On the properties of stochastic power sources in combination with local energy storage

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(Revised version, 21.4.2005)

***Index Terms*— stochastic sources - energy storage technology - time constant - availability - round cycle efficiency - forecast**

I. Introduction

Compared to traditional generation schemes, renewable energy sources show two significant operational disadvantages, namely the stochastic power production and the relatively low amount of full load hours. For many years, the installation of energy storage devices at the point of the stochastic infeed has been considered as viable option to attenuate these negative effects. First considerations about the technical implications, which can be expected when combining stochastic sources with storage devices, have been published in the 1970s (e.g. in [1]), whereas the ongoing liberalisation processes have stimulated further studies, also incorporating economical issues (as published e.g. in [2], [3] or [4]). This publication presents an investigation where the existing discussions are extended to some technological aspects of energy storage devices (ESDs), which are suitable for this purpose. In order to find optimal ESD ratings and technologies - depending on the stochastic source to be supported - the mentioned flaws are approached from a theoretical level, showing that even highly simplified modelling procedures help to gain insights. In this study, the system consisting of stochastic source and energy storage device is primarily used to follow a defined load. It must be noted that here the task of the ESDs in the present study is load levelling, which includes relatively long term energy storage. Further benefits which can be achieved with local storage devices, as e.g. local voltage control, short term bridging, power quality support, etc. are not considered. Fig. 1 shows the principal configuration of the stochastic source and the ESD with respect to a load (a single load or a grid with a given "power requirement") and the degrees of freedom in the configuration of the model which were used by the authors.

II. Elements of the simulations

A. Stochastic sources

Two different cases for a stochastic source were looked at: Measured data from a large photovoltaic (PV) plant

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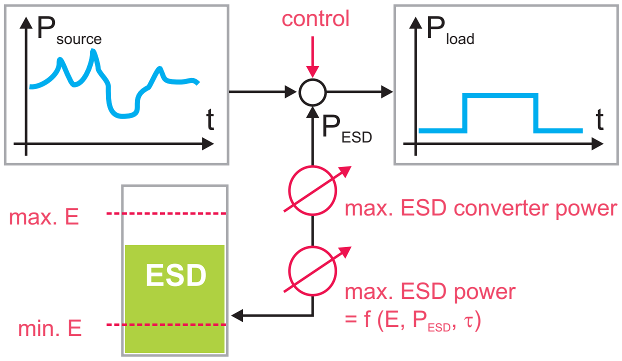

Fig. 1. Principal configuration under investigation. The stochastic source is assisted by an ESD in order to be able to meet the demanded load profile. In the simulations, the principal design parameters of the ESD as well as the control strategy were subject to variation.

and synthetically generated power data from a hypothetical wind energy conversion system (WECS) of the same nominal power. The PV plant data was supplied by an academic partner of the authors' institution ([5]); the sample width Δt is 5 minutes, which means 105120 power values for the regarded year.
For the synthetic WECS, a standard algorithm for the generation of data out of a given weibull distribution was used, in which the mean wind speed was assumed to be 8 m/s and the shape factor was $k = 2$. The sample time was 1 hour in this case. The wind speed was then transformed into electrical power by a wind turbine characteristics given by a cut-in wind speed of 4 m/s, a nominal wind speed of 12 m/s and a cut-out wind speed of 25 m/s. The power between 4 and 12 m/s was assumed to follow a cubic function, indicating a variable speed generator featuring C_p-tracking.

B. Storage technologies

For energy storage technologies, there are basically four different properties which can be regarded to be important with respect to utilisation and technical implementation: The minimum and maximum energy content and the minimum and maximum power that can be transferred into or out of the ESD. Any storage technology can be reduced satisfyingly accurate to one of the three basic storage technology types, namely kinetic, capacitive or potential ESDs, which are different in their time-dependent behaviour during charge and discharge. While a kinetic ESD (e.g. a SMES or a flywheel) is not limited in its discharge power and the standby losses are not zero, a capacitive ESD (e.g.

