Dynamic Properties of the Virtual Synchronous Machine (VISMA)

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Abstract

The increasing integration of decentralized electrical sources is attended by problems with power quality, safe grid operation and grid stability.

The concept of the Virtual Synchronous Machine (VISMA) [1] discribes an inverter to particularly connect renewable electrical sources to the grid that provides a wide variety of static an dynamic properties they are also suitable to achieve typical transient and oscillation phenomena in decentralized as well as weak grids.

Furthermore in static operation, power plant controlled VISMA systems are capable to cope with critical surplus production of renewable electrical energy without additional communication systems only conducted by the grid frequency.

This paper presents the dynamic properties "damping" and "virtual mass" of the VISMA and their contribution to the stabilization of the grid frequency and the attenuation of grid oscillations examined in an experimental grid set.

Keywords

Virtual Synchronous Machine (VISMA), virtual mass, damping, frequency stabilization, inverter, decentralized energy generation

1. Introduction

The VISMA concept describes a new type of grid feeding inverter entirely operating as electromechanical synchronous machine. It consists of a generator and an energy storage on the DC side, a hysteresis controlled three phase inverter and a process computer including voltage and current transducers. The inverter needs a coupling inductance at the AC side to operate the hysteresis control mode. The basic principle of a VISMA is demonstrated in Fig. 1.

Three subprocesses amount to a complete VISMA functional chain. It starts with the real-time measurement of the grid voltage (1) to feed the virtual synchronous machine algorithm (2) on the process computer that performs the mathematical model of an electromechanical synchronous machine also under real-time condition. The results are the stator currents of the virtual synchronous machine present as process variables. To complete the cycle, the calculated currents have to take effect at the grid. For this purpose the fast hysteresis controlled inverter (3) carries over the current signals to drive these currents at the grid immediately.

The performance of the virtual synchronous machine is adjustable by modification of the VISMA model parameters at the computer any time while the process is running. The variation of the parameters directly affects the calculated stator currents and thus the operation of the inverter.

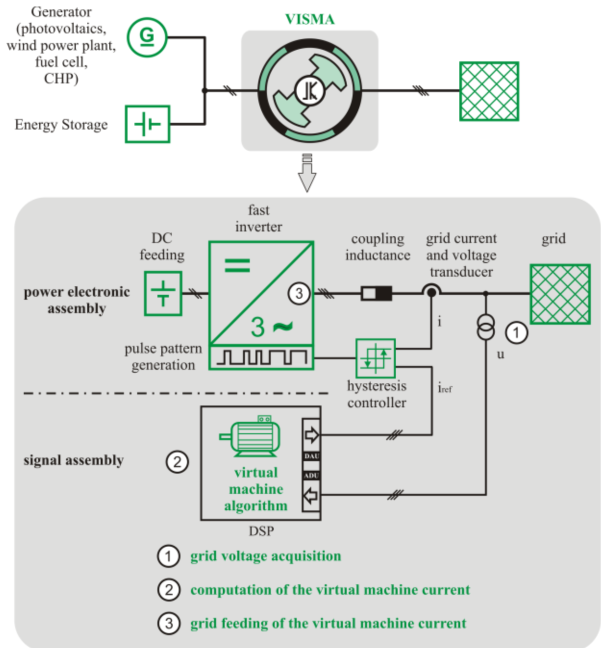

Fig. 1. Basic principle of the VISMA

In the course of the research of VISMA systems, two different machine models, a d-q [1] and a three-phase model shown below, were considered with the focus on practical applicability. It became clear that in case of unsymmetrical load or rapidly occurrences in the grid, d-q based models tended to unsteady states due to AC components in the d-q input voltages of the machine model caused by the standard d-q transformation. Therefore a more robust three-phase model was applied for the investigation in respect of dynamic processes in the grid. Besides using the arrangement in Fig. 1 it is also possible to compute compensation currents to suppress grid harmonics [2]. Compensation and VISMA currents are freely superposable.

The three-phase model in Fig. 2 reproduces the stator circuit of a synchronous machine and the mechanical subsystem, which provides the features of virtual mass and virtual damping according to the electromechanical power balance. Instead of a field circuit, the pole wheel induction voltage in the stator is considered and the damping attribute is directly incorporated in the mechanical subsystem. These simplifications result to begin with a lack of transient and sub-transient stator current components. However, by implementing a parallel secondary machine with the same structure but more dynamic stator parameters and subsequent summation of the instantaneous stator current signals, the transient features are facile extendable. In this way, the transient machine behavior could be set almost freely.

