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FLYWHEEL BASED POWER QUALITY IMPROVEMENT IN A MEDIUM VOLTAGE GRID

Dr. P. von Burg, ASPES Engineering AG, Zurich, Switzerland
J. Allmeling, Swiss Institute of Technology Zurich, Zurich, Switzerland

1. ABSTRACT

Voltage sags of up to 7 % nominal voltage lasting between 70 and 2000 ms have been measured in a 16 kV grid close to Zurich, Switzerland. The sags are caused by short-circuit tests made in a high current laboratory.

Since a direct integration of the laboratory into the high voltage grid would be too expensive alternative solutions had to be found to protect the remaining consumers within this grid from the voltage distortion. Due to the dynamic behaviour of the sags conventional technologies such as var compensators or controlled tap transformers fail for compensation. However, a voltage source inverter (VSI) inserting a variable voltage in series with the line can keep the voltage level within an acceptable tolerance. An energy storage unit or the grid itself can provide the needed active power.

First tests using a 70 kW flywheel system in a smaller grid proved the general feasibility of this technology. The added voltage in phase and amplitude and the flywheel’s stored energy are controlled by a microprocessor based control unit. Measurements show that the power quality can be significantly improved as voltage distortions with frequencies from close to DC up to 1 kHz are almost completely compensated. A pilot installation is planned and scheduled to be operational this year. In addition simulations have been performed on different topologies, including one without energy storage unit.

2. INTRODUCTION

Power quality is becoming a major concern in energy distribution networks [1,2]. The widespread use of computers and microprocessors demands a much better power quality than passive loads like electrical machines or light. Although the standards regarding power quality are rather strict they are widely not fulfilled. Existing problems on the grid are often unknown to consumers and utilities. Even if grid problems are identified, economical solutions are not yet available on the market. Over-dimensioning of the grid has been the strategy to guarantee power quality so far, but in a liberalised energy market the utilities try to avoid grid reinforcement when the costs cannot be passed on to the customer.

This paper describes a solution for a power quality problem, for which conventional techniques fail due to high costs.

3. THE FEHRALTORF CASE

On a medium voltage grid close to Zurich, Switzerland, voltage sags of up to 7 % have been observed. The sags are caused by a high current lab doing short circuit tests.

A sag typical for the present case is shown in figure 1. Notice the rather long duration in comparison to disturbances usually discussed.

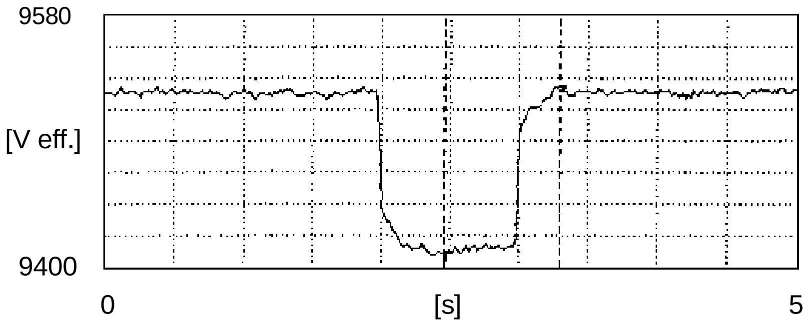

Figure 1: Voltage sag characteristics

Almost all energy of the sag is in a frequency spectrum below 5 Hz. The energy of this sag in the whole medium voltage grid is up to 1 kWh, whereas the power needed for a complete compensation may be as high as 15 MVA.

The high current lab is connected to the high voltage grid via the same feeder as the small village Fehraltorf. A dedicated high voltage feeder with an own substation only for the lab has been considered as too expensive. Therefore another solution to protect the remaining consumers from the voltage sags had to be found. The grid is shown in figure 2.

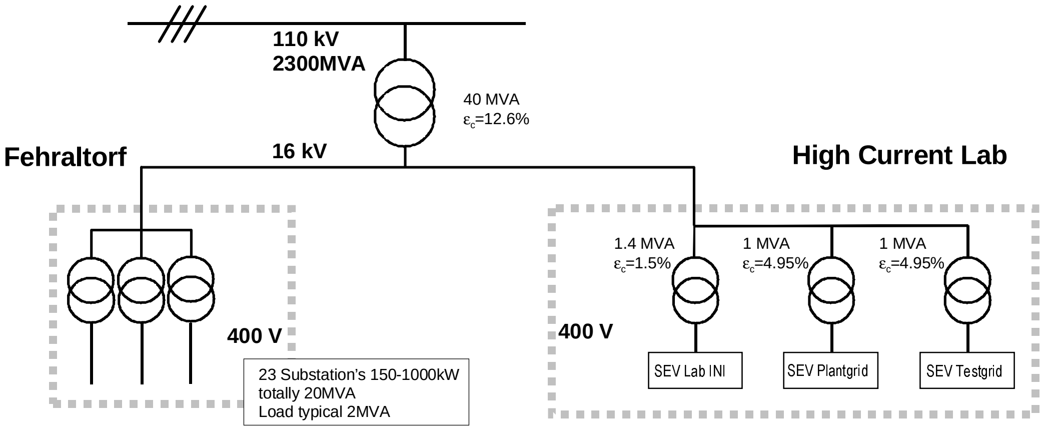

Figure 2: Grid situation of Fehraltorf

4. DIFFERENT STORAGE TECHNOLOGIES

At a first glance, a compensator for voltage drops must include a short time energy storage device in order to provide the missing energy for the grid. Due to the high power to energy ratio and the high number of load cycles batteries are not suitable for this application and have not been considered further. Emerging technologies such as kinetic energy storage devices, SMES and super-capacitors might cover the technical demands and have thus been compared. SMES storage systems have been investigated and built in small units by various researchers. However, a recent study shows that SMES systems can hardly compete with other storage technologies neither in investment nor in operating costs [3]. Regular capacitors have limited capacity [4] while super-capacitors with the required ratings are still difficult to obtain on the market [5]. Consequently an already existing flywheel energy storage system has been chosen to demonstrate the feasibility of the compensator. As all short time energy storage technologies are under intense development the result of such a comparison may change within the next few years.

5. TOPOLOGIES CONSIDERED IN THE SIMULATION

Figure 3 shows the simulation model of the Fehraltorf grid in a single-phase representation. The HV grid, the HV/MV transformer and the line are modelled as the equivalent voltage source and the grid impedance seen from the busbar. The busbar represents the point of common coupling where the line splits to the village of Fehraltorf and to the high current laboratory. The load of the village (totally 2 MVA) is represented by a RL combination. The laboratory is modelled as a switched predominantly inductive load. Since the lines from the busbar to both of the loads have no major impact on the voltage deviations in the village their impedance was added to the corresponding load.

In the simulations performed the dynamic voltage restorer (DVR) is inserted between the busbar and the village. The DVR consists mainly of a transformer in series with the line whose secondary winding is fed by a voltage source inverter (VSI). The voltage level in the village is controlled by adding the VSI output voltage to the busbar voltage. The busbar voltage itself is not influenced due to the comparably low MV grid impedance. Thus, to keep the voltage in the village at a constant level during voltage sags on the busbar the VSI output voltage needs only to be as high as the sag. Hence, the maximum load in the village multiplied by the maximum relative voltage deviation, i. e. 7 %, determines the rated power of the DVR.

During voltage sags the DVR has to provide active power. Due to the relatively long duration of the sags the power cannot be taken from the DC link capacitor. Therefore, an additional power source must be linked to the system. Figure 4 shows two possible DVR topologies with different power sources. In topology 1 the power is provided by a flywheel storage system, whereas in topology 2 the power is taken from the grid via a shunt connected VSI. Both topologies show nearly the same performance, but in certain cases they have different restrictions.

Topology 1: To reload the flywheel storage after a sag the reference voltage for the village must be lowered slightly, e. g. by 0.5 %. This allows the VSI to absorb active power. As a consequence the DVR cannot keep the village exactly at the rated voltage, though usually the voltage deviations are quite small. Furthermore the finite energy capacity of the flywheel limits the duration of compensated sags.

