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Some Aspects of Distributed Generation – Voltage Drop and Energy Storage

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Abstract— **Present paper examines two aspects of distributed generation. The first part focuses on the question of local voltage control. A Hungarian village is modelled using DIgSILENT PowerFactory for simulation. A possible method is investigated to keep control of the voltage values, and it is shown, that energy injection of distributed generators can result even in the overloading of the MV/LV transformer without exceeding voltage limits. Second part of the paper focuses on the question of a local storage facility, for an 800 kW wind generator. After the statistical processing of the measurement data, the aim is to set a possible storage strategy in order to decrease the amount of energy injected into the grid during the off-peak period of the night. The determination of the size of the storage facility is followed by the examination of different types of storage systems that can be suitable for this task.**

Index Terms—**distributed generation, energy storage, flow battery, voltage drop**

I. Introduction

CHANGES, that have taken place in the electric system during the last few years have highlighted distributed generation and the utilization of renewable energy resources. In Hungary this manifests primarily in the headway of wind generators. More than 112 MW power was in action by mid 2008 in the country. These energy suppliers have caused several problems, because their system-integration shows some weakness.

Among these problems, one is the weather-dependence of production, which may result in the rapid and huge change of the produced energy. The high level of wind generator production can result in many problems, two of which are investigated in this paper. The system operators' job becomes more difficult because of the compulsory purchase of the renewable energy. According to the EN 50160 standard, local voltage value at medium voltage level must not exceed the ±3% range compared to nominal, which is sometimes violated by wind generators. To avoid this phenomenon, either limiting the production of the generators may be a possible solution, or the generators can be taken into the local voltage control process, using their power electronic devices. Both ways are investigated through computer simulations. A Hungarian village, Bakonszeg served as the base of the 12-bus model. At first, simulations included only one generator, to see the strength of each bus and the voltage drop at a certain amount of energy injection. To maintain the power quality, local reactive power compensation was used. A probable scenario was set up, to invert the power flow, using multiple generators. Latter simulations showed that we can reach even 100% loading of the transformer, with power flowing from low voltage level to medium voltage level!

The other problem in connection with weather-dependence is, that due to the low total load level and the high renewable energy production, sometimes it may be necessary to decrease the production of base power plants. These effects can be eased or even eliminated though, using some kind of energy storage device. The latter ones however have a broad palette; different technologies may prove sufficient for each task, and the requirements often end in contradiction. When investigating the possible solutions, it is necessary to talk about the power- and energy-range, the lifespan and the costs. To answer the questions concerning sizing, a one year long energetic purpose wind measurement was used. Cost calculations were performed for both the upper and the lower segment of the price-range and the probable future prices of the storage devices as well.

II. Voltage Change Caused by Distributed Generators

A. Motivation

Some years ago, the Hungarian Energy Office and the Hungarian Transmission System Operator (MAVIR Ltd.) have agreed, to limit capacity for wind generators in Hungary to 330 MW. The reason for this decision is simple, Hungary lacks energy storage power plants and devices. Because no such construction is planned, investors are starting to favour units under 50 kW rated active power. This activity results in disadvantages though, mainly for those consumers, who consider micro generation as a support for their own household, not an economic investment. Some of these problems are mentioned in the following paragraphs.

Regulations in force have been developed to treat micro generation like any public consumer. There is no possibility to reject the connection of such generator; even the contract may remain unchanged, if line capacity is sufficient. If any investment is required to maintain power quality, it is the duty

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of the DSO. The consumption and the production of the micro generators are rarely at the same period of the day. The low-voltage network is used as a puffer in this case. It may also happen, that power has to be transformed to higher voltage levels, but neither the TSO nor the DSO receives financial support in form of tariffs for this. Other questions remain yet unanswered, like what technological changes will happen, if micro generation reaches certain level, and results in the need for investments. Regulations are under development regarding power electronic devices, measuring and billing problems, protection, etc..

For the reasons mentioned above, every Hungarian DSO has set its limit regarding the apparent power of the micro generators. The highest value among them is 50 kVA, we used this during our investigation.