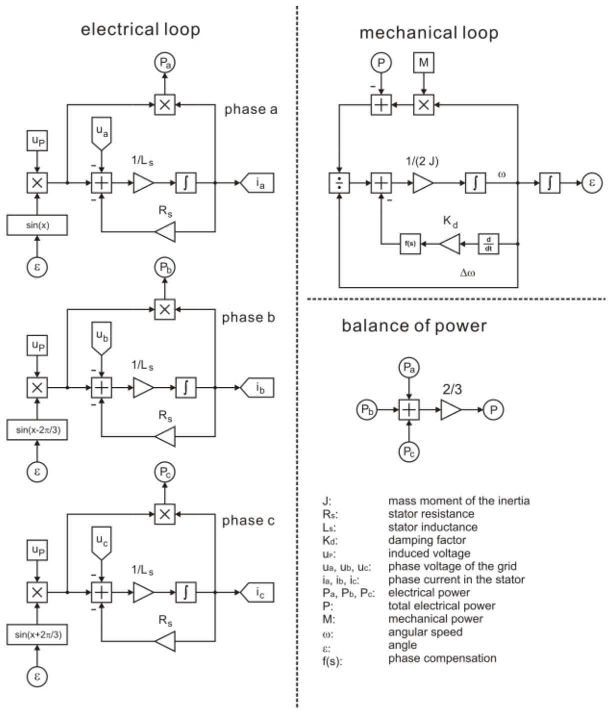

Fig. 2. Simplified three-phase model of the synchronous machine

2. Experimental Grid Set Up

In order to study the dynamic properties of the VISMA system in the laboratory, an experimental grid was set up which consists of two asynchronous-synchronous machine-sets (ASM-SM-sets) with a nominal power of 15 kW each and two VISMA systems with one battery group for each system featuring 5 kW nominal power. Fig. 3 indicates an overview of the experimental grid.

The two ASM-SM-sets represent conventional controlled power plants so it is possible to model common frequency and voltage changes in the grid caused by load activity. With the electromechanical synchronous machines the experimental grid can be run in island-mode. By switching S0 on, a parallel operation to the external grid can also been achieved. Instead of a complete generator-storage-system of the VISMA systems, only battery units are provided for the DC-link, which is usually fed by Photovoltaic and wind generators, fuel cells and CHPs. Despite of this simplification all relevant operating conditions particularly the bidirectional energy flow on the DC side can be still examined. The local spread installed storages of the VISMA systems can also serve as charge station for electromobiles.

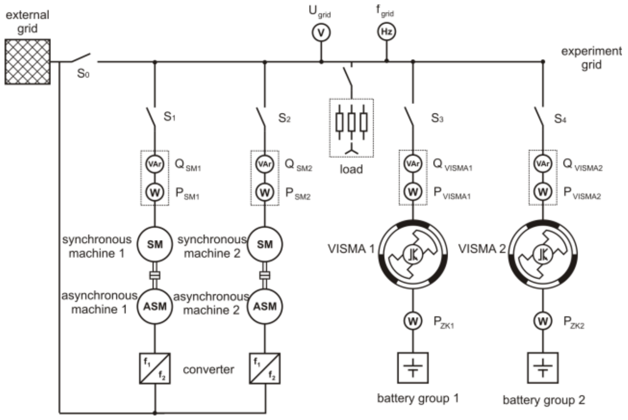

Fig. 3. Overview of the experimental grid

3. Measurement

The experimental grid allows the study of all static and dynamic characteristics of VISMA systems including special cases like coarse synchronization and pulling out of synchronization. In this paper the efficacy of the VISMA damping and the virtual mass are presented.

A. *Frequency Stabilizing effect of the virtual mass*

In the conventional electric grid there is a close relation between the grid frequency and the rotor speed of all synchronous generators. Because of the moment of inertia, the rotor speed and thus the grid frequency cannot alter suddenly while load activity. Hence the dynamic frequency stability is growing with the total rotating mass.

