"Value of Storage Devices in Congestion Constrained Distribution Networks"

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Value of Storage Devices in Congestion Constrained Distribution Networks

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Abstract— **This paper investigates the value of storage devices in congestion constrained distribution networks. Subject of the investigations is a load which cannot be supplied with the desired security at all times during the day. It is analyzed what the requirements would be if a storage device would be installed at the load bus instead of network reinforcement. To compare these two possible solutions, the implications on the load flow, including loss reduction and the possibility of local voltage control, are investigated. Furthermore the availability of a system with three lines is used to determine failure and repair rate requirements for a storage device. Finally some general economical considerations are outlined.**

I. INTRODUCTION

In the recent years some installations of large storage facilities have taken place [1], [2]. Usually, these storage devices have been installed to either ensure the power quality for sensitive industries or to bridge supply interruptions of a few minutes. Utilities and companies are hence starting to recognize and also to use storage devices as an option to enhance supply quality and reliability. In this paper it is investigated if the installation of a storage could be a realistic alternative to a network enhancement.

The focus of the study lies on a small system, consisting of a commercial load which is connected to the grid through two parallel identical lines. Thus it is a typical configuration found in distribution systems where the load is supplied with an 'n-1' redundancy. The 'n-1' criterion is based on the assumption that the load demand is always below the maximum capacity of a single line. However it is assumed that the load has recently been increasing significantly due to new buildings, and the power demand starts to exceed the maximum capacity of one line at certain times during the day. If during such a high peak period one of the lines would fail, the load could not be further supplied since the remaining line could not be overloaded for the time needed to repair the damaged line or until the load demand falls below the line capacity again.

The standard solution to this problem would be to either replace the existing lines by two stronger ones or to add a third identical parallel line, immediately doubling the margin for the 'n-1' criterion, and actually resulting in a 'n-2' security during non peak times. However, in cities where the described situation could—and eventually more often will—be found, it is a difficult and costly task to install a third line. In a liberalized market, where customers are more cost and service sensitive, such an installation could be regarded as disproportionate, considering the third line as a standby component, particularly if the load was non-critical.

As several technologies for the storage of electrical energy are maturing and as the mentioned installations of larger storage facilities show, the possibility to locally install a storage device becomes realistic and could offer an interesting alternative. The storage device would be dimensioned in a way that it could supply the difference between the load demand and the feeder capacity in case of the failure on one line. Furthermore, if no line outage occurs, the stored energy can be used to shave peaks and reduce losses on the feeder during high peak times. If the device is installed in a network with different tariffs, it even allows a reduction of operational costs by charging the device during low price times. A further argument for investing in a storage device is its modularity, allowing designing the dimensions to cover demand increases for only a limited time, as later a second device could be installed at the same location.

In order to find out which of the two suggested solutions is the more favorable one—even without reliable operation data of existing storage devices—the following points are investigated:

- influence on and changes in the load flow behavior of the feeder, due to
  a) the possibility to reduce the load power peaks and
  b) the possibility to reduce the network losses either through reduced power flow and/or through local voltage control,
- influence on the supply reliability, by
  a) examining the existing supply availability,
  b) examining the availability with a third line,
  c) and by determining failure and repair rate requirements for storage devices in order to be competitive.
- estimation of the costs to be expected for both solutions, including
  a) planning, rights of way and installation costs,
  b) operation and maintenance costs

The aim of this study is to find out whether a storage device could be an alternative to a third line in general. Thus, technology dependent details as the dynamic behavior in the different operational states or trickle charge demands of a storage device are neglected in order to focus on fundamental energy and power consideration.

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II. System Layout

The investigated system is a part of a distribution network and consists of a commercial load which is connected to the grid by two identical lines in parallel. As the load demand will exceed the capacity of one line at certain times during the day, it is necessary to enhance the existing system in order to guarantee an all-time redundant supply of the load. The investigated enhancement options are either the installation of a third line or the installation of a storage device at the load bus, depicted in figure 1a) and 1b), respectively.