a bank of supercaps or a surface mounted compressed air storage tank) is limited by its intrinsic primary loss mechanism during discharge, but shows very low standby losses if designed well. The available power of a potential ESD finally is by nature almost independent of the energy charge state, (e.g. pumped hydro plants or battery storage installations)[1], but the maximum deliverable power again is limited by the loss mechanism. Therefore a simulation program capable of looking at all of those properties is able to calculate the losses and thereby the instantaneous efficiency of the ESD with respect to the energy charge state and the technological implementation. For a simulation time step of $\Delta t = t_2 - t_1$, the energy E_2 at $t = t_2$ can be calculated by

$$E_2 = E_1 - P_{ESD} \cdot \Delta t - E_{loss} \quad (1)$$

where E_1 is the energy content at $t = t_1$ and E_{loss} is the energy lost during the time interval Δt. Since the premise of time discrete simulation of ESDs is a constant terminal power P_{ESD} during Δt, a good measure to improve the calculation accuracy of E_2 is to solve the differential equation for the energy $E(t)|_{t_1 \to t_2}$ and calculate the loss energy accordingly. The loss energy therefore is a function of the (constant) terminal power, the time constant of the ESD and the time step:

$$E_{loss} = f(E_1, P_{ESD}, \tau, \Delta t). \quad (2)$$

This approach makes use of technological properties of ESDs on the utmost theoretical level and in fact introduces variable charge and discharge efficiencies depending on the actual energy content E, the terminal power P and the technological implementation, or, strictly spoken, the quality of the technology, represented simply by a time constant. Similar theoretical approaches for the classification of ESDs were already formulated in [6], [7] and [8], but not applied to stochastic power signals for the extraction of additional information on long-term losses and system availability.

C. Control strategies

Two control algorithms for charge and discharge were applied in the simulations, namely one simple strategy which uses information on the instantaneous technical power limits only and another one capable of looking into the future development of the source power for a short period of time:

1) The control strategy in standard operation is a straightforward procedure: The demanded load power is compared to the instantaneous source power, and the difference between the two is fed into or extracted out of the ESD. If the demanded P_{ESD} violates the power limits of the ESD (dependent on the energy charge state and converter power limits), P_{ESD} is reduced to the maximum possible value. This holds true for positive as well as for negative values of P_{ESD} and is done for each time slot. The loss energy is calculated according to analytical solutions of the differential equation of the respective ESD type (equ. 2) and out of this the energy content after the time step Δt follows according to equ. 1.
2) The second aspect which was looked at is the possible impact of a WECS/PV power forecast on losses and availability. The implementation of the sensitivity analysis is done in the following way: Each day of the year at the same time (in this case 00:00), the data of the following 72 hours is taken out of the time series and manipulated. This manipulation includes scaling of the values of the wind speed or the PV power with gaussian distributed noise, the standard deviation σ of which is increasing non-linearly with the third power of time. This model therefore accounts for relatively good forecast quality for the following day and rather bad quality for the 2nd and 3rd day. It must be noted at this point that these values for σ are estimated values without theoretical background, since at present the related literature covers absolute values for the power prediction error only [9]. However, the aim of this work was rather to find estimates for the sensitivity of the system relatively to good or bad prognosis models. These manipulated vectors are then used in an algorithm which determines whether the demanded power can be fed into the system during the next three days, or, if it cannot, to which value the load power would have to be be resized. The goal of this algorithm therefore is to use information on the short-term development of the source power to maintain the infeed window at the desired value (i.e. to feed power into the load during the time window a under all circumstances). The value of such considerations is to find answers to the question if a good prognosis technique can turn a non-dispatchable, stochastic source into a deterministic generator by virtue of an additional energy storage device and an accurate prognosis technique. Fig. 2 shows the development of the infeed power with knowledge of the next 3 days. It can be seen that around day n+3 the power is reduced in order to maintain the infeed window. This perspective seems to be of particular interest, since the value of a production site in an arbitrary system increases with increasing capability to contribute *proportionally* to the daily system load.

D. Load profiles

The load profiles were selected to be rectangular shapes centered around 12:00. Variation of the duration between 3 and 24 hours (the latter case would imply constant demanded infeed around the clock) were made. The duration (here designated as the load window a) is the fixed value.

[1] It must be noted that there exist very good and sophisticated models for the detailed representation of the dependence of effective energy content on the discharge current of battery systems, however for the sake of simplicity they are not used in the estimation procedure presented here.

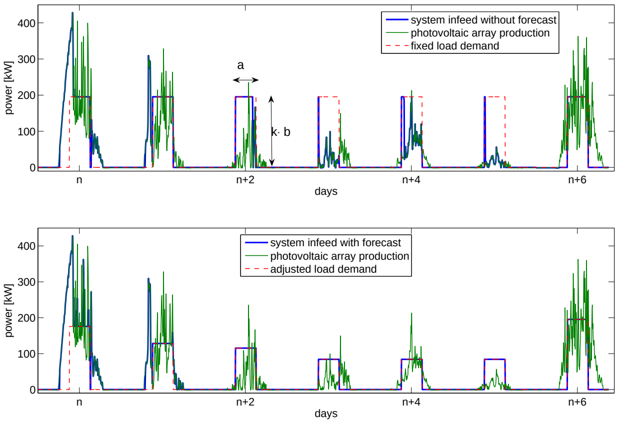

Fig. 2. Comparison between actual system infeed without forecast (top figure) and with forecast (bottom figure). The load window duration a and the load power value $k \cdot b$ define the daily energy demand.

The annual average energy produced by the source per day is $\sum P_{source}\Delta t/365$, therefore the initial power value of the load window would be $b = \sum P_{source}\Delta t/365a$. Since this holds true only for a lossless ESD, an additional scaling factor of $k = 0.8$, representing the overall efficiency of the ESD during one year, was introduced in the simulations. A straightforward determination of this value is not possible in all cases, even with knowledge of all data and model parameters since an optimisation algorithm may produce multiple optima. Suited algorithms for more accurate determination of k will be defined in future work.

III. Interpretation of the simulation results

A. Losses

Since the models discussed in the present paper include the principal loss mechanisms of ESDs, a central question was if the losses would vary greatly for different storage technologies but equal maximum and minimum energy contents. The answer is that they do indeed; the reason is the difference in the mode of operation. Kinetic ESDs always show standby losses while capacitive and potential ESDs do not necessarily. Even using rather optimistic time constants for kinetic ESDs (in the range of some hours) and taking really pessimistic time constants for the other techniques (in the range of some minutes including the losses in the conversion equipment) led to the result that the overall losses of kinetic ESDs for load levelling of stochastic sources are considerably larger than for the other basic energy storage techniques. A simple interpretation is that we face a typical long term storage situation, where a high level of stored energy means increased availability and security of operation. Unfortunately, the instantaneous losses of a kinetic ESD are related to the energy content E via $P_{loss} = 2E/\tau$ and are independent of the terminal power. The conclusion which could be drawn from the loss inspection was that only kinetic ESDs of extremely high technological quality can reach the same energetic performance and round-cycle efficiency as do comparable capacitive or potential ESDs.

The round-cycle efficiency is a value which is often used to classify ESDs. Here, it was calculated by

$$\eta_{rc} \approx 1 - \frac{\sum E_{loss}}{\sum P_{ESD,\ charge} \cdot \Delta t} \approx \frac{\sum P_{load}\Delta t}{\sum P_{source}\Delta t} \tag{3}$$

It must be mentioned that this number depends not only on the efficiency during charge and discharge, but also on the average time the energy remains in the ESD. This fact produces unexpected figures of the effective round-cycle efficiency of different ESDs when compared with the same data and has - to the best of our knowledge - not yet been investigated.

The number of virtual round-cycles of the ESDs was investigated as well according to the following condition:

$$vc \approx \frac{\sum \mid P_{ESD} \mid \cdot \Delta t}{2E_{max}} \tag{4}$$

It could be shown that the number of virtual round-cycles does not depend a lot on the technological implementation of the ESD.

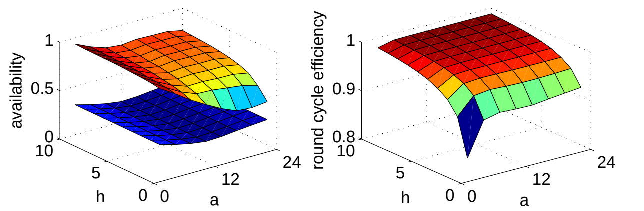

Fig. 3. Example for a simulation result of the following configuration: Source: PV, ESD capacitive: τ=0.3h, $E_{min} = 0.5 \cdot E_{max}$. The surface plot on top (right side) shows clearly the influence of the presence of the ESD on the availability. The round cycle efficiency shows deep values especially for low values of a and low maximum ESD energy contents. The parameter h designates the maximum energy content of the ESD via $E_{max} = h \cdot P_{ref}$, where $P_{ref} = 500\ kW$.

B. Availability

The availability of the system source/ESD was investigated due to the usual criteria and compared to the properties of the stochastic source alone, without ESD. The availability was defined to be 1 if

$$P_{source} + P_{ESD} \geq P_{load}, \tag{5}$$

otherwise it is 0 (this index could in further studies be extended to a multi-state model in order to get deeper insight). In operation, this value is zero in case that the deliverable power from the non-ideal ESD cannot fill the gap between the source power and the demanded load power. This is the case when the ESD is empty at this point in time, or when the power limit of the converter is violated. For the time window operation, when power should be fed into the load only for a period of time each day, this availability index can be extended to the definition to be 1 in case that

$$P_{source} + P_{ESD} \geq P_{load}|_{P_{load}\neq 0}. \tag{6}$$

This definition is somewhat stricter, since the times where no power is demanded are not regarded any more.

C. Variables in the simulations

1) Maximum converter power: The maximum ESD converter power affects mainly the availability for low values of a adversely. This is logical and due to the fact that the demanded power is then in some cases not limited by the physical limits of the ESD but rather by the power limit of the converter.

2) Minimum ESD energy content: This parameter is crucial for the losses and therefore the round-cycle-efficiency of capacitive ESDs. For potential and kinetic ESDs, it has little influence on the result. The lower the minimum ESD energy content is, the higher becomes the availability of the ESD, therefore raising its usefulness.

3) Differences between wind power results and PV results: The tendency shows that the maximum ESD converter power affects the availability of a wind power system more than the availability of a PV system, which is partly due to the fact that the load curves are centered around 12:00. PV availability without ESD shows minimum values for a around 10 h, an effect which is attenuated by an ESD. Generally spoken, the results for all inspected values except availability with and without ESD do not differ a lot between wind power and solar power as stochastic source.

4) Influence of a 3-day-forecast: A general statement about the influence of forecast techniques is that the quality of the forecast affects the overall results to a lesser extent than was assumed before the investigation. The reason is the maximum storage time h of 1 to 10 hours, which is relatively short in relation to a 72-hours forecast. In other words, the first, relatively well forecasted day "helps a lot" in improving the availability performance of the system. Another aspect has to be mentioned at this point: for a forecasted system with a fixed demanded power value b, the availability will be falling in any case due to the definition of availability. If the demanded load power is redefined to be the resized original power, the availabilities can reach values above 0.9 over a wide range of parameters for a and h.

IV. Conclusions

- Energy storage devices can be used for load levelling of stochastic sources to a certain extent. However, turning a stochastic source into a deterministic one is possible only with large amounts of locally stored energy (in relation to the energy produced at this site).
- Capacitive and potential ESDs are better suited for this application than kinetic ESDs when overall losses and overall system availability is the criterion.
- Short term forecasting of the source power is valuable only if the availability is defined via the forecasted optimum value for b. This is dependent on the market and power dispatch environment.

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V. Summary

The influence of the choice of the energy storage technology and its control on the overall losses and availability for the load levelling of a stochastic source is presented. The investigation includes choice of preconditions for the stochastic source power, the modelling of general energy storage devices using values for power, energy and time constants only and the definition of two fundamentally different control strategies to fulfill the load requirement. The load is an arbitrary system load of constant value during a fixed period of a day. With this approach, sensitivities of technical implementations, choice of power and energy limits for the energy storage device and load requirements were detected and isolated in a large number of simulations. The results indicated that a complete transformation of a stochastic source into a deterministic generator is only partially possible. Forecast technologies and a flexible market environment could however boost the availability of such a configuration.