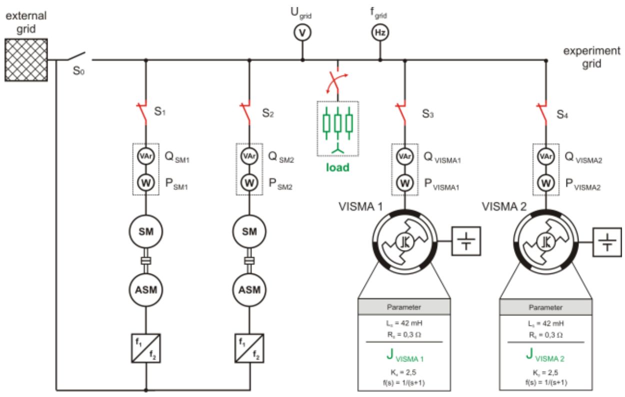

Fig. 4. Configuration of the experimental grid to investigate the effect of virtual mass

This transient frequency stabilizing effect is also inherited in the VISMA concept by implementing a virtual rotating mass. So it has to prove that the virtual mass takes the same effect to the grid as the physically mass of conventional generators.

To investigate this property, the grid configuration shown in Fig. 4 was arranged and different amounts of virtual mass were examined.

To illustrate the dependence of the frequency backing and the number of active VISMA systems in the grid, the VISMA systems and the grid bothering load were switched according Table 1. All experiments started with the state A and ended with the state I. The state indicators are noted down on all plots for time distinction.

Tabel 1. Switching sequence

state	VISMA 1	VISMA 2	Load
A	on	off	off
B	on	on	on
C	on	on	off
D	on	off	off
E	on	off	on
F	on	off	off
G	off	off	off
H	off	off	on
I	off	off	off

The moment of inertia of the SM with both $J_{SM} = 0.12kgm^2$ dominates the total moment of inertia of the ASM-SM-sets. In order to investigate the effect of the virtual mass, hence the moment of virtual inertia of the VISMA systems were chosen to $J_{VISMA} = 0.06kgm^2$ and $J_{VISMA} = 0.24kgm^2$ each. The measurement results are illustrated in Fig. 4.

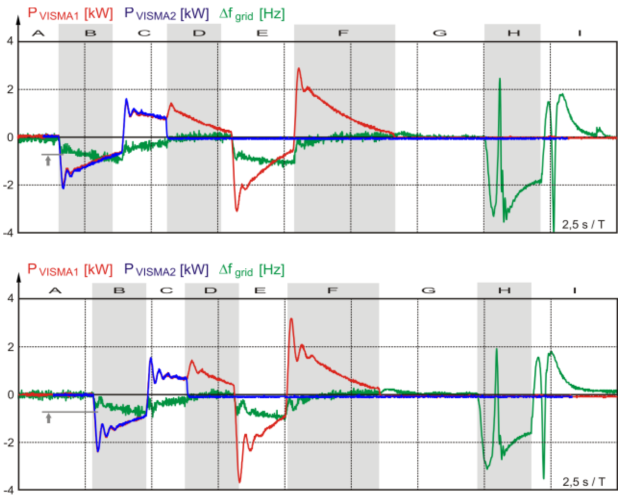

Fig. 4. Frequency stabilizing effect of the VISMA systems (Top plot: $J_{VISMA\,1} = J_{VISMA\,2} = 0.06kgm^2$, bottom plot: $J_{VISMA\,1} = J_{VISMA\,2} = 0.24kgm^2$)

At the beginning of the periods B, E and H in both plots the activated load causes frequency drops in the grid and the VISMA systems pointing out active power response. Comparing the periods B and E it is obvious that the frequency drop increases skipping from the two to the one VISMA constellation. The attempt to activate the load in period H without any VISMA leads the grid near to a collapse since the SM synchronization units strike an error due to the large frequency drop. The load is fitted to meet its error trigger level barely.

Stepping up the virtual masses of the VISMA systems from $J_{VISMA\,1} = J_{VISMA\,2} = 0.06kgm^2$ to $J_{VISMA\,1} = J_{VISMA\,2} = 0.24kgm^2$, less frequency decrease is distinguishable. But by means of the grid frequency course it can also be observed that the pole wheel oscillation of the electromechanical synchronous machines rises accompanied by power oscillation between virtual and real synchronous machines because the virtual masses affect the dynamic properties of the overall system. One possible solution to mute these oscillations is the extension of the base machine model by a parallel operating virtual machine with transient features. This will be considered in the following paragraph.

Different virtual mass moments of inertia of the VISMA systems results to different active power responses at the moment of load activation and therefore deviant frequency backing. Fig. 5 illustrates such a case. In period H the synchronization units barely held the grid.

