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Concepts for the improved integration of wind power into the German interconnected system

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Abstract: The ongoing increase in wind power in Germany requires the accomplishment of a number of challenges. Most notably, the substantial strain on the transmission grid and the increasing requirement of control reserve capacity need to be tackled. Therefore the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety has commissioned a scientific study, in which novel concepts for optimised integration of wind energy into the German interconnected system are being evaluated. The Institute of Power Systems and Power Economics (IAEW) of RWTH Aachen University and the Research Centre for Electrical Systems and Power Economics cooperatively handles the study. The investigations carried out by IAEW are focused. They comprise a generation management (GM) of wind turbines and an improvement in load forecast, both in terms of a reduction in necessary control reserve, an improved integration of wind power because of the utilisation of intraday markets, a demand-side management in order to provide control reserve and the potentials of modern storage technologies. Primarily, the application of GM proves to be of significant economical benefit. Moreover compressed air energy storages may prove to be a suitable utility for the integration of wind power.

1 Introduction

Political support in general and the Renewable Energy Sources Act particularly (EEG) have yielded an unequalled increase in the installed wind power in Germany. At the end of 2006, nearly 19 000 wind turbines with a rated power of 20 600 MW were in operation and generated >30 TW h, which accounts for 5.7% of the German consumption of electrical energy. The German government's goal is to increase the share of renewable energies in the electricity supply to at least 12.5% by 2010 and to double the share to at least 20% by 2020. The greatest potential for the envisaged expansion lies in the wind energy sector, particularly offshore wind power. But the government needs to tackle various challenges in order to ensure an ongoing increase in wind power. The 2005 finished dena grid study [1] already investigated the consequences of the expected growth of installed wind power capacity for the German interconnected system and pointed out emerging technical problems and increasing costs, for example, for frequency control and network reinforcements. Therefore the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety has commissioned a scientific study, in which novel concepts for optimised integration of wind energy into the German interconnected system are being evaluated. It is anticipated to determine the most promising approaches and consequently to set up the objective for already scheduled continuative studies.

The below-mentioned subjects, handled by the Institute of Power Systems and Power Economics, are presented in the following sections.

- Generation management (GM) of wind turbines in terms of a reduction in necessary control reserve.

- Improved integration of wind power because of the utilisation of intraday markets.

- Demand-side management in order to provide control reserve.

- Improvement of load forecast in order to reduce the necessary control reserve.

- Potentials of modern storage technologies.

The topics, as per particulars given below, are handled by the Research Centre for Electrical Systems and Power Economics. They are not carried out in the following paper.

- Utilisation of AC cables as well as DC cables instead of AC overhead lines because of expected ease of legislation.

- Power flow control for optimised use of transmission capacity.

- Review of grid code requirements.

- Increased transmission capacity by utilisation of overhead line monitoring or application of seasonal standards.

2 GM of wind turbines

As mentioned in the introduction, wind power in Germany nowadays constitutes a noticeable share of the total generation capacity. The major barrier towards its system integration and consequently its further expansion lies in its intermittency. As a matter of principle, the actual wind power generation always differs from the predicted value. Similar to power plant outages and load forecast error, there has to be held control reserve (sum of secondary control reserve and minute reserve) [2] for this so-called wind power forecast error in order to maintain the balance of load and generation at all times. With increasing installed wind power capacity in Germany, the demand of control reserve because of wind power forecast error and consequently the total amount of control reserve needed – as indicated in former studies [3] – will rise almost linearly.

The wind power forecast error causes an additional requirement of both positive and negative minute reserve [4]. Therefore it is reasonable to investigate, how much control reserve may be saved because of the application of GM and whether this could be done economically feasible. In the following context, GM is only enforced in order to reduce the required control reserve and emphatically not in order to avoid violations of transmission system standards, primarily equipment overload.

In order to save positive control reserve, it would be required either to reduce the wind power feed-in permanently below the technical optimum or to shut down single wind turbines just to switch them on in case of demand. This approach is both ecologically and economically unfavourable because a rather large share of available wind power is discarded. It is therefore not investigated any further.

