Enhancing photovoltaic systems with shortest time storage to compensate feed-in gaps caused by cloud shadows

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Abstract

As a result of the transition of energy systems towards regenerative solutions, the share of PV power will increase considerably. Voltage stability of PV systems is becoming increasingly important as the feed-in peak is during the period of peak load and short-term weather phenomena will increase as a result of climate change, here in particular cloud draught. By using short-term ultracapacitor systems and expanding these storage systems with battery and methanol storage systems, it is possible to stabilise the grid and consumer voltage even under conditions of high PV feed-in. Voltage fluctuations that occur as a result of surplus or deficit feed-in can be limited or prevented by storage systems adapted to the feed-in power.

Keywords: PV unit, weather phenomena, grid stability, ultracapacitor, batteries and power to methanol.

SUMMARY

The expansion of renewable energies, especially photovoltaics, creates new problems regarding grid stability. For this reason, new solutions for maintaining grid stability are presented here, which are combined with a description of shortest-time storage systems. Knowledge of the structure and mode of operation of short-time storage systems supports their further development and optimisation regarding their use in PV systems and combinations thereof.

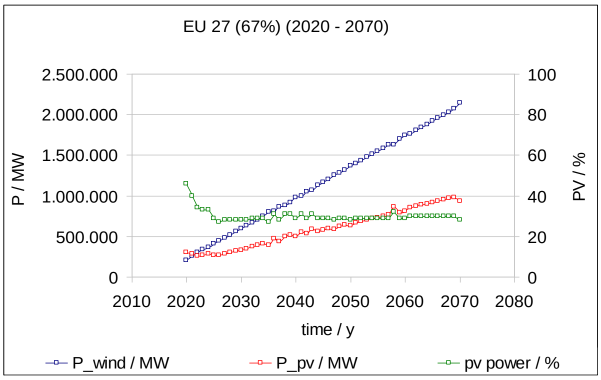


Fig. 1. Expansion of photovoltaics (932 GW; 2070) in EU27

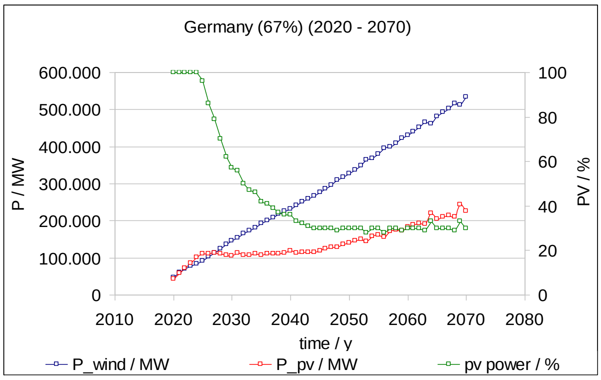


Fig. 2. Expansion of photovoltaics (226 GW; 2070) in Germany

1. INTRODUCTION

1.1 Energy transition and PV expansion requirements

PV systems use the sun's solar radiation and feed enormous amounts of energy into the connected grids in Europe, preferably in the summer months. The prospective development of PV expansion is shown in Fig. 1 and Fig. 2, starting from 2020 to 2070, using Europe and Germany as examples. The high PV expansion targets result from the enormous annual energy demand and the far too low full load hours of photovoltaics.

1.2 Climate change and weather phenomena

As a result of climate change, weather phenomena such as heat waves, hurricane-like storms, thunderstorms and increased cloudiness will occur very frequently in the near future, all of which will influence both feed-in power and consumer behaviour. While heat waves are relatively slow-moving events, hurricane-like storms, thunderstorms and increased cloudiness are short-lived events. In particular, cloudbursts, see Fig. 3, place special demands on the installed storage systems. The storage systems required here must respond extremely fast and have low losses in the case of extreme current gradients. Furthermore, the storage systems should have an extremely high number of cycles and operate in summer and winter with almost the same internal resistance.

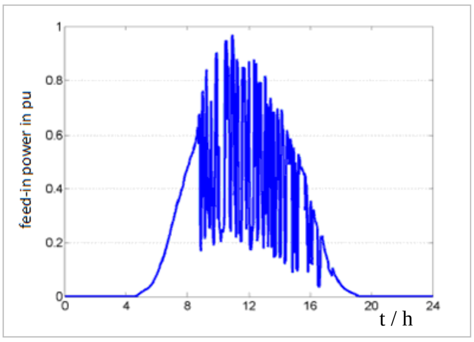


Fig. 3. Effect of clouds on PV feed-in

1.3 Impacts on grid stability

Grid stability has so far only been influenced by internal and external disturbances. Internal disturbances include switching operations. These switching operations affect generator and consumer units equally. External disturbances concern weather events, short circuits or line interruptions. While short-circuits can usually be remedied by briefly disconnecting and then reconnecting the short-circuited line, this is not possible in the case of line interruptions. Here, only redundant lines can mitigate the failure. Taking into account a changed feed situation as a result of the expansion of renewable energy generation, additional switching operations or feed fluctuations, for example due to PV systems, are added. The frequency of switching operations can lead to premature ageing of equipment such as cable sleeves (see Fig. 4) in cable networks.

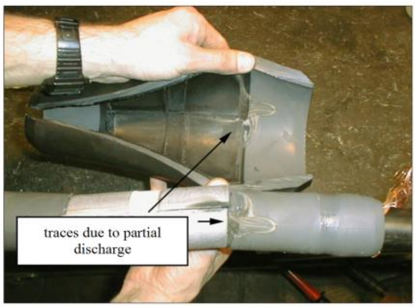


Fig. 4. Incorrectly mounted sleeve damaged by partial Discharge [1]

1.4 Storage systems

The storage of electrical energy from PV systems, see also Fig. 5, is today primarily accomplished by battery storage. Sooner or later, when grid stability plays a greater role, ultracapacitors and methanol storage will supplement battery storage. While ultracapacitors and battery storage belong to the short-term storage category, methanol storage belongs to the long-term storage category. Methanol storage units are continuous storage units that are not dependent on charging and discharging processes.

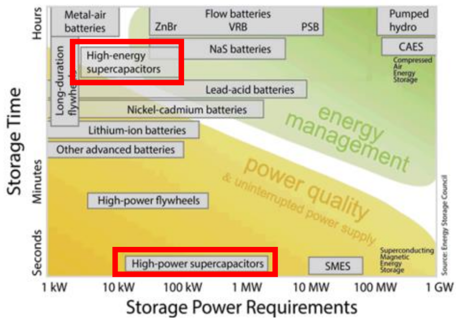


Fig. 5. Energy storage technologies [2]

1.4.1 Ultracapacitors

Ultracapacitors belong to the shortest time storage devices. Their construction is relatively uncomplicated, which is why they also have enormous long-term stability. In terms of stored energy and their charging and discharging behaviour compared to batteries, they could be considered power storage devices. Unlike batteries, ultracapacitors can store less energy. On the other hand, they can deliver the stored energy to the consumer more quickly and at much higher currents. This advantage over batteries makes them very interesting for short-term events. Fig. 6 shows the structure of an ultracapacitor.

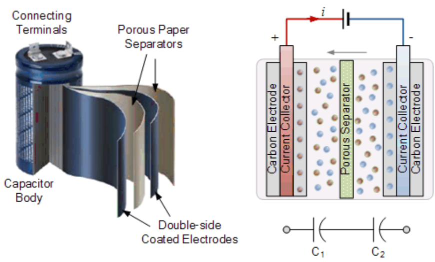


Fig. 6. Design of an ultracapacitor [3]

1.4.2 Batteries

Batteries belong to the group of short-term storage devices, see Fig. 7. It is known that batteries can achieve relatively long operating times if properly maintained and operated. This is especially true for car batteries. The use of Li-ion batteries also shows that batteries show a considerable energy density at a favourable weight, which is why they are currently being used for e-mobility applications. Nevertheless, there are specific requirements that must be taken into account. This applies in particular to voltage balancing, cell temperatures and charge / discharge management.

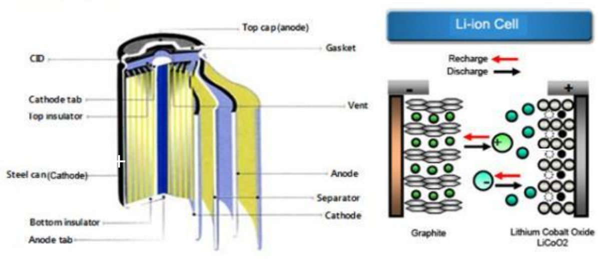


Fig. 7. Design and operating principle of a Li-ion battery [4]

