ECONOMIC EVALUATION OF DISTRIBUTION GRID AUTOMATION SYSTEMS – CASE STUDY IN A RURAL GