity generators. In analogy to the electromechanical synchronous machine, the virtual shaft of the VISMA is provided with a positive virtual torque for transferring active power from the grid to the storage of the electricity generating system.

Also in analogy, the virtual rotor is excited and then stabilises at a new angle with a speed depending on the configuration of the damper. With the nearly optimal damper configuration shown in figure 8 the rotor stabilises at its new position after a single overshoot. The power of the overshoot is fully effective in the grid and indicates the existence of the virtual mass.

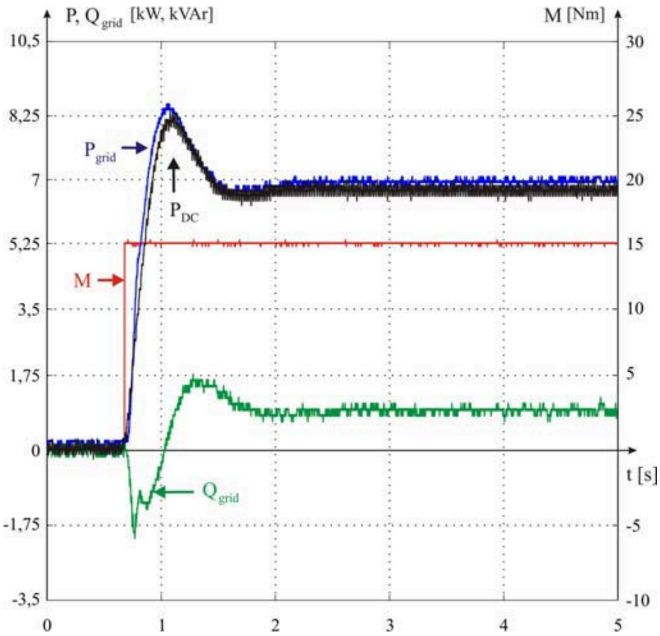


Figure 8. Transfer of active power from the grid to the intermediate circuit under almost optimal conditions. M: virtual torque of the machine model, PDC Power of intermediate circuit

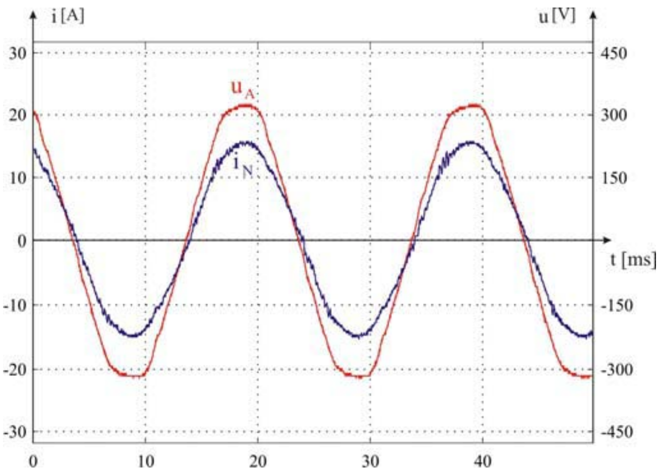


Figure 9. Output voltage and grid current of the VISMA under stationary power conditions (see fig 8) when using the VISMA in a motor mode

Figure 9 shows in addition the output voltage of the VISMA as well as the current drawn from the grid for the motor mode after decaying of all transients.

Figure 10 shows the effect of a change in the grid angle which alternates within seconds in the range of in a trapezoidal shape.

The grid angle is defined as the displacement angle between the three phase voltage system and the virtual rotor of the VISMA. It was possible to change it freely when connecting the VISMA to a space vector modulated inverter for autonomous electricity grids which can control amplitude, phase and frequency.

The rotor must be prevented from following the changes of angle as this would result in an average displacement angle value of zero. This is easy to achieve with the VISMA by setting the logical parameter of rotor inertia to as large a value as necessary. As regards the grid, this corresponds electrically to a synchronous machine with a rotating mass sufficiently large that the rotor angle remains constant solely due to grid interaction.

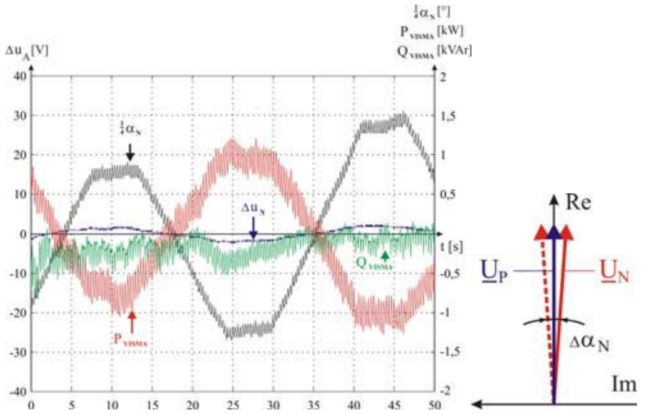


Figure 10. Remote dispatch of active power from the VISMA by changing the grid angle in relation to the virtual rotor rotating at a fixed speed

A positive grid angle as shown in fig. 10 corresponds to an offset of the three phase voltage system along the time axis and thus an angle related lag. This causes the VISMA to act in a generating mode because the rotor has been parameterised with a very large virtual mass and thus continues to rotate unaffected. In addition to increasing the virtual mass of the VISMA, a control algorithm corresponding to a power action controller can be used and can set the machine angle to the desired value.

Reactive power can be drawn from a VISMA running neutrally in parallel to the grid without active or reactive power transfer by changing the grid voltage in complete analogy to the electromechanical synchronous machine.

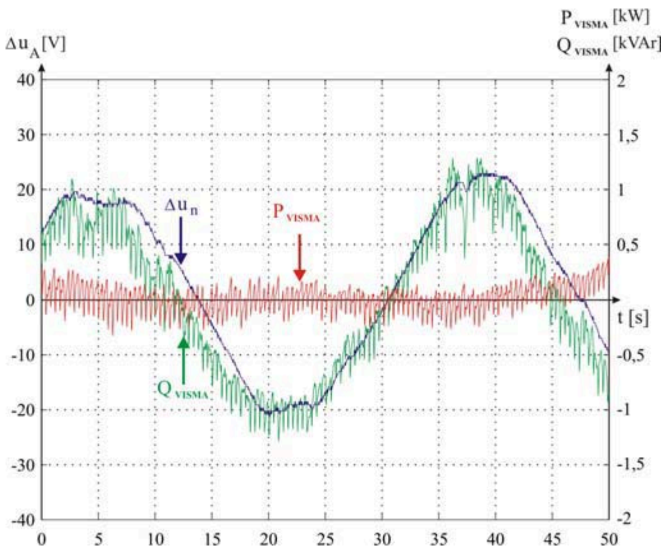


Figure 11. Remote dispatch of reactive power from the VISMA by changing the grid voltage, respectively the output voltage of the VISMA

Fig. 11. shows this using an almost trapezoidal change in voltage and the subsequent response of reactive power as an example. If the virtual excitation voltage is maintained, a drop in the grid voltage causes an overexcitation of the VISMA and results in the supply of capacitative reactive power.

The linear parts in the curves of as in fig 10 as well as in fig 11 reflect the PQ control of the VISMA. As the machine parameters can be freely set and an additional power station control algorithm can be superimposed, the proportionality factors of the PQ control can be modified simply.

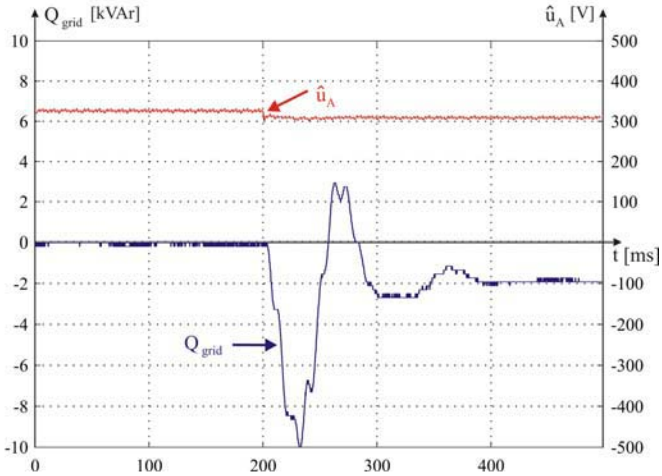


Figure 12. Reaction of VISMA to a grid voltage drop: reduction in the voltage drop by supplying dynamic capacitive reactive power as well as supplying constant capacitive reactive power (2 kVAr) after the transients because the grid voltage is still reduced

Fig. 12 shows the demand for dynamic capacitive reactive power to support the grid.

A 35 V voltage drop caused by connecting a large load to the grid connecting point of the VISMA for which the short circuit power has been reduced leads in the first instance to a strong dynamic reactive power response which counteracts the voltage drop. After the decay of the transients in the virtual machine, there is a constant supply of capacitive reactive power as long as the grid voltage depression is maintained.

The power electronics modelling of the synchronous machine, as regards the properties of the damper, offers the advantage that the energy in the damping process is not converted to heat in the damper of the electromechanical machine, but transferred to the intermediate circuit as a result of the analogy between the damper and intermediate circuit and can thus be reutilised.

Oscillations of the grid in the form of periodic changes in the grid voltage lead to an excitation of the damper system of the VISMA as shown in figure 13. To demonstrate the effect, a sinusoidal phase change of the voltage of the grid forming inverter used in the experiments was introduced. The phase change had an angle of (see fig 10, right) and a frequency of 12 Hz. In order to make a comparison with the undisturbed state, the disturbance was initiated after ca. t = 2.5 s and removed after ca. t = 40 s.

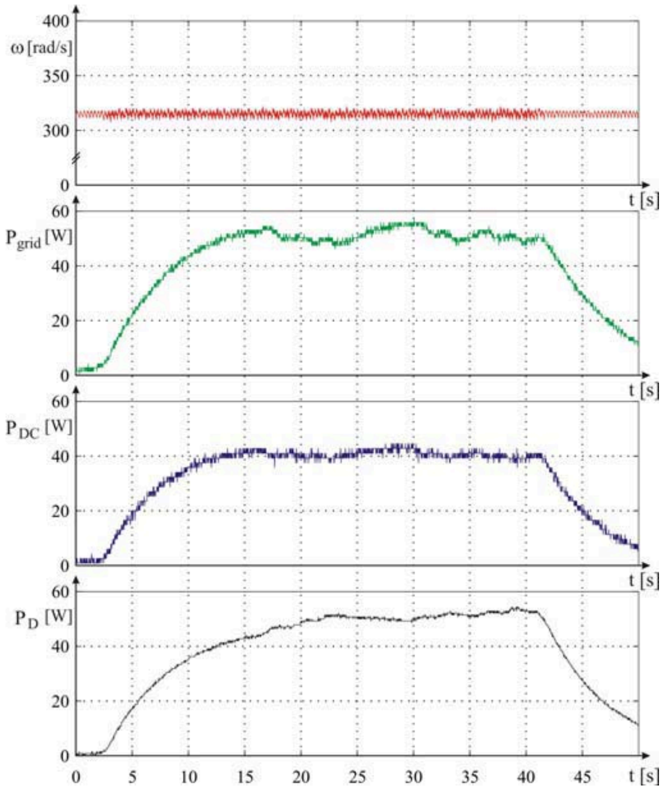


Figure 13. Damping of a sinusoidal oscillation of the phase angle of the three phase grid voltage with an elongation of at 12 Hz. From top to bottom: virtual rotating speed of VISMA, active oscillating power absorbed from the grid, active power transferred to the intermediate circuit, calculated active power stored in the modelled damper system

The rotor of the machine model remains almost unaffected due to its virtual mass, while the power (see fig 13) becomes effective in the damping system. The power values were filtered with relatively large time constants to suppress the effect of disturbances.

It was possible to transfer the calculated power of the damping process to the intermediate circuit of the VISMA inverter thus confirming the energy based analogy of the damping system of the electromechanical machine and the intermediate circuit of the VISMA.

Sufficient computational capacity is necessary to build a real time machine model. The rapid prototyping DSP system DS1103 from dSPACE was used for the VISMA prototype. It was able to calculate the complete model of the VISMA including all auxiliary algorithms for signal filtering and alternating current measurements within a cycle time of approx. 100 µs. Currently the development is being carried out using a single board process computer on the basis of the Tricore microcontroller made by Infineon Technologies AG.

## V. Summary

The VISMA concept as presented here makes it possible to connect every kind of decentralised electrical, preferably renewable, generators, such as wind, PV and fuel cell systems also to weak grids. Due to the analogy to an electromechanical synchronous machine, conventional and proven grid operation with all the usual static and dynamic properties is possible.

On account of the exact modelling of the synchronous machine the self organising grid parallel operation is possible via the three phases of the grid with any number of generators without additional communication lines.

A further aim of the development of the VISMA concept is to establish the properties of a power station by superimposing a virtual machine control system.

Such an operating mode also offers the advantages of free parameterisation during operation.

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