1.4.3 Power to Methanol storage

With Power to Methanol, see also Fig. 8, a Power to X solution, it is now possible to store large quantities of energy. While ultracapacitors and battery storage can compensate for short-term fluctuations in the generator or consumer area, power to methanol storage is considered seasonal storage or long-term storage. Seasonal storage of PV energy becomes interesting whenever there is a very large excess supply of PV power in the upstream grid. Preferably in the summer months, feed-in power may exceed demand and the excess energy must be supplied to suitable storage facilities. Power to methanol storage take surplus electricity from PV systems and convert it into a liquid energy carrier. Methanol is now a synthetic energy carrier that can be used in many different ways. It is both an excellent fuel for all vehicles with combustion engines and a basic chemical for C1 to C4 chemistry.

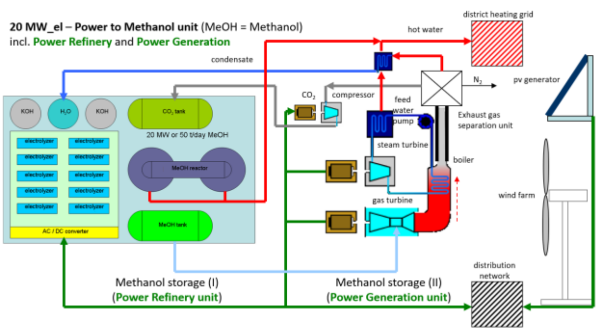


Fig. 8. Power to Methanol storage

2. PV SYSTEMS

Photovoltaic systems are largely state of the art. Their base material, silicon, is the second most abundant element available on earth after oxygen. Looking at the progress of mankind's social development, we see in many places that we are already in the midst of the information age, in which large-scale communication systems and computers have conquered our working and leisure worlds.

The use of high-purity silicon for microelectronic circuits requires large quantities of silicon. The incurring excss material can be re-used to produce PV cells thereby contributing to an efficient material flow. Photovoltaic users produce renewable electricity, which is paid for by all citizens through the kilowatt hour price. This keeps the price of microelectronic products low and enables everyone interested in information technology to purchase microelectronic products.

In the context of the energy transition, which demands a rapid expansion of renewable energies, measures must be taken to maintain grid stability. These include the use of batteries, ultracapacitors and power to methanol units.

While batteries and ultracapacitors belong to short-term storage, power to methanol storage can be grouped among long-term storage. The efficient use of Power to Methanol storage requires an additional interconnection of the energy storage units via HVDC system.

2.1 PV-unit (PVU)

Simple PV units, see Fig. 9a, consist of a PV generator and an inverter. The PV unit is connected via an inverter to the power grid or to an isolated grid with alternating current. Such units have a rated power from 5 to 50 kW. A converter connected between the PV generator and the DC busbar provides voltage matching and system control.

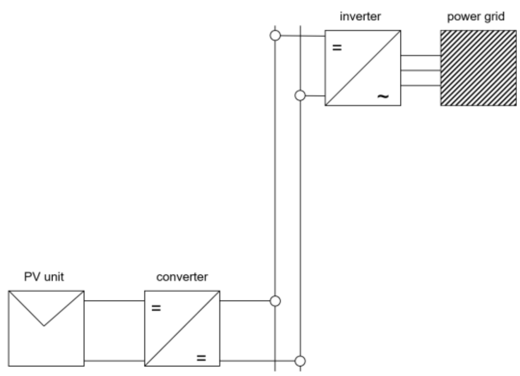


Fig. 9a. Simple PV unit without storage

These simple units are not in a position to stabilise the grid voltage. Due to the lack of storage elements, they rather contribute to risking the grid stability.

Furthermore, a large number of small units can contribute to increasing the nominal voltage above the permitted level, see Fig. 9b. The voltage increase, see Fig. 9c, at the feed-in point and the feed-back of the surplus energy into upstream grids contribute to an increased stress on the operating system.