Topology 2: When taking active power from the grid during sags, the grid is stressed additionally. Although further decrease in the voltage can be prevented by means of supplying reactive power, over-current conditions may lead to an overall outage in the grid. This could be a problem especially if several consumers try to keep their own loads supplied.

Yet another approach to keep the voltage level in the whole grid would be a shunt connected active filter near the laboratory. This topology is indicated in cases where the disturbing load draws active current, and little reactive power is sufficient to raise the voltage. Here however, the disturbing current itself is reactive, so that the filter's ratings need to be as high as the disturbance's, i. e. 15 MVA. This is about 100 times the power rating of the DVR.

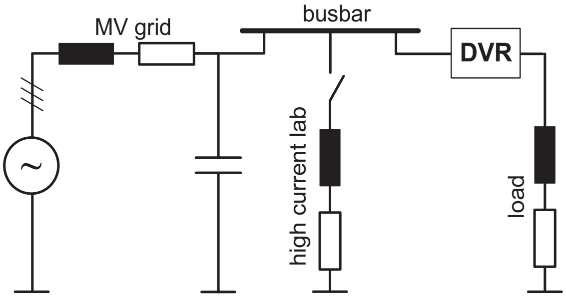

Figure 3: Simulation model of the grid

The voltage control algorithm is based on a dead-beat controller. A discrete time controller has the advantage over a continuous one that delays of the system can be taken into account. This is important due to the large delay caused by the VSI with its relatively low switching frequency.

An additional requirement for the DVR is the ability to suppress harmonics in order to have a sinusoidal voltage in the village. This can be achieved by adding an appropriate harmonic voltage to the distorted busbar voltage. The controller was designed in such a way, that a stationary 5th, 7th, 11th, 13th, 17th and 19th harmonic as well as the negative sequence are completely eliminated.

For both simulated topologies two-level VSI were chosen with a switching frequency of 3600 Hz and a rated power of 250 kVA. With this rating the DVR can handle a maximum load of 3.6 MVA if the voltage sags do not exceed 7 %. The resonant frequency of the LC output filter for the series VSI is 2000 Hz.

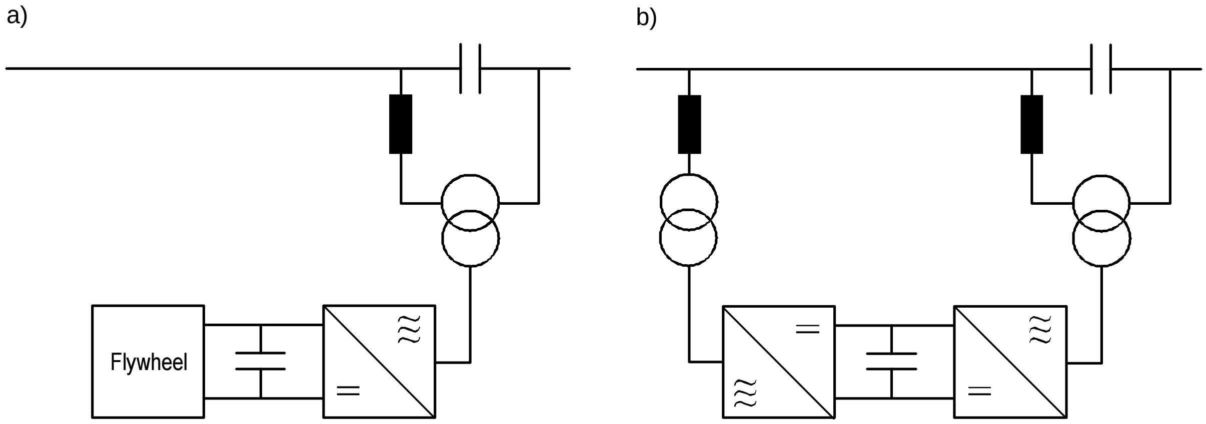

Figure 4: DVR topologies

6. SIMULATION RESULTS

Figure 5 shows a 7 % sag in the magnitude of the busbar voltage caused by a test performed in the high current laboratory. The corresponding voltage in the village restored by the DVR can be seen in figure 6. The rise time is less than 2 ms. Before the load voltage has fully settled after about 20 ms, several peaks can be observed. These are due to the controller's harmonics compensation. Here, topology 1 using a flywheel storage was simulated.