In contrast, it seems reasonable to temporarily reduce the wind turbines' output in order to reduce the demand of negative control reserve. As these interventions are of short duration, only a minor share of wind power stays unused. For this reason, the following analysis refers only to reduction in negative control reserve.

A possible approach for the application of GM is depicted in Fig. 1 showing an exemplary wind power forecast error over the course of 24 h. In order to reduce the demand of negative control reserve, the wind power feed-in is curtailed in a way that the maximum positive wind power forecast error is limited to a certain value as illustrated in Fig. 1. If the wind power forecast error is about to rise above this value, which is marked as a dashed line, the GM takes action rapidly.

In the following, the potential reduction of control reserve by means of GM is exemplarily estimated for the year 2020 using a well-proven probabilistic model, which is based upon the convolution of input data that are represented by its statistical distributions. The data series of wind power forecast and wind power generation are provided by the wind power management system (WPMS) [5], which is the current

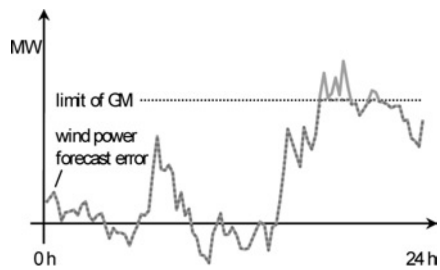

Figure 1 *Wind forecast error before GM and the resulting deviation, which has to be compensated by control reserve*

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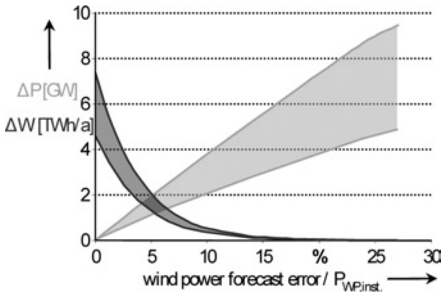

Figure 2 *Demand of control reserve because of wind forecast error and discarded wind power feed-in in dependency on the opted maximum positive wind forecast error*

wind power prediction tool of all four German transmission system operators (TSO). According to the aforementioned dena grid study, the expected installed wind power capacity for the year 2020 is varied in the range from 30 to 48.2 GW. Hence, in Fig. 2, the demand of control reserve, as well as the unused wind power feed-in, is shown as bandwidths. The upper boundaries refer to the maximum expected installed capacity of 48.2 GW, whereas the lower boundaries refer to the minimum expected installed capacity of 30 GW.

In Fig. 2, the bright bandwidth represents the additional control reserve ΔP, which is caused by the wind power forecast error. The dark bandwidth refers to the unused wind energy ΔW on account of GM. The right ends of the curves mark the case of no GM at all, whereas the left ends of the curves mark the case of entire GM, for example, even at the slightest positive wind power forecast error, GM takes action. For a certain maximum wind power forecast error in relation to the installed wind power capacity, the according demand of control reserve (bright band) as well as the unused wind power feed-in (dark band) can be read off.

If GM took place above a maximum positive wind forecast error of 14% (corresponding to an application of ∼100 h/year), the required negative control reserve on account of the wind power forecast error would be lowered to 5.2 GW (in case of 48.2 GW of installed wind power capacity), which corresponds to savings of ∼45%. Admittedly, this would imply a curtailment of 200 GW h/a of wind power feed-in, which accords to 0.2% of the annual generated wind energy.

In order to have an objective evaluation of GM, its efficiency E is regarded, which is defined as the savings of negative control reserve ΔP divided by the unused wind energy ΔW. The efficiency E is shown in Fig. 3. In case of a high maximum wind power

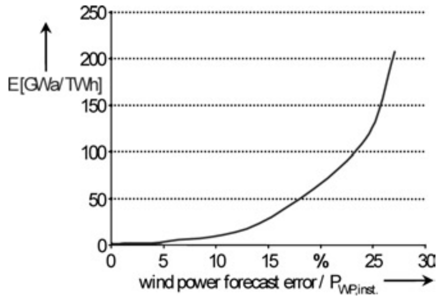

Figure 3 *Efficiency of GM in dependency of the opted maximum positive wind forecast error*

forecast error, which is similar to an infrequent enforcement of GM, the efficiency of GM is very high. With increasing frequency of GM, the savings of negative control reserve ΔP as well as the discarded wind energy ΔW rise. Because of a steeper rise in the discarded wind energy, the GM's efficiency drops with increasing frequency of application.