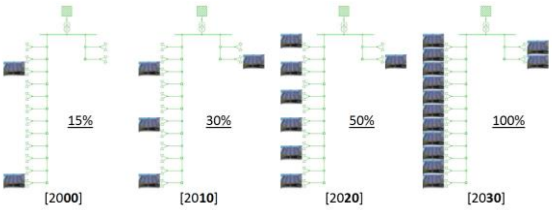


Fig. 9b. PV unit penetration

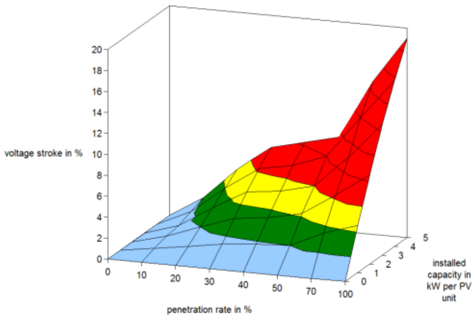


Fig. 9c. Voltage stroke

2.2 PV-battery-unit (PVBU)

The expansion of PV systems with battery storage, see Fig. 10, is always advantageous when the PV electricity cannot be directly utilized at the time of generation and must be fed into the power grid for relatively low returns. The electricity stored in the battery can be used in the evening or early morning by the owner of the PV unit. The installed battery should have a unit capacity adapted to the PV unit. Furthermore, the capacity should be related to the actual demand.

In a future grid supporting smart meter operation, the battery management can also ensure that the battery is charged or discharged depending on the current electricity price. No PV feed-in is required for this. If the PV unit owner owns an electric car, the electric car can be charged via the battery of the PV unit.

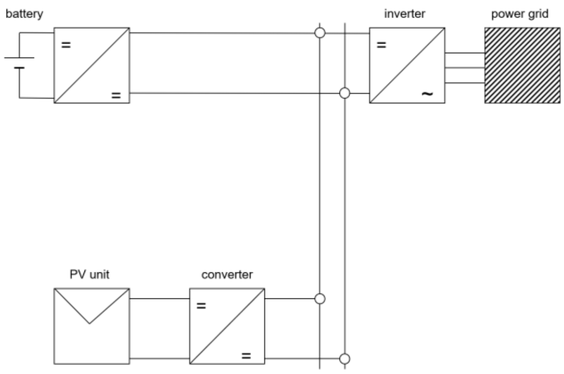


Fig. 10. PV battery unit

2.3 PV-battery-ultracapacitor-unit (PVBUU)

While PV battery units can be classified in the power range from 5 to 50 kW, PV battery ultrapacitor units, see Fig. 11, can be assigned to a power range from 50 to 1000 kW. Here, questions of grid stability play a significant role. Smaller grids would be very sensitive to voltage fluctuations due to the weather event with clouds. For this reason, ultracapacitors must react very quickly to voltage fluctuations and compensate as far as possible. The downstream battery storage is connected via a slower DC/DC converter. Only after the ultracapacitor has been fully utilized, the battery is subjected to the disturbance event and included in the voltage stabilization.

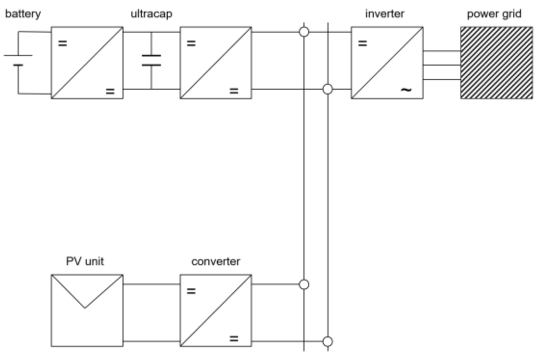


Fig. 11. PV unit with battery and ultracapacitor

2.4 PVBUU with power to methanol unit

PV units above 1 MW installed capacity can have additional storage and grid connections. The feed-in power, especially in the summer months, could be used for long-term storage of PV electricity. While surplus PV electricity can be converted into methanol during the day via a power to methanol unit, see Fig. 12, a battery storage system could ensure that the power to methanol unit does not have to be switched off immediately after sunset, but instead runs through the night at low output. In order to avoid excessive battery power for larger systems, an HVDC connection could be used to take inexpensive surplus electricity from other regions and convert it into methanol. In return, the PV battery ultracapacitor and power to methanol unit could also convert methanol back into electricity and provide grid support when the ultracapacitor and battery are no longer able to do this. The feedstock required for the storage system is provided by a recovery system. The water and CO2 contained in the flue gas are separated and stored.