The computer model was prepared with DIgSILENT PowerFactory, a powerful tool for such small-power simulations. Fig. 1. shows the scheme of Hungarian village Bakonszeg, which served as the base for the 12-bus system. The MV/LV transformer is an NA 100/20 Yz5 type 100 kVA transformer. The loading of the unit is approximately 33%. The external grid has short-circuit power of 100 MVA and serves as the slack bus.

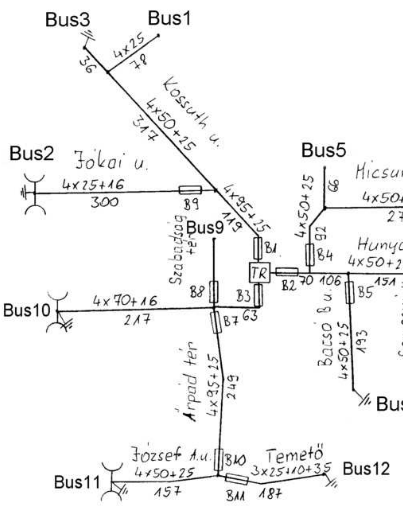

Fig. 1. Scheme of the village

The simulation mainly consists of load-flow calculations. 6 buses were selected, and a 50 kVA generator was connected at each one of them (at once only one). Their production was treated purely active, while no compensation was needed. After reaching this point, local compensation was used – virtually the power converter produces and consumes reactive power.

B. Voltage Change without Reactive Power Compensation

The first group of simulations represents the weakness of current regulations. The generator is connected to a bus, and its production is increased in 1 kW steps. 3 buses were selected as reference; among these we can find the strongest and the weakest network point as well. Fig. 2. shows the results for these scenarios. It can be noticed, that bus 9 is the only one, which can accept the maximal power, without violating voltage limits of the EN 50160 standard. Bus 4 can accept 26 kW, while bus 8 can accept only 15 kW with same conditions. The results clearly point out, that in most cases reactive power compensation is needed.

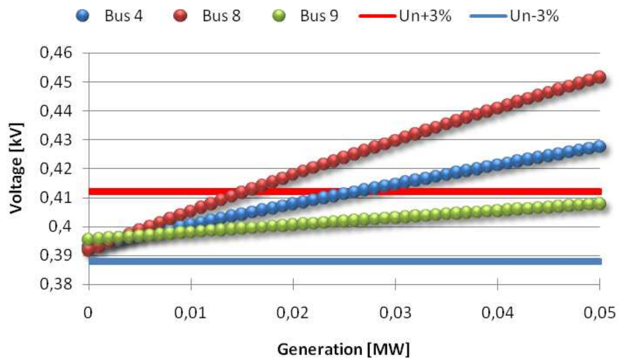

Fig. 2. Voltage change without reactive power compensation

C. Voltage Change with Local Reactive Power Compensation

In the second group of simulations, compensation was used, to keep the voltage limits. There are two possible ways regarding compensation. We can either aim to keep the voltage at the value, it was before connection of the generator, or we can aim only to keep it within the ±3% limit. Fig. 3. shows the first case; the generator is connected to bus 8, and the target voltage value is approximately 0,39 kV. Since bus 8 is the weakest point of the network, the amount of reactive power is increasing fast, as the production rises. Because reactive power is supported by the medium-voltage grid, the power flow creates a significant voltage drop on the low-voltage side of the transformer. The production of the micro generator is still less than 10 kW, when the voltage at the transformer is already lower than the permitted value. This concludes that we cannot aim to keep the start-up voltage values.

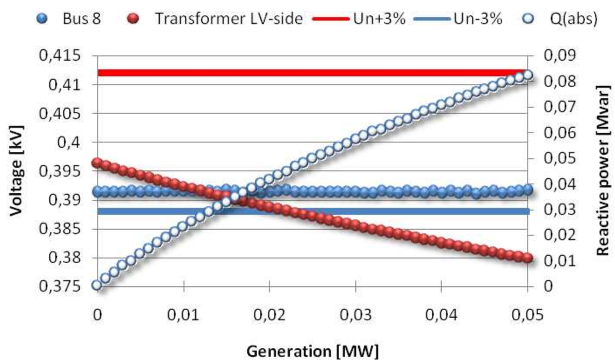

Fig. 3. Compensation at bus 8, the target is the start-up value

Fig. 4. and Fig. 5. display the results when the target voltage value is 3% higher than the nominal (but still permitted by the standard). In the case of bus 4 (shown on Fig. 4.) compensation proves to be sufficient, and voltage at the transformer is still above the limit. Though the level of