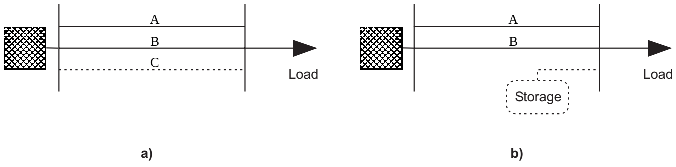

Fig. 1. a) Existing system plus third line. b) Existing system plus locally installed storage device.

The load curve has been derived from measurements at a commercial load. The curve was however scaled in order to represent the load behavior of a recently developed commercial area which is connected to the grid through one feeder, thus not offering the possibility to build an open ring solution. The load is represented as a quarter-of-an-hour load curve showing the peak power demand for each period of fifteen minutes (fig. 2). The load ranges between a maximum of P_{load}^{max} = 12.11 MW and a minimum of P_{load}^{min} = 5.38 MW, with an average power demand of P_{load}^{avg} = 8.72 MW. Figure 2 shows also the capacity of each of the two 16 kV VPE-cables, which is P_{line}^{max} = 11 MW. The time, during which the maximum capacity is exceeded by the load, such that 'n-1' security cannot be guaranteed, sums up to a total of 7.75 hours (see the load duration curve in figure 3).

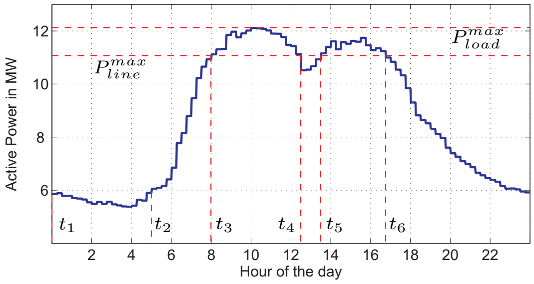

Fig. 2. 15-minute averaged power demand curve for a workday. The dashed line showing the capacity of one feeder at 11 MW.

III. Load Flow Considerations

A. Peak Shaving

A local storage device can be used to shave load peaks according to different objectives such as technical, economical and/or reliability [3]. This paper focuses on peak shaving due to both reliability and economical requirements whereas the former is implicitly related to a technical issue.

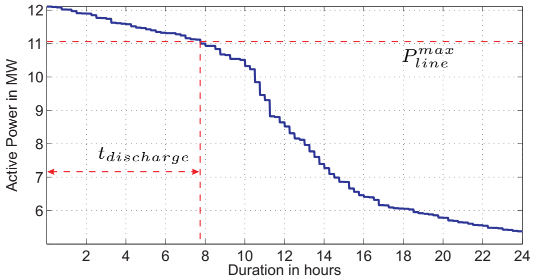

Fig. 3. Load duration curve for one day. The intersection between the line capacity and the curve corresponds to the amount of hours, during which the load is not redundantly supplied.

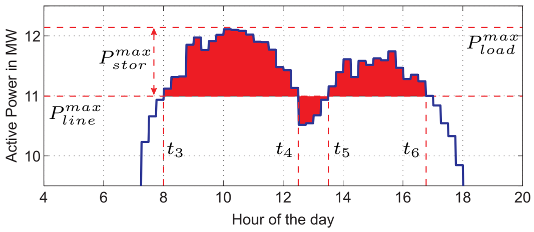

Fig. 4. Load curve, focus on critical area.

The reliability objective is valid as long as the storage is intended to provide power in order to reduce the line power flow. The necessary condition for 'n-1' security is that the line power flow P_{line} does not exceed the line capacity P_{line}^{max}:

$$P_{line} \leq P_{line}^{max} \tag{1}$$

The power rating of the storage P_{stor}^{max} can be derived from this condition. The storage has to deliver the difference between the maximal power demand P_{load}^{max} and the maximal line power flow P_{line}^{max}:

$$P_{stor}^{max} = P_{load}^{max} - P_{line}^{max} \tag{2}$$

This is the power rating of the storage device that arises from the reliability requirement. The energy rating has to be computed as the cumulated energy during the time when the storage delivers power to the load. Note that during the load peak in figure 4 the load power falls below the line capacity for a certain time. This area can be used to charge the storage until the line limit is again exceeded. By doing so, the amount of energy required to be stored can be reduced.

The second objective is an economical issue and concerns the charging period of the storage. The aim is to minimize energy costs according to a tariff signal. Nighttime-produced electricity is commonly available and should be used to fill the device. The storage is charged during nighttime tariff period lasting from t_1 to t_2 (see figure 2). Assuming such a fixed time interval where the storage has to be charged completely leads to another requirement concerning the storage power rating.

Hence two requirements concerning the storage power rating arise. The first one comes from the maximal power the storage has to supply during the load peak, the other one comes from the necessary storage energy which has to

TABLE I

RESULTING STORAGE DATA.

Quantity	Value
Line capacity	$P_{line}^{max} = 11$ MW
Load peak	$P_{load}^{max} = 12.11$ MW
Max. storage power	$P_{stor}^{max} = 1.11$ MW
Max. storage content	$E_{stor}^{max} = 4.55$ MWh
Storage efficiency	$\eta = 0.70$
Charging energy	$E_{stor}^{char} = 6.5$ MWh
Charging time	$t_{char} = 5.86$ h

be accumulated during the low tariff period. In this paper, emphasis is put on reliability, hence the power rating is only determined from the maximal power the storage has to deliver. Consequently, the charging period may exceed the low tariff interval.

The energy rating of the storage is calculated by integrating the desired power over the time:

$$E_{stor}^{max} = \int_{t_3}^{t_6} P_{stor} \cdot dt \tag{3}$$

whereas the storage power has to compensate the line overload

$$P_{stor} = P_{load} - P_{line}^{max}. \tag{4}$$

E_{stor}^{max} is the energy the storage has to deliver during the peak shaving period.

As mentioned it is assumed that the storage has a certain efficiency $\eta < 1$ what results in a charging energy higher than the delivered energy:

$$E_{stor}^{char} = \frac{E_{stor}^{max}}{\eta} \tag{5}$$

E_{stor}^{char} is the energy that is consumed from the storage during its charging, E_{stor}^{max} is the content that is stored after the charging period. The length of the charging period can be calculated from the energy requirements:

$$t_{char} = \frac{E_{stor}^{char}}{P_{stor}^{max}} \tag{6}$$

The results for the necessary power and energy rating of the storage due to the peak shaving requirements are shown in table I and figure 5.

B. Loss Reduction

It has been shown that the utilization of distributed energy resources influences network losses [4], [5]. Since line losses are proportional to the line current squared, they can be reduced by levelling the line power flow curve. This can be achieved with peak shaving as described in the previous paragraph.

Line losses can be minimized by completely balancing the line power flow during a day so that finally constant power flow is achieved. Limitations arise from the power and energy rating of the storage device. In this paper, storage is dimensioned due to a reliability requirement. The possibility of loss reduction is seen to be an additional benefit but not the major motivation for the installation of storage.

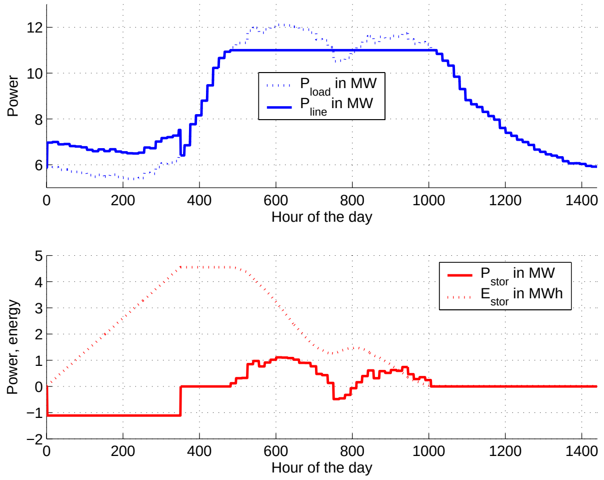

Fig. 5. Resulting load, line and storage power and energy.

In table II the total energy losses during a day are compared for the two alternatives (third line or storage). With a third line, the loss reduction is 1/3 and independent of the line length. Using a storage would reduce the transmission losses by 1.1%. Note that this value depends on the line length and would increase for longer lines.

TABLE II

NETWORK LOSSES.

Quantity	Value
Line resistance	$R' = 0.16$ Ω/km
Line inductance	$L' = 0.61$ mH/km
Line capacitance	$C' = 0.27$ μF/km
Line length	1 km
Active line losses without storage	1.251 MWh/d
Active line losses with storage	1.237 MWh/d
Active line losses with third line	0.830 MWh/d
Loss reduction with third line	33.33%
Loss reduction with storage	1.1%

C. Local Voltage Control

Many storage devices are interfaced with the grid via power electronic devices. Certain converters are able to control active and reactive power flow independently what offers the possibility of local voltage control or power factor correction respectively [1], [6]. This could be seen as another benefit of a storage installation.

As illustrated in figure 6, the converter output power is limited due to its apparent power rating S_{con}^{max}. For a certain active power exchange P_{con} (which is requested due to the mentioned objective) it is possible to generate reactive power Q_{con} due to the apparent power rating of the converter:

$$Q_{con} = \sqrt{(S_{con}^{max})^2 - P_{con}^2} \tag{7}$$

During the charging period the storage consumes maximal active power $P_{con} = -S_{con}^{max}$, hence $Q_{con} = 0$ and voltage regulation is not possible.

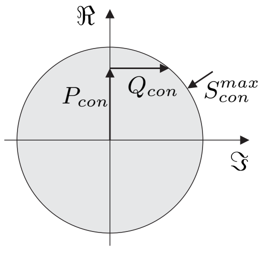

Fig. 6. Apparent power limit of the converter.

When the storage delivers power to the load, the voltage control capability is limited due to the current active power flow. The available reactive power during this period can be calculated according to equation (7). Figure 7 shows the reactive power that can be used for power factor correction/voltage control during the day.

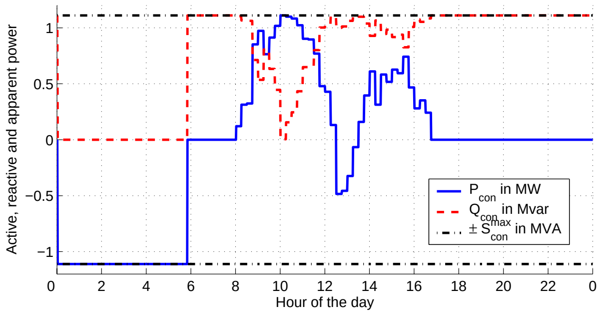

Fig. 7. Available reactive power of converter.

From figure 7 it can be seen that reactive power is available during the low and medium load period, hence reactive power is available for compensation during non peak times. An increased apparent power rating of the converter would enable voltage control also during the load peak.

IV. RELIABILITY CONSIDERATIONS

Installing a third line with the same characteristics as the existing ones will lead to an improved availability of the supply. If a storage device should be comparable to a three line system it should thus at least be able to guarantee the same availability of supply. Hence, a basic availability analysis of the existing system as well as of a system with three lines was performed. These results are then used to derive requirements for a storage device.

The three different topologies can be analyzed by modelling the systems as stationary Markov processes [7], since the failure and repair rates are constant and as the time intervals are assumed small enough such that the probability of more than one transition at a time happening can be neglected [8].

In order to focus on the two pivotal elements, both busbars and the circuit breakers as well as the connection between the storage device and the busbar are assumed to be 100% reliable. This assumption is valid for all three investigated systems and is justified because the results of the comparison of the systems should be fairly independent from it.

A. Reliability of Existing System

With both lines having the same failure rates λ_l and repair rate μ_l, the possible states and transitions can be depicted as in figure 8.

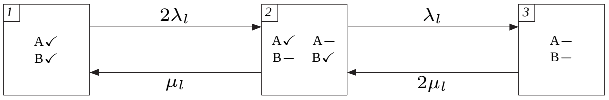

Fig. 8. State space diagram for existing system. A and B stand for the two busbars (see fig. 1) and the signs ✓ for operating and − for interrupted. Thus, state 1 corresponds to the situation with both lines in operation, state 2 to the state with either one of both lines operating and state 3 with both lines interrupted.