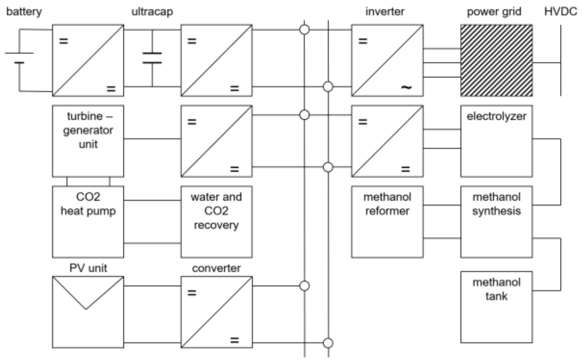


Fig. 12 PVBUU with power to methanol unit [5, 6, 7]

3. ULTRACAPACITORS

Ultracapacitors should be used in such a way that the storage capacity is utilised efficiently. Since ultracapacitors, in contrast to batteries, have a lower energy density, ultracapacitors should always be used when a short charging process is to be expected in addition to a short discharging process. Oscillations, as represented by clouds, are short-term events in which both processes take place at short intervals within seconds. The special design and physical properties of ultracapacitors make these special capabilities possible.

Whereas in batteries, for example, Li-ions are conducted from one electrode to the other by an electric field between the electrodes and must pass through a separator that protects the electrodes from a short circuit, the situation is completely different in an ultracapacitor. Here, the salt ions dissolved in a solvent, e.g., acetonitrile, are separated by a cyclic process and stored in tiny pores of activated carbon. If charging and discharging processes take place after a completed charge carrier separation, in this case cyclisation, the salt ions embedded in the pores of an activated carbon matrix move only minimally. In principle, no more charge carrier transports, here salt ions, take place within the ultracapacitor. Only the much lighter and smaller electrons are now absorbed by the ion fields within the pores of the activated carbon matrix or released into the activated carbon matrix.

3.1 Structure and mode of action

The ions enclosed in activated carbon pores with a diameter of approx. 100 nm form virtual ion electrodes. While the electrode precharged with positive ions binds electrons in its environment, the electrode precharged with negative ions binds positive holes in its environment. Since the ions no longer leave the pores, any number of charging and discharging processes can be carried out. During the cycling process, which after all involves charge separation, in this case positive and negative ions of a salt, as many electron-hole pairs are formed in the respective electrodes during cycling as it is possible for the salt ions in each electrode to bind via their field forces. While the ions remain in the pores, electron-hole pairs can form at all locations within the activated carbon matrix of the electrodes. Since their number is balanced and in equilibrium with the respective number of ions in each electrode, a shift of charge carriers from one electrode to the other can now take place by applying a charging voltage. It is interesting to note that up to half of the maximum voltage (2.5 V), i.e., 1.25 V, an almost linear charging process takes place. In the range from 0V to 1.25V, virtual ion electrodes form within the pore region, creating an additional capacitance, a pseudo-capacitance. Above 1.25V, the formation of the ion electrode within the pore spaces is completed and the virtual ion electrode now moves very slowly towards the activated carbon surface of the pore. Shortly before reaching the maximum charging voltage (2.5V), a limit is reached where no further approach to the activated carbon matrix is possible, and the ions are pushed into each other. These processes, nearing and concentration, also result in the formation of pseudocapacities. This process is exemplified by a simulation of the ion distance from a fictitious activated carbon surface in Fig. 13b. Here it can also be seen that after a stagnation of the approach process, a concentration process presumably takes place, whereby the distance increases somewhat. If further charge carriers are added via a charging process, the distance decreases again.

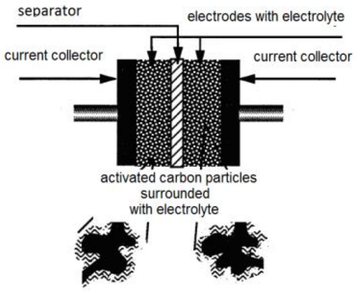


Fig. 13a. Ultracapacitor assembly

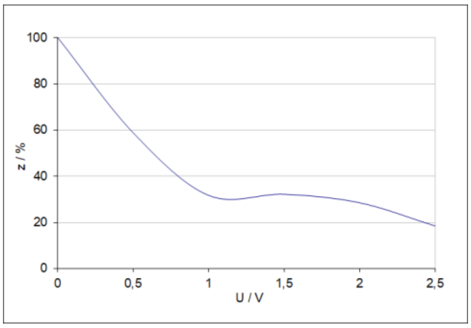


Fig. 13b. Simulation of the ion distance from a fictitious activated carbon surface and the formation of the pseudo-capacitance during the charging process (e.g.: z = f(U) in % starting with initial distance of 100 %)

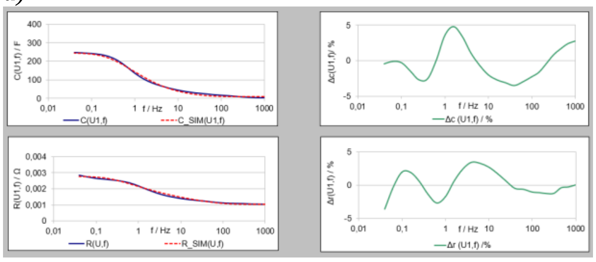
Fig. 13a shows the basic structure of an ultracapacitor. It consists of a current collector, activated carbon surrounded by electrolyte and a separator.