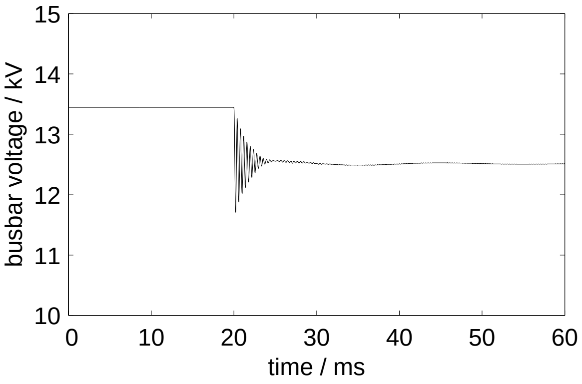

Figure 5: Saged voltage magnitude

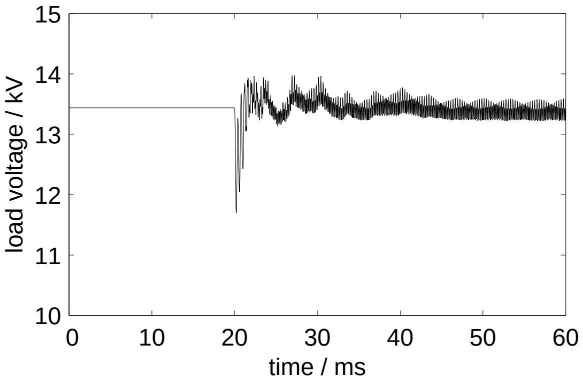

Figure 6: Restored voltage

If instead topology 2 is used, harmonics originated from the shunt connected VSI can be seen on the busbar voltage in figure 7. The load voltage in figure 8 also shows a slightly higher harmonic content. In the following simulations, topology 1 was used again.

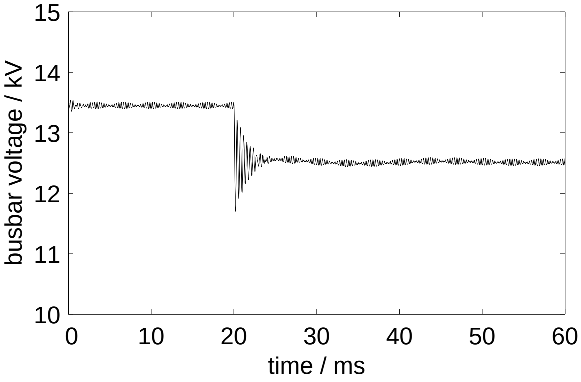

Figure 7: Saged voltage magnitude

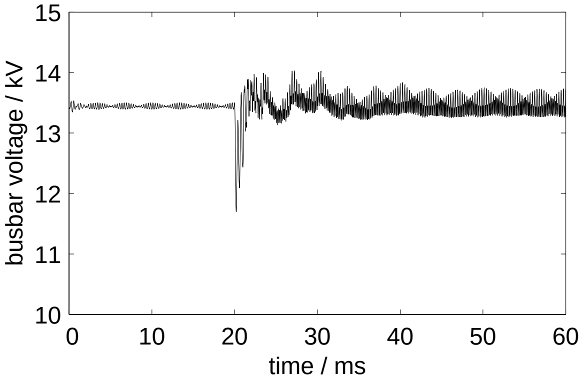

Figure 8: Restored voltage

How the DVR performs if the disturbing load, i. e. the high current laboratory, draws an unsymmetrical current can be seen in a three-phase representation of the voltages in figures 9 to 10. At the busbar the amplitude of two phases is lowered at t = 20 ms, where the voltage in the village is kept symmetrical.