The resulting probabilities for the three states of the original system with 2 cables, denoted $P_{1^{or}}$, $P_{2^{or}}$, and $P_{3^{or}}$, are then:

$$P_{1^{or}} = \frac{\mu_l^2}{(\lambda_l+\mu_l)^2} \quad , \quad P_{2^{or}} = \frac{2\lambda_l\mu_l}{(\lambda_l+\mu_l)^2}, \qquad P_{3^{or}} = \frac{\lambda_l^2}{(\lambda_l+\mu_l)^2} \tag{8}$$

During the critical phases, i.e. when the load P_{load} exceeds the line capacity P_{line}^{max}, the system is only available if both lines are operating (state 1). As the load curve consists of $n_{tot} = 96$ quarter-of-an-hour values, the share of quarters, during which the supply is not 'n-1' secure, i.e. critical, can be calculated as $n_{cri} = (t_4 - t_3) + (t_6 - t_5) = 31$ (see figure 4). This gives the factors for the critical and noncritical proportions cr and ncr, respectively:

$$cr = \frac{n_{cri}}{n_{tot}} = \frac{31}{96}, \quad ncr = \frac{n_{tot} - n_{cri}}{n_{tot}} = \frac{65}{96} \tag{9}$$

The system's availability A_{or} thus results as:

$$A_{or} \quad = \quad ncr \cdot (P_{1^{or}} + P_{2^{or}}) + cr \cdot (P_{1^{or}}) \tag{10}$$

B. Reliability of System with 3rd Line

The modelling of the system enhanced with a third line can performed accordingly with the previous section. Again, the number of possible states can be reduced due to the identical characteristics of the lines. The state space diagram is shown in figure 9 and the resulting state probabilities $P_{1^{3rd}}$, $P_{2^{3rd}}$, $P_{3^{3rd}}$, and $P_{4^{3rd}}$ in equations 11.

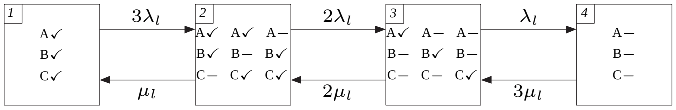

Fig. 9. State space diagram for existing system with a third line. A, B and C representing the lines as in figure 1.

$$P_{1^{3rd}} = \frac{\mu_l^3}{(\lambda_l+\mu_l)^3} \quad , \quad P_{2^{3rd}} = 3\frac{\mu_l^2\lambda_l}{(\lambda_l+\mu_l)^3} \tag{11}$$

$$P_{3^{3rd}} = 3\frac{\mu_l\lambda_l^2}{(\lambda_l+\mu_l)^3} \quad , \quad P_{4^{3rd}} = \frac{\lambda_l^3}{(\lambda_l+\mu_l)^3}$$

When determining the availability $A_{3^{rd}}$, again the critical period n_{cri} must be taken into account, requiring that at least 2 lines must be operating to supply the load during these times.

$$\begin{aligned} A_{3^{rd}} &= ncr \cdot (P_{1_{3^{rd}}} + P_{2_{3^{rd}}} + P_{3_{3^{rd}}}) + \\ & \quad cr \cdot (P_{1_{3^{rd}}} + P_{2_{3^{rd}}}) \end{aligned} \tag{12}$$

C. Reliability of System with Storage Device

To simplify matters, it is assumed that if during the charging time from t_1 to t_2 both of the lines fail, the storage device will not be able to operate at all. This probability equals P_{3or} (see equation 8) as this corresponds to the failure of both lines of the existing system. Further, the device is assumed to have completely failed if a failure occurs during the discharge time, independent of when the failure happens.

For the two critical periods during the day, the state space model can be found as in figure 10, using the storage failure and repair rates λ_s and μ_s. The corresponding state probabilities $P_{1^{st}}$, $P_{2^{st}}$, $P_{3^{st}}$, $P_{4^{st}}$, $P_{5^{st}}$, and $P_{6^{st}}$ are denoted in equation 13.