reactive power is quite high (30 kvar at maximal production), a modern power electronic device enables such consumption; the power factor is better than 0,8. The case of bus 8 (shown on Fig. 5.) is slightly different. Higher amount of reactive power is needed to maintain the voltage level, but again this results in the decrease of the voltage at the transformer (and thus, in the whole village). If we take into account, that an inverter would work with a capacity factor better than 0,8, we can easily recognize, that the reactive power need is way too much. Fig. 6. displays the results of the simulation, when this limit is also taken into account. It can be noticed, that when the voltage of bus 8 reaches its upper limit, the amount of reactive power rises fast, until it is restricted by the capacity factor. From this point on, the inverter is not able to limit the voltage rise, it violates the standard value.

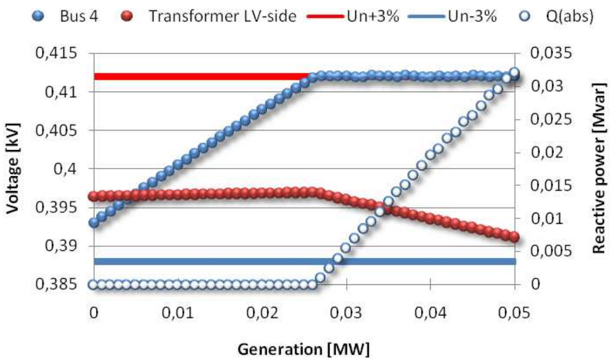

Fig. 4. Compensation at bus 4, target is Un+3%

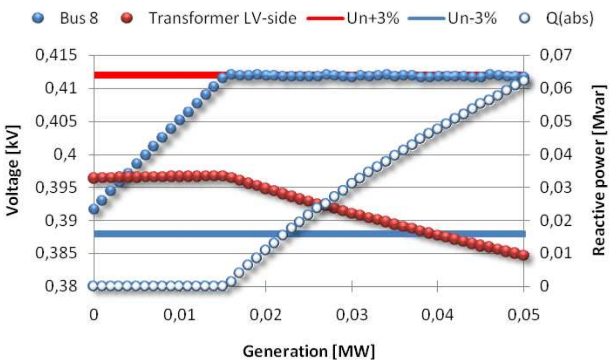

Fig. 5. Compensation at bus 8, target is Un+3%

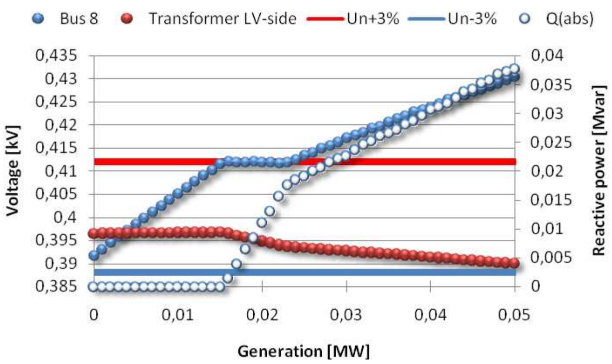

Fig. 6. Compensation at bus 8 with limited power factor, target is Un+3%

Insufficient reactive power capacity is not the only thing that makes high level compensation unavailable. Fig. 7. shows that the loading of the different line sections is also above their thermal limit. While bigger cross-section size causes no problem regarding this question, the last (and the thinnest) section of the line proves to be inadequate to host the active and reactive power flow.

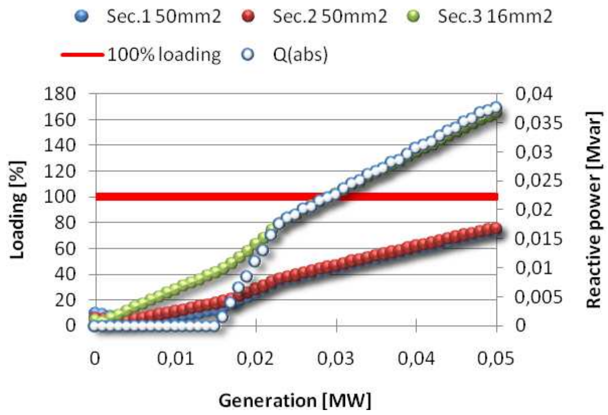

Fig. 7. Line loading, compensation at bus 8

Another aim of the simulations was to find the maximal capacity of micro generation, that we can inject into the network, without violating the voltage limits. The results show, that more than 130 kW active power is available, with five generators placed at different buses (25 kW at bus 5, 7, 10 and 11, 34 kW at bus 9). Though this would result power flowing from low-voltage level to medium-voltage level, the only element of the network that would near 100% loading, is the transformer.