For a rough estimation of its economic efficiency, the savings of negative control reserve may be valued with a nowadays average cost of 25 000€/MWa [6]. The discarded wind energy is priced at an average German feed-in tariff of 0.07€/kW h. Because of this estimation, GM in Germany is cost-effective up to an efficiency E of 2.8 GWa/TW h, for example, up to a major extent. A maximisation of social welfare under consideration of climate protection would call for the regard of more details.

3 Utilisation of intra-day markets

With the number of wind turbines increasing, the impact of turbulences as well as the gradients of their summary power production is reduced, as gusts do not strike all the wind turbines at the same time. Because of this smoothing effect among spatially distributed wind turbines, the generation of major wind power capacities, such as the German one, has comparatively small gradients [4]. Therefore short-term forecasts of wind power, which are a few hours in advance, have significantly higher qualities than today's prevalent day-ahead forecast [7]. These short-term forecasts are not meant to replace the day-ahead forecast but to supplement it. Although the short-term forecast error is balanced by means of minute reserve, the deviation between short-term and day-ahead forecast is offset by a fairly long-term hour reserve. Because of the longer activation time, the acquisition of such a long-term hour reserve could be accomplished by the utilisation of a sufficiently liquid intra-day market. The lower technical standards regarding the activation time compared with 15 min in case of the minute reserve indicate the expectance of lower specific costs for hour reserve.

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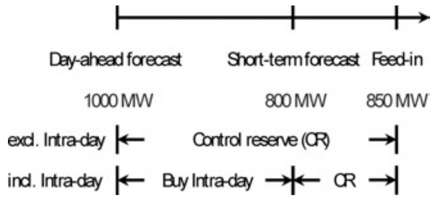

Figure 4 *Utilisation of Intra-day market*

Similar to Section 2, the estimations are based upon a probabilistic model using data series provided by the WPMS. These estimations show the benefits and downsides of using an intra-day market as illustrated in Fig. 4. Without utilisation of the intra-day market, the inevitably emerging deviation between actual wind power production and the predicted value needs to be compensated during operational control by means of control reserve. In the depicted example, a positive control reserve of 150 MW is necessary in order to balance the difference between 1000 and 850 MW. In case of an additional short-term forecast, the deviation between day-ahead prediction and short-term prediction may be traded at the intra-day market. In the example, 200 MW would be purchased via the intra-day market. At the time of actual feed-in, 50 MW needs to be balanced by negative control reserve.

The major advantage of intra-day market is that the required amount of control reserve can be reduced significantly. However, this implies the implementation of an additional forecast and an additional reserve. As the sample in Fig. 4 shows, the combination of control reserve and hour reserve may lead to counteracting commitments. Therefore the required control energy will rise as a matter of principle.

Fig. 5 shows the total costs for provision of control reserve for an exemplary control area and a total German wind power capacity of 30 GW. For today's non-existent product of hour reserve, it is assumed that it has no demand rate in contrast to control reserve, which has a considerable demand rate. The

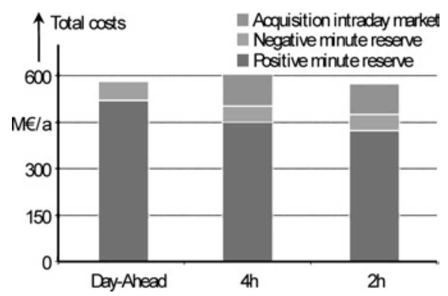

Figure 5 *Total costs for provision of control reserve for an exemplary control area and a total German wind power capacity of 30 GW*

hour reserve's energy rate is assumed to match the average spot market price. These assumptions accord to an analysis of today's European intra-day markets.

As shown in Fig. 5, the acquisition of hour reserve via intra-day markets yields no significant economical benefit in comparison to today's exclusive provision of minute reserve. This is attributed to the increasing total demand of reserve, which counterbalances the lower specific costs of hour reserve. The increasing total demand of reserve accrues from opposite controlling of hour reserve against minute reserve, which cannot strictly be avoided. Moreover, the trade volume at the lately introduced German intra-day market is – in conformance with the development of anterior European intra-day markets—far below the expected demand for hour reserve.