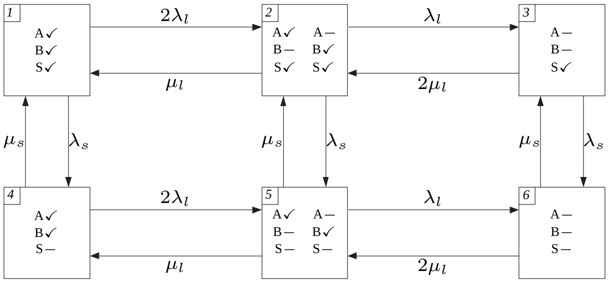

Fig. 10. State space diagram for existing system with a storage device, critical periods

$$\begin{aligned} P_{1^{st}} &= \frac{\mu_l^2 \mu_s}{(\lambda_l+\mu_l)^2(\lambda_s+\mu_s)}, & P_{2^{st}} &= \frac{2\mu_l\lambda_l\mu_s}{(\lambda_l+\mu_l)^2(\lambda_s+\mu_s)} \\ P_{3^{st}} &= \frac{\lambda_l^2 \mu_s}{(\lambda_l+\mu_l)^2(\lambda_s+\mu_s)}, & P_{4^{st}} &= \frac{\mu_l^2 \lambda_s}{(\lambda_l+\mu_l)^2(\lambda_s+\mu_s)} \\ P_{5^{st}} &= \frac{2\mu_l\lambda_l\lambda_s}{(\lambda_l+\mu_l)^2(\lambda_s+\mu_s)}, & P_{6^{st}} &= \frac{\lambda_l^2 \lambda_s}{(\lambda_l+\mu_l)^2(\lambda_s+\mu_s)} \end{aligned} \tag{13}$$

The supply is guaranteed as long as the system stays in the states $P_{1^{st}}$, $P_{2^{st}}$, and $P_{4^{st}}$. In order to be able to compete with the three line solution, this availability must equal or exceed the availability of the three line solution during the critical period. Further, the possibility that the storage device could not be charged must be included. Since both states $P_{1^{st}}$ and $P_{4^{st}}$ supply the load independently of the storage device, only the state $P_{2^{st}}$ must be multiplied with the probability that the storage device could be charged. Thus, the following condition can be found for the critical period:

$$P_{1^{st}} + P_{2^{st}} \cdot (1 - P_{3or}) + P_{4^{st}} \geqslant P_{1_{3^{rd}}} + P_{2_{3^{rd}}} \tag{14}$$

Solving this inequality for the two unknown variables λ_s and μ_s leads to the following relation:

$$\frac{\mu_s}{\lambda_s} \geqslant 1 + \frac{\mu_l}{\lambda_l} \tag{15}$$

With $\mu_l \gg \lambda_l$ this relation simplifies to

$$\frac{\mu_s}{\lambda_s} \geqslant \frac{\mu_l}{\lambda_l}. \tag{16}$$

As the storage device basically takes over the function of the third line, this result is not further surprising. As failure rates for cables are expressed in values per 100 km and year usually, the here used lines with a length of 1 km result in a high requirement for a storage device, being a hybrid combination of electrical, mechanical and/or chemical systems. In other words, the more remote a load will be, the lower will be the availability requirements for a storage device. Since storage technologies for larger applications are still very young it can also be expected that the reliability will increase with the number of installed devices. Concluding it must be noted that equation 15 results from a comparison to the availability with three feeders. If the storage device would be compared to the originally planned availability before the load began to exceed the capacity, the requirement would also become less strict.

V. ECONOMICAL CONSIDERATIONS

A. Tariff System

In common tariff systems both the consumed energy E and the peak load P_{max} (15-minute average) influence the total costs C [3], [9]:

$$C = a \cdot E + b \cdot (P_{load}^{max} - P_{load}^{avg}) \tag{17}$$

where a is the energy coefficient in \$/MWh and b is the power coefficient in \$/MW.