III. Investigation of the Storage Facility

The aim of this part of the paper is to investigate the construction and operation of a storage facility. Production of wind generators is highly weather-dependable, thus it is hard to create a schedule for them. The total load of Hungary is low during the off-peak period, and it even occurred that production of the nuclear power plant had to be limited, because of the obligatory purchase of the wind power.

The Enercon E-48 generator, that was examined, is mounted in the periphery of the Hungarian village, Mecsér. The wind speed measurements began in 2005, followed by the construction on March 2007. This wind turbine represents a good average of Hungarian turbines, so it was perfect for further investigation.

A. *Evaluation of the measurement data*

The measurement data was received from Horvath Engineering Office Ltd.. The examined period includes almost every day of 2006. Two sensors were used, 30 and 60 meters above ground. These anemometers simultaneously record the speed and the direction of the wind, and store several values every 10 minute.

The first problem that we faced is that these wind speed values had to be converted to the height of the generator; 75 meters in this case. This conversion is done using the proper formula of wind speed sheer rate; the only unknown parameter is the Hellmann-number. Papers that are investigating the questions concerning the Hellmann-number point out, that the formula should be used only for wind speeds above 2-3 m/s, and only, if the measurement has been taken between 20 and 60 meters. Equalization of the atmosphere in Hungary occurs at about 50 meters above ground, and wind speed measurements are recommended to be taken above this level. Is also has to be mentioned, that the Hellmann-number is not a constant value, it depends on the time of the day, and the month as well. Regarding all these facts, we made the necessary approximations, used the 60 meter data as base, and treated the Hellmann-number as a constant value. Results of the conversion are displayed on Fig. 8..

The figure shows both the wind speed and the energy distribution of 2006. Some facts are highlighted; the most important is that Hungary lacks really high wind speeds. The highest 10-minute average wind speed value was only 20 m/s, and it was recorded only once in 2006. Even 17 m/s was passed only 9 times. This determines the generation as well. While the majority of wind speed values are between 3 and 8 m/s, most of the energy is produced by wind between 6 and 11 m/s. Almost 67% of the energy is the result of winds over 8 m/s, which range covers 26% of the wind speed values.

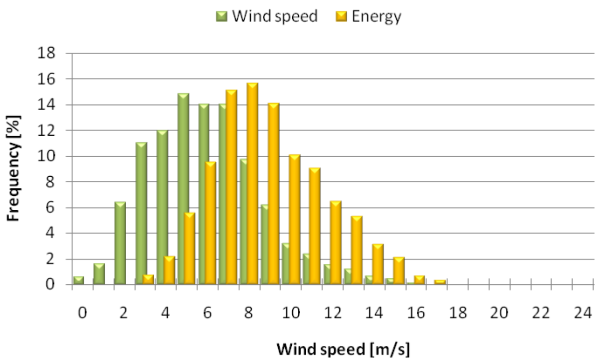

Fig. 8. Distribution of wind speed and energy, converted to 75 m

As it was pointed out, the aim of the storage is some kind of peak shaving. Our goal would be to store all energy produced by the generator in the off-peak period, and use it during the day. The Hungarian Energy Office defines the off-peak period differently for summer time and winter time, for workdays and weekends, public holidays. During our investigation we have treated the off-peak period the same for every day; it lasts 4 hours, between 2:00 and 6:00 AM. After this approximation, we are able to calculate some cornerstone values for our storage unit. Some noticeable data: the highest production during the off-period in 2006 was on 13th March, with 793 kW, while 1 kW also occurred 5 times. The annual average power was 139 kW (significantly below the 24 hour average that was 171 kW). Fig. 9. summarizes the results, and highlights, that even a little storage unit may be sufficient for the task. A 66 kW storage would cover the production 53% of the time. This can be increased, by using a 120 kW device (68%) or a 191 kW device (82%). Using an oversized storage would not be reasonable, and it would also mean more cost.