3.2 Modeling

The modeling is based on the idea of generating large surfaces, which correspond to the well-known capacitor plates from physics. If we try to make a reference to biology, we could imagine that large surface areas could be created, for example, by pyrolysis of wood. If the question is asked, how do trees grow, two interesting stages of development can be observed. While young trees show almost linear growth, older trees grow exponentially at a certain stage of development. Since these growth phases can also be transferred to the fruits of the trees, linear and exponential growth take place here within a few weeks. For example, in a coconut there are shell sections from linear and exponential growth phases. While shell sections from a linear growth phase have small surface areas, the surface areas from the exponential growth phase are very large. Using this knowledge for a new and interesting technology, natural raw materials can be used to achieve interesting physical effects. Activated carbon produced in this way has enormous surface areas within the existing pores. Fig. 14 shows an activated carbon layer on a current collector with a film thickness of s = 150·10^-6 m and particles with a diameter of d_{Pa} = 15·10^-6 m. The particles obtained via pyrolysis have macro-, meso- and micropores. The largest pores have often a diameter of d_{Po_max} = 100·10^-9 m and the smallest of d_{Po_min} = 10·10^-9 m.

Due to the consideration of an exponential growth, model equations also result for the capacitors examined here, which take this special feature into account. Using exponential growth functions, parameters can now be determined that describe both the situation in the capacitor and the behaviour of the capacitor within an electrical or electronic circuit. It is of great interest that the deviations of the impedance spectra from the model and the original are as small as possible, see also Fig. 14a) and 14b). The method used here varies the parameters of the growth functions step by step until an optimal model has been found with minimal deviations.

a)



b)

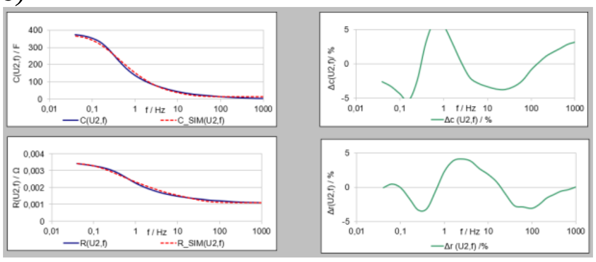
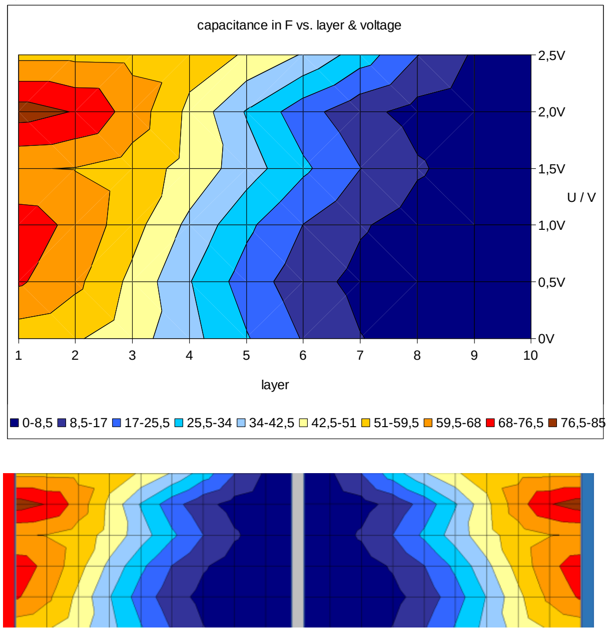


Fig. 14. Capacitance and resistance spectra of an Ultracapacitor and associated relative errors for
a) U_1 = 0V and
b) U_2 = 2.5V