4 Demand-side management

During normal operation, the power balance between generation and consumption is continuously disturbed by the arbitrary behaviour of the consumers and is sporadically disturbed by failure events as, for example, power plant failures. In today's interconnected system, the balance between generation and consumption is ensured by the provision of control reserve, that is, by an adjustment of generation. Adjustment of consumption is just as well possible, but only used to a minor extent. Because of the integration of wind power, which subjects the generation side to increasing uncertainties, an intensified use of demand-side management should be considered. In this context, demand-side management is referred to as controlled switching-on and switching-off, respectively, of electrical units in order to substitute control reserve.

As the TSO is responsible for warranty of system security, it has the responsibility for commitment of control reserve. Therefore the TSO is required to have the responsibility for demand-side management as well. Control reserve needs to be available with a guaranteed level of security. In case of single customers with large electrical units, that is, industrial customers, this security may be guaranteed via today's process of prequalification. In the case of customers with low consumption, such as households, the available power, which may be switched, can only be predicted for a sufficiently wide collective.

To some extent, industrial customers already take part at the reserve market in consideration of the strict standards for prequalification. Their incentive for participation depends on the attainable profits. Therefore the future level of prices will be the crucial factor.

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Furthermore a demand-side management of private customers is conceivable as well. As the customer's quality of life may not be restricted, only the disposable consumption of electric devices, such as washing machine, dishwasher, dryer and refrigerator, is to be considered. The potential savings of control reserve in Germany range between 3 and 7 GW depending on the time of day. Even so, most customers disapprove of the externally triggered interruption of devices. Former field studies [8] point to the fact that the affected customers miss their personal control of the device. Anymore, in case of an area-wide application, the big potential savings of control reserve are counterbalanced by the substantial acquisition cost per household for electronic measuring devices, displays, controllers and signal transmission.

5 Improvement of load forecast

The so-called unbundling of the utilities because of the liberalisation of electricity markets in Germany led to a change of TSO's information basis and their processing of grid operation. This has especially strong impacts on the load forecast error, which is the deviation of the physical load's 15 min mean value from its predicted value. Because of the size of system load and its continuous fluctuation, it has a major effect on the demand of control reserve. Hence, in this section, there are approaches for improvement of the load forecast assessed, not by the accuracy of the load forecast itself, but by the influence of the organisation of load-frequency control on the demand of control reserve. Therefore approaches are questioning today's separation of Germany into four control areas, each with their single load forecast and single balance of generation and consumption.

Similar to Section 2, the potentials for a reduction in control reserve are determined for an exemplary control area in Germany assuming a total installed wind power capacity ranging from 30 to 48.2 GW. The estimations are again based upon the probabilistic model based upon the convolution of input data that are represented by its statistical distributions. The data series of wind power forecast and wind power generation are again provided by the WPMS.

Today's standard deviation of a control area's load forecast error is usually assumed to be 2.5% of the peak load. The correlation between today's load forecast errors in the control areas is unknown, hence the standard deviation of the resulting total load forecast error in Germany is varied in three steps from 1.3% over 2% to 2.5% of the peak load. A total load forecast error of 1.3% would represent the best case, in which today's load forecast errors were completely uncorrelated. Indeed, due to the rather strong correlation of temperature and brightness over Germany, which are the major influencing factors on the load forecast, completely uncorrelated forecast errors are seen to be unrealistic. The investigation of this case is just for identification of the theoretically maximum potential. A total load forecast error of 2% would comply with a 50% correlation of today's load forecast errors. The lowest potential corresponds to a total load forecast error of 2.5%, which matches with the complete correlation of today's load forecast errors.

In Germany, there has been an immediate equalisation of wind power feed-in between the control areas since the EEG amendment in 2004 [9]. Likewise, it is possible to pool today's load forecast errors and apportion them accordingly to the share in annual electricity sales in each control area. The advantage of this approach is that today's – as a matter of principle possible – oppositional compensations of load forecast errors in the respective control areas are prevented. Hence, the total demand of control reserve in Germany is to be reduced.