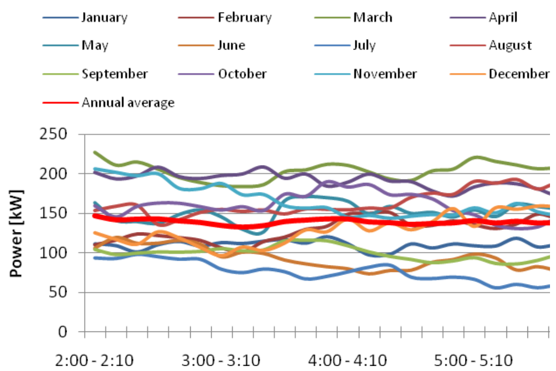

Fig. 9. Average power of the off-peak period

B. *Comparing different technologies*

Using the results of the previous section, we can determine the approximate size of the storage unit. We need a device with 100-150 kW/400-600 kWh combination. Looking at the different storage technologies, this is a relatively low power and high energy storage, which is best implemented by three opportunities: batteries (including NaS), flow batteries, and hydrogen storage. We have not dealt with hydrogen this time.

If we compare batteries, and flow batteries, some major differences can be noticed. It is like a choice between a well-known technology, and a solution that is still under development. Flow batteries have a huge lifespan (over 10 000 cycles), their reaction time is short, and the most important thing is that their energy and power rating can be decoupled. We have chosen this novel technology for further investigation.

The charge and discharge of a flow battery is based on the reversible electrochemical reaction of two liquids. These electrolytes are stored separately in two tanks. During the operation, the liquid electrolytes flow through an electrochemical cell, in which chemical energy is converted into electricity. The power of the flow battery is determined by the cell stack, while the energy capacity depends on the volume of the electrolytes. Today, several companies are producing units of different sizes. We compared three better known constructions, the vanadium (V/V), the polysulphide bromide (PSB) and the zinc bromine (ZnBr).

V/V batteries use two vanadium electrolytes, a V^{2+}/V^{3+} and a V^{4+}/V^{5+}, both in mildly acid solution. During the charge and discharge cycles H^+ ions are exchanged through a proton-permeable polymer membrane. One advantage of the V/V concept is that both half-cells contain only vanadium, so cross-contamination as a result of ion-diffusion causes no problem. In PSB flow batteries, solutions of sodium bromide (NaBr) and of sodium polysulphide (S_n^{2-}) are used as electrolytes. During charging and discharging Na^+ ions pass the membrane, while Br and S accept and emit electrons. The ZnBr concept has slightly different construction. The zinc-negative electrode and the bromine-positive electrode are detached by a micro-porous separation, while solutions of zinc and a complex bromine compound are circulated through these two compartments. Thus the electrodes serve as substrates for the reaction, and performance of the battery may be degraded if it is not completely charged after discharged. For our examination, the vanadium redox flow battery would be the best suitable solution. Its cycle life efficiency is around 75-80%, and its lifespan is above 12 000 cycles. It needs little maintenance; the most vulnerable parts are the electrolyte-pumps.

C. Financial calculations

In this part of the paper we introduce the financial side of the calculations, the method and the results as well. The method of the examination was the following: the wind speed values are paired with the proper generation, which is known by the power curve. If the average power of the generator in a 10-minute period is lower than the nominal power of the storage unit, the total amount is stored. If production is above the nominal power of the storage, surplus is sold during the off-peak period. The stored energy is sold during peak-period, to maximize income. We have to deal with the cycle efficiency of the technology as well. According to manufacturers, the optimal charge/discharge ratio of the vanadium redox battery is around 1,8:1. This equals 55%, which is significantly lower than the maximal 75-80%, but it is necessary if we want to use it for the longest lifespan possible. Prices of the energy under mandatory purchase are determined by the Hungarian Energy Office. By the date of the examination, peak and off-peak periods were taken into account with 98 €/MWh and 36 €/MWh respectively. These tariffs are raised every year in correspondence with the ratio of the annual inflation, which was treated as constant 1,5% for the whole lifespan. The investigation uses a 30 year period, practically the lifetime of a wind generator. For this interval, all costs and incomes are summed up to see whether the construction of a storage facility is cost-effective or not. Regarding investment costs, the construction of the storage unit means the major part. Operation and maintenance costs are significantly lower, and they are not included in the present examination. Current prices are to decrease in the future, so these scenarios were also included. Fig. 10., 11. and 12. show the main results.