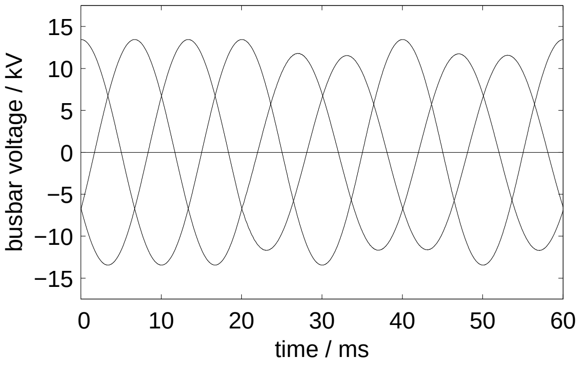

Figure 9: Saged voltage magnitude

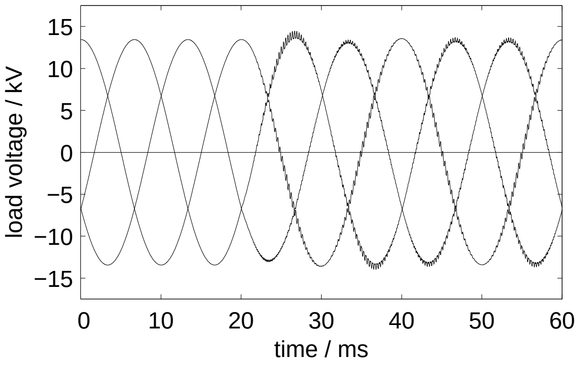

Figure 10: Restored voltage

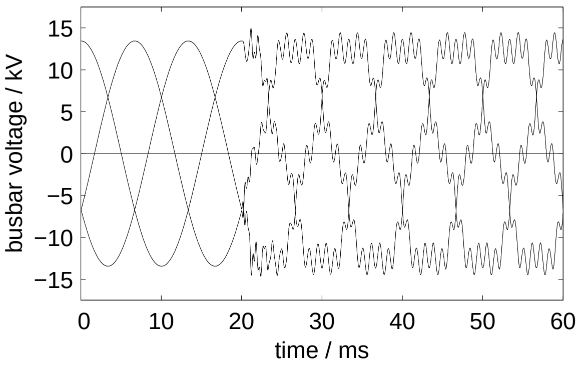

Figure 11: Harmonic Pollution

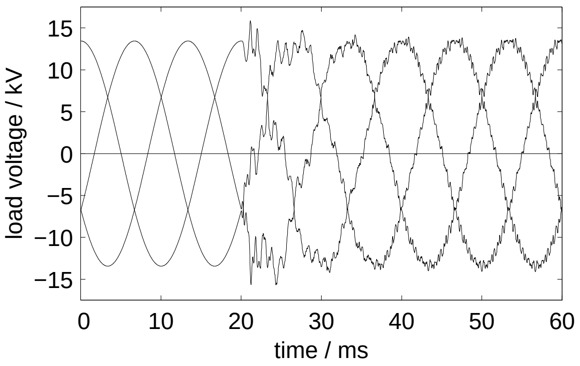

Figure 12: Removed Harmonics

In another simulation the disturbing load current consists of a 5th and 19th harmonic only. The resulting busbar voltage is plotted in figure 11. Less than 20 ms after the beginning of the disturbance the voltage in the village is sinusoidal again (figure 12). Only the higher harmonics caused by the switching of the VSI remain in the restored voltage.

7. FIRST TESTS

In the lab a first reduced set-up showed the technical feasibility of the planned installation. The voltage disturbances from almost DC up to 600 Hz have been reduced significantly, the measured THD has been reduced by a factor of four and is within the tolerated level now. Further optimisation to minimise the switching frequency of the inverter and adapt the filter characteristics to the maximal tolerated level of distortion are under work. The next step will include a pilot installation for a 1 MVA grid. With the successful completion of this pilot installation we expect to install similar devices for the remaining grid.

8. CONCLUSION

Voltage sags in a medium voltage grid can be kept away from dedicated customers using a Dynamic Voltage Restorer (DVR). This has been shown by hardware tests on a laboratory system and by simulations. Furthermore, a DVR can significantly reduce the harmonics in the customer's voltage.

As a series compensator the DVR adds an appropriate voltage to the remaining voltage in the grid. Therefore, the power rating of the DVR can be small compared to the supplied load. The active power needed for the compensation can either be taken from a storage system or from the grid.

9. REFERENCES

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