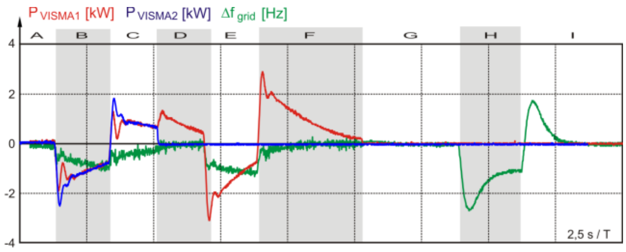

Fig. 5. Frequency stabilizing effect of the VISMA systems ($J_{VISMA\,1} = 0.06kgm^2$, $J_{VISMA\,2} = 0.24kgm^2$)

B. *Damping effect of the VISMA*

The frequency and rotational speed drop can be reduced by increasing the virtual mass but in the present case with the chosen grid configuration the SM units tend to pole wheel oscillation.

The machine model considered yet only regards the stator impedance thus it is without sufficient transient behavior. This can be obtained upgrading the model according Fig. 6. The base model used before is operating further with unchanged parameters while adding a second machine with the same structure but different parameters so that better dynamic performance could be achieved. The parameters of the secondary machine are largely scalable to the requirements of damping in the grid. The additional coupling factor is to tune the needed transient response. Adjusting the transient VISMA response there is to note that the DC side is always able to serve the energy demand.

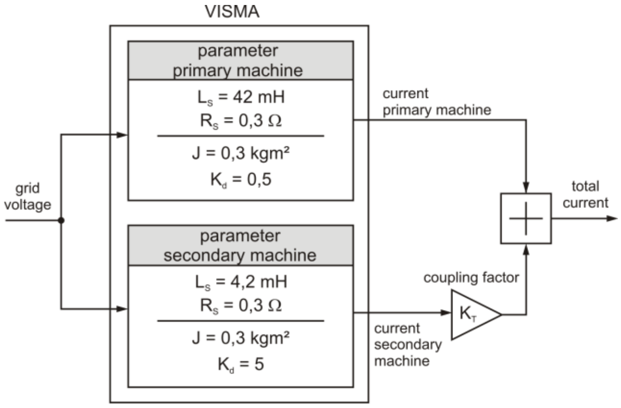

Fig. 6. Upgrading of VISMA model with transient behaving machine

In the following experiments, the VISMA was operated without and with the secondary machine. The power response and the change of grid frequency were recorded in both cases. The table 2 shows the sequence of activities during the experiments. The results of measurement are illustrated in Fig. 7 with the given period indicator A to F.

Table 2: Switching sequence

state	VISMA	load
A	only primary machine activ	off
B	only primary machine activ	on
C	only primary machine activ	off
D	primary and secondary machine both activ	off
E	primary and secondary machine both activ	on
F	primary and secondary machine both activ	off

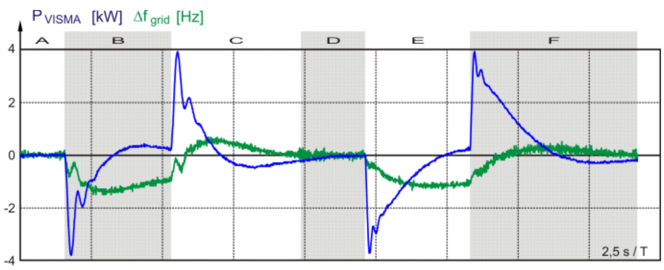

Fig. 7: Investigating the damping effect of VIMSA without secondary machine and with it by switching a load.

During the time period A to D the VISMA was operated only with the primary machine, whereas during the time period E and F second machine was also active. At the beginning of periods B and E, a load was switched on. This activity leads to a grid frequency drop immediately which causes a power response of VISMA. It is clearly to see that the frequency has a larger oscillation at the beginning of period B in comparing to period E. The VISMA with secondary machine has a better damping effect for frequency oscillation because of transient power response, which can be adjusted by setting the coupling factor K_T in Fig. 6

In order to investigate the damping effect of parallel operated VISMA systems in the grid, different experiments were implemented in the experimental grid as represented in Fig. 8.