The capacitance and resistance distribution within one of the two almost identical electrodes of an ultracapacitor, see Fig. 15, clearly shows that during the charging process of the ultracapacitor there are changes within the activated carbon matrix or the activated carbon particles. While almost no changes can be detected in the higher layers, there are significant changes in the lower layers near the current collector. Since most of the salt ions have been absorbed into the particle pores here, the ions react very sensitively to the applied voltage and the influx of charge carriers, in this case electrons. In particular, in Fig. 15a) it is noticeable that in the lowest particle layers the capacitance increases continuously up to 1.25V, then remains unchanged, and then gradually increases again. These effects, which can be attributed to the pseudocapacitance, presumably take place within the particles and there in the pores. If the resistance spectrum is consulted, it is noticeable that a considerable increase in resistance takes place in the deeper-lying particles in the region of the maximum charging voltage. This increase in resistance in combination with a slight drop in capacitance indicates that shortly before the maximum charging voltage is reached, there are less freely moving electrons available in the activated carbon matrix, which can explain the increase in internal resistance, see also Fig. 15b) a)



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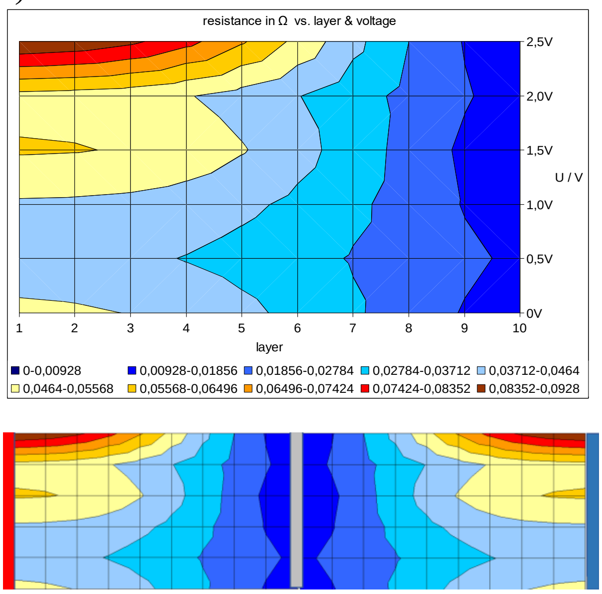

Fig. 15. Capacitance a) and resistance b) distribution as a function of the number of layers n=10 and the charging voltage U=[0...2,5]V

3.3 Simulation

Based on the capacitance and resistance distributions from the ultracapacitor parameter determination, a simulation model can now be created. The simulation model is subjected to a charge and discharge test and the results of the simulation are compared with a measurement on the real ultracapacitor. These tests are demonstrated here using a 1F ultracapacitor as an example. An optimum number of layers of n=10 particle layers was also found for the ultracapacitor used, see also Fig. 16.

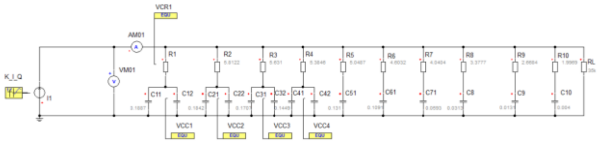

Fig. 16. Simulation model of a 10-stage RC model for a 1F ultracapacitor [8]

For the parameterization of the 10-stage model, 2 x 20 parameters were taken from the ultracapacitor parameter analysis and preset according to the required voltage control.

To validate the ultracapacitor parameters, an original ultracapacitor is charged and discharged with a suitable measuring system. The charging and discharging currents as well as the charging and discharging voltages are measured, recorded, stored and displayed graphically, see Fig. 17 and 18.

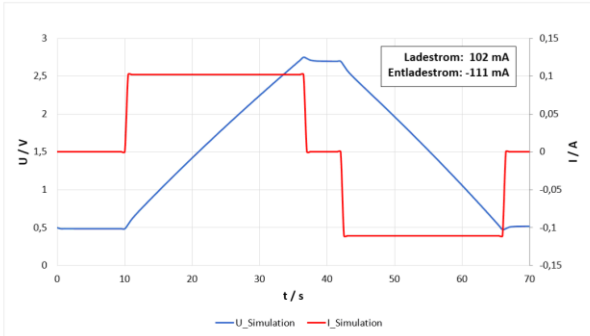

Fig. 17. Simplorer simulation of charging and discharging a 1F ultracapacitor using the ultracapacitor equivalent circuit shown in Fig. 16