The demands of positive ($P_{pos.}$) and negative ($P_{neg.}$) control reserves, respectively, depending on the standard deviation of load forecast error σ_{LF} and installed wind power capacity $P_{WP,inst.}$ are shown in Fig. 6. The displayed bandwidths result from the variation of load forecast error from 1.3% (lower boundary) to 2.5% (upper boundary). A standard deviation of 2.5% corresponds to both today's demand of control reserve and the worst case, which is the entire correlation of today's load forecast errors. In the best case, corresponding to an installed wind power capacity of 30 GW and a total load forecast error (σ_{LF}) of 1.3%, there are potential savings of 20% (positive control power) and 14% (negative control power), respectively, feasible.

In case of a joint control area in Germany, all causes for control reserve are compensated jointly. These are in detail power plant outages, load disturbances, the load forecast error and the wind power forecast error. The

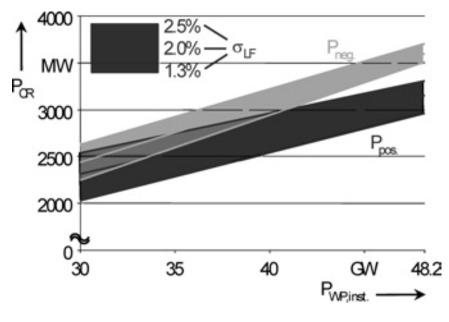

Figure 6 *Demand of control reserve in case of immediate equalisation of wind and load forecast errors between control areas*

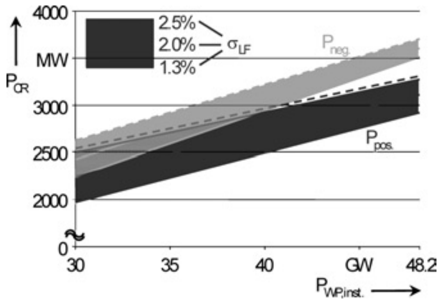

Figure 7 *Demand of control reserve in case of joint control area in Germany*

share in control reserve to be hold for each TSO is apportioned in accordance with the particular annual electricity sales.

The demand of control power depending on the standard deviation of load forecast error, as well as the installed wind power capacity, is displayed in Fig. 7. Similar to Fig. 6, today's demand of control power is shown as a dashed line. In contrast to Fig. 6, it is not the same as the worst case, entire correlation of today's load forecast errors, which is marked by the upper boundary of the corresponding band. In the best case, there is a potential reduction of 22% (positive control power) and 15% (negative control power), respectively, possible.

Both approaches offer potential savings of ~20% of control reserve in the best case. Nevertheless, due to the non-complete correlation of today's load forecast errors, these values would not be reached in practice. The potential savings to be realised will rather be lower.

Furthermore, in both approaches, the evolving power flows because of the joint compensation cause additional strain on the transmission grids. In case of an immediate equalisation of wind power and load forecast errors, an oppositional algebraic sign of load forecast errors would cause a compensating power flow between the two concerned control areas. Because of the above-mentioned correlation of today's load forecast errors, the magnitude of this compensating power flow would be rather small. In case of a joint control area, a power plant outage could cause a much higher strain on the affected tie-lines.

Furthermore, both approaches raise additional operating expense. Today, there is no general enforcement of load forecast; it is merely used for validity check of generation schedules in the corresponding control area. Commitment of control reserve is carried out because of the secondary control deviation and therefore independently from the cause of deviation. Hence, in both approaches, the load forecast has to be enhanced in order to be used in network operation. Furthermore, to determine the load forecast error, the actual value of the physical load has to be determined first. But because of the netting of subsidiary grids, the current total load is unknown to the TSO, which implies an additional expense for metering. Furthermore, the immediate equalisation of wind and load forecast error requires a circuit-entering of the deviation between physical load and forecast of load. A joint control area in contrast would require the establishment of an independent system operator.

An advantage of the immediate equalisation approach over the joint control area is that in this case today's possibility of helping each other out among the four control areas would persist. In case of the joint control area, the probability for power deficit surplus needs to be lowered from today's value in order to maintain the current level of system security. This would further narrow the above-mentioned potential savings.

6 Storage technologies

The major barriers at the integration of wind power into the established power system originate from the wind power's lack of controllability. Therefore it is a viable approach to decouple the intermittent wind power production from the interconnected system. This could be implemented by combining wind power and a suitable storage technology to a so-called virtual power plant, whose generation had the character of a conventional, that is, despatchable, power plant.

This purpose requires storages that are adaptable in their installed capacity, their storage volume and their geographical location towards the capacities and locations of wind power generation. The contemplated specifications are particularly fulfilled by the technology of compressed air energy storages (CAES), whose operation is related to those of pumped-storage plants [10]. Air masses are densified up to a level of 100 bar by electrically powered compressors and stored in underground cavities, which are at state-of-the-art salt caverns. The technology of CAES has been well tested over many years and is commercially available at costs, which are in the same order of magnitude as those of pumped-storage plants. In contrast to those, CAES has the particular advantage of a significant potential capacity in Germany along with potential locations in the coastal regions. Therefore CAES enable an effective interference of power flows in order to avoid congestions in the transmission grid.

The technical–economical evaluation under the assumption of historical market price data shows that erecting a CAES for the exclusive use of spot market

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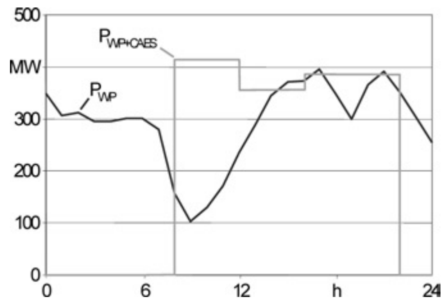

Figure 8 *Concept of refining wind power*

is not economically reasonable. In contrast, there is a profit attainable by exclusive operation for marketing control reserve. This result seems reasonable in consideration of the fact that the world's first CAES, built in 1978 in Huntorf, Germany, was designed as a reserve power plant and is today still operated in this manner. However, the German level of price for control reserve is high in relation to that of its European neighbours. Continuance of this level of price is therefore arguable. As the future development of the reserve markets and therefore the attainable profits at these markets are not satisfyingly assessable, they cannot justify a capital investment in CAES for use as a reserve power plant.

Another option next to the operation as a reserve power plant is the application for refining wind power as illustrated in Fig. 8. The exemplary power generation of a wind park P_{WP} is dependent on the wind speed and therefore both intermittent and stochastic, as depicted. The CAES is therefore operated in a manner that the virtual power plant consisting of wind park and CAES generates, for instance, the illustrated power $P_{\mathrm{WP+CAES}}$, which is despatchable and in accordance with the generation schedule consequently. The combination of wind park and CAES may hence be used and despatched just as a conventional power plant. The wind park included in the virtual power plant is thus no longer a requirement of control reserve, which is to be seen as an additional advantage of this kind of operation. The technical–economical evaluation shows that refining of wind power is the best operation in terms of the maximisation of social welfare and far superior to the provision of baseload wind energy [11]. Moreover, given the assumed model and historical market price data, CAES refining wind power has been evaluated to be a profitable investment.

In contrast, an erection of CAES for the primary use of avoiding network congestions is no reasonable alternative to today's network reinforcement because of the considerably higher investment costs. Nevertheless, in case of a suitable CAES' location, a temporary deployment for a reduction in network load and hence prevention of GM may be applicable in excess of above operations. Furthermore, there are additional benefits, which currently do not yield any revenues for investors in CAES, such as a reduction in the difference between peak price and base price at the spot market and raise of the capacity credit of wind power. As the assessment of CAES' future profitability is affiliated with high uncertainties because of the numerous applications and consequently the complex unit commitment, further research in this field of study is necessary.

7 Conclusions

In order to ensure an ongoing increase in wind power in Germany, a number of challenges need to be tackled. These are primarily the substantial strain on the transmission grid and the increasing requirement of control reserve capacity. Therefore novel approaches for the improved integration of wind power are presented and evaluated. Besides the need for further investment in the quality of forecasting tools, especially the application of GM proves to be of significant economical benefit. Moreover, CAES may prove to be a suitable utility for the integration of wind power, but further research needs to be done with regard to the future profitability in order to find potent investors for this today's sparsely used technology.

8 Acknowledgment

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