The scenario of Fig. 10. was calculated with the higher investment costs of today, namely 700 $/kWh. The horizontal axis shows the size of the storage unit, while the summed profit values are displayed by the vertical axis. The other variable of the figure is the tariff of the off-peak period. The top curve represents the current market situation with 36 €/MWh. In the future, the Energy Office may decrease this price, in order to force the generators to stop during the night. The decision would not be one of its kinds, because some years ago, off-peak tariff for small CHP units was also cut by 60%! So the tariff is decreased in 11 steps, until it reaches zero. Every curve is marked by a dot at the maximal amount of profit. It is clear by Fig. 10. that feed-in tariffs have to be lowered very much to facilitate the construction of a storage device.

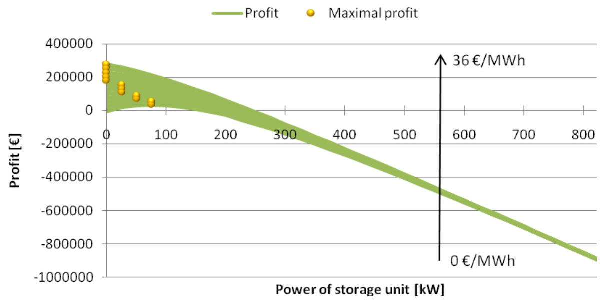

Fig. 10. Profit calculated for 30 years, investment cost is 700 $/kWh

The scenario of Fig. 11. was calculated with investment costs around 400 $/kWh. In this case we still receive the biggest profit if we sell all energy directly after producing it. But even minor reduction of the tariff would make a 50 kW storage unit feasible, while even bigger ones would prove to be cost-effective with a major cut.

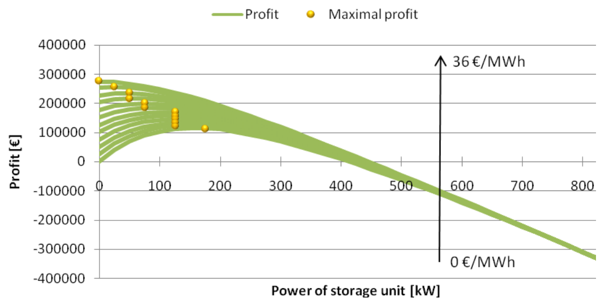

Fig. 11. Profit calculated for 30 years, investment cost is 400 $/kWh

Another aspect was investigated, when the off-peak tariff remains the same (36 €/MWh), but the investment cost of the flow battery is decreasing in 11 steps, from 700 $/kWh to 150 $/kWh. Studies mention the latter one, as the possible price within 5-10 years, depending on how fast the technology will spread. It can be recognized on Fig. 12., that in some years time, it could be a good option, financially as well. As we reach the 350 $/kWh case, a 25 kW storage seems to be the best solution. From this point on, every 50 $ decrease of the investment price would result a 25 kW increase in the size of the optimal storage. This figure shows the high price-dependency best.

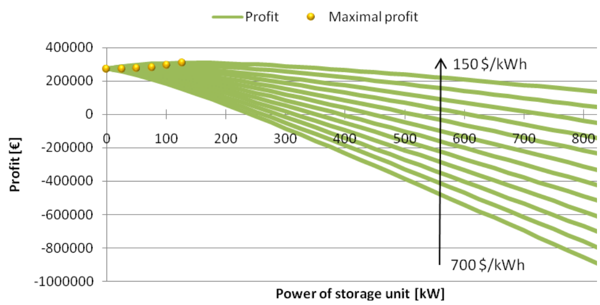

Fig. 12. Profit calculated for 30 years, investment cost is variable

To summarize the investigation, current market regulation and feed-in tariffs are not making the construction of a flow battery storage cost-effective. The regulator can force producers to invest in the technology by decreasing tariffs, and future improvements may also result a cheaper investment price.

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V. Biographies

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