Peak shaving affects the total costs in two ways. The peak load P_{max} is reduced and part of the energy $E_{low} < E$ is consumed during a low tariff period billed with an energy coefficient $a_{low} < a$. Equation (17) can be re-stated considering this:

$$C_{red} = a_{low} \cdot E_{low} + a\,(E - E_{low}) + b \cdot (P_{load}^{max} - P_{stor}^{max} - P_{load}^{avg}) \tag{18}$$

The saving due to peak shaving and low-tariff charging hence equals

$$\Delta C = C - C_{red} = E_{low}\,(a - a_{low}) + b \cdot P_{stor}^{max} \tag{19}$$

From the previous equations it is obvious that there is an optimum concerning the power and energy rating of the storage which is dependent on the tariff system.

In table III the power and energy coefficients of a Swiss utility (Elektrizitätswerk der Stadt Zürich) are listed.[1] It can be seen that there is a significant difference between the low and high tariff coefficients, in summer it is $a_{low}/a \approx 0.3$.

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[1] Data for large commercial customers with a consumption of more than 60 MWh/a are taken from [9]. The additional factor for the increase of the monthly peak demand based on the average peak of the last year is not considered here.

TABLE III

EXAMPLE OF POWER AND ENERGY COEFFICIENTS [9].

Quantity	Value
High tariff summer	$a = 0.175$ CHF/kWh
Low tariff summer	$a_{low} = 0.05$ CHF/kWh
High tariff winter	$a = 0.225$ CHF/kWh
Low tariff winter	$a_{low} = 0.175$ CHF/kWh
Energy coefficient	$b = 96$ CHF/(kWa)

B. Investment

An estimation of the total investment is difficult since it depends on a number of uncertain factors. Storage technology is still under development, also the prices are subject to rapid changes. The cost for ancillary hard- and software components such as electrical equipment, protection and control depend very much on the present installation.

However three major investments have to be made for a storage plant:[2]

- Storage device: This part of the investment costs is depending on the storage technology and its energy and power rating [11]. Prices are subject to changes since technologies are still in a development stage.
- Electrical equipment: Transformer, switchgear, power-electronic converter, protection and control have to be installed. The corresponding costs can be stated proportional to the square root of the storage power rating [3].
- Building: An estimation for the building investment is given in [3], the costs are assumed to increase linear with the energy rating of the storage.

In general, it must be considered that a storage device can be installed in one building, including all the necessary ancillary components. Compared to the installation of an additional line, whose planning often includes costly rights of way negotiations as well as digging of streets and the high cable costs itself, this is a clear advantage. Note also that storage installations such as battery plants can be designed in a modular way such that the investments can be split up and performed when needed. This possibility has to be regarded when investigating storage economics [6].

C. Operation

Operational costs arise from service and maintenance. However manpower, spare and wear parts have to be provided to achieve high reliability. Operational costs can be considered to increase linearly with the storage energy rating [3].

VI. DISCUSSION AND CONCLUSION

It has been shown that storage can significantly affect the network power flow. Load curves are levelled and transmission losses are slightly reduced. The possibility of local voltage control/power factor correction using the features of power electronic converters can get useful if the power rating of the converter is increased in order to deliver reactive power even if the active power limit is reached.

If a storage device should be able to guarantee the same level of availability as a third parallel line would offer, the failure rate requirements for the storage device should be equal to those of a third line. This could be a high requirement since storage technology is complex and still in an young stage.

Shaving the load power peak and loading the storage during a low tariff period, results in an energy cost reduction if the tariff system is sensitive to both energy and peak demand. Economical values such as investment and operational costs are hard to estimate since they depend very much on the local circumstances. A storage installation offers a certain modularity, which means that the device can be supplemented later when more energy is needed. Thus, the starting investment and the costs due to credit interest can be kept comparably low.

Concluding it can be remarked that a storage device offers several benefits a third line cannot offer. With operational data of a larger storage device it should also become possible to model the storage device in more detail and to focus on customer savings and on customer interruption costs. An optimization aim could be to define energy and power rating of a storage device not solely considering reliability but rather optimal cost savings in a tariff system and optimally low customer interruption costs.

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[2] The total investment for the battery energy storage system (BESS) of Golden Valley Electric Association in Fairbanks, Alaska, were about USD 30 million for a rating of 27 MW during 15 min. For this project the total costs can be divided into the three almost equal parts: storage device, building and electrical equipment [2], [10].