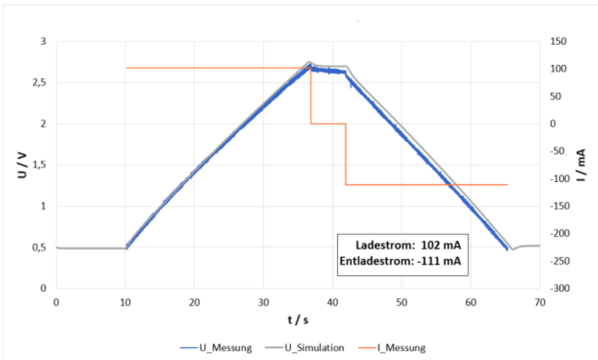

Fig. 18. Comparison of simulated and measured charge and discharge voltage

As can be seen in Fig. 18, the simulation and the measurement of the charge and discharge voltage is well matched. From this it is concluded that the method used to determine ultracapacitor parameters, see Fig. 14 and 15, is correct and that the actual physical conditions within the electrodes have been correctly described.

In this way, a new and innovative method was presented and verified that allows both the description of electrode processes within the activated carbon matrix of an ultracapacitor and the dynamic simulation of an ultracapacitor on the basis of an ultracapacitor parameter determination.

The advantages of the method are to find out new knowledge about the internal ultracapacitor processes. Furthermore, the materials used and their efficiency can be optimised.

With regard to the application of ultracapacitors to compensate grid instabilities caused by fluctuating feed-ins from regenerative energy generation systems, it is now possible to generate very accurate equivalent circuits for ultracapacitors.

Using the equivalent circuits, a wide variety of weather scenarios and the effectiveness of the ultracapacitors can be investigated.

4. RESULTS

The decline of fossil energy sources requires a rapid expansion of renewable energies. While wind energy provides annual full-load hours significantly higher than those of photovoltaics, the feed-in from the latter is better tuned to the demand over the day. Furthermore, photovoltaics can be installed close to consumers, as the operating conditions do not have a harmful effect on humans and animals.

However, the installation of photovoltaic systems close to the consumer also means at the same time that the supply systems must not be stressed additionally by photovoltaic systems. Serious problems occur when enormous back-feeding takes place, for which the existing supply systems are not designed.

Furthermore, weather phenomena such as heavy cloud cover can occur more frequently in conjunction with other harsh conditions due to climate change. This is currently being discussed very intensively, as it can lead to an additional stress on the energy supply systems as a result of switching operations.

While a few photovoltaic systems do not pose any problems for the power grid, a clustered installation of photovoltaic systems leads to a significant voltage increase in the consumer area.

Based on these challenges, this paper described what storage solutions could look like to fulfil long-term objectives.

4.1 Internal voltage stabilisation

New storage solutions for photovoltaic systems require measures that contribute to both internal and external voltage stabilisation.

Only when it has been ensured that internal voltage stabilisation is guaranteed can external voltage stabilisation also take place.

The storage systems to be used must therefore be designed for both internal and external requirements.

While smaller systems can be equipped with ultracapacitors and batteries with little effort, larger systems require more attention in terms of internal and external compliance with supply stability.

Photovoltaic systems in the higher power range must be kept connected to the grid under all circumstances to avoid supply interruptions.

Power-to-methanol photovoltaic systems provide long-term storage for electricity, heat and fuel supply to residential areas, hospitals, airports and other consumers, even as stand-alone solutions.

4.2 External voltage stabilisation

With the expansion of renewable energy generation, fluctuations within the supply grids will increase and, under certain circumstances, critical supply situations will occur when either too much or too less energy is available. In this context, PV systems with storage could take on a grid-supporting function. This requires the use of storage in PV systems.

The concrete contribution to grid support results from the installed storage systems and their characteristics.

Furthermore, it is assumed that powerful high-voltage direct current transmission systems will be used, which also provide night-time electricity from wind energy. This night-time electricity could be stored by PV systems with storage and used for long-term storage of electricity in methanol.

In addition, PV systems with storage could help supply the industry with basic chemicals, in this case methanol.

5. OUTLOOK

The expansion of renewable energies requires the simultaneous expansion of short- and long-term storage. The efficient use of renewable energies is only possible through the use of storage. Shutdowns of renewable energy producers mean losses in sustainability and economic success.

The use of ultracapacitors can help to remedy the fluctuations generated by renewable energies and make renewable energies stable sources of energy supply.

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