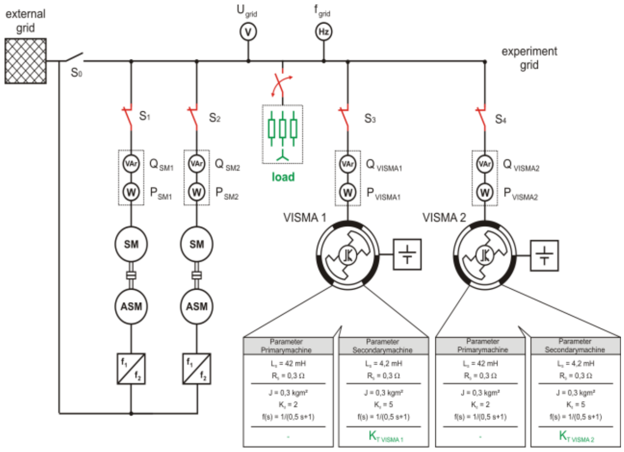

Fig. 8. Configuration of the experimental grid to investigate the effect of virtual damping

During the experiments, the coupling factor values of two VISMA were chosen equally and unequally. For each configuration, the power response and the change of grid frequency were recorded under the condition that a load was switched on and off according to the table 3.

Table 3: Switching sequence

state	Load
A	off
B	on
C	off

Firstly, the coupling factors of the secondary machines were set to zero so that the secondary machines has no effect. It can be observed that at the beginning of period B and C according to Fig. 9 the frequency and pole wheel oscillation of the electromechanical synchronous machines occurred immediately after switching the load.

The maximum oscillation amplitudes are visible in the top diagram while the secondary machines are inactive. Subsequently the coupling factors were increased to $K_{T\,VISMA\,1} = K_{T\,VISMA\,2} = 0.15$ by observing the stability of the grid. The middle plot of Fig. 9 shows the nearly disappearing oscillations due to the activity of the secondary machines. The noise on the frequency course in period C is only caused by the PLL frequency measuring unit. The bottom diagram illustrates the different active power response of the VISMA systems operating with divergent coupling factors.

Comparing the frequency courses it is noticeable that a one-sided decline of damping will partly compensated by the VISMA system with unaffected damping properties.

It is proved that the grid frequency oscillation caused by the load activity can be attenuated by purposeful modification of the dynamic VISMA parameters.

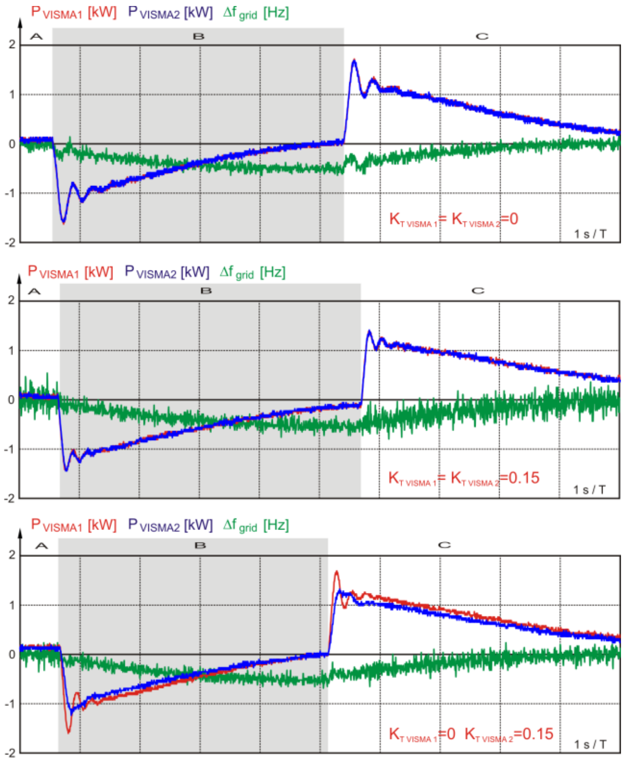

Fig. 9. Damping effect of two VISMA systems

A communication between the VISMA units is not necessary; however, the dynamic parameters of the spread installed systems can be adjusted as needed centrally.

4. Conclusion

This paper presents the essential dynamic properties of VISMA systems pointing out the effects of virtual mass and damping. The virtual mass counteracts grid frequency drops and the virtual damper suppresses grid oscillation so these features are equally effective to electromechanical synchronous machines. In contrast to such ones the parameters of VISMA systems can be modified with a high level of freedom as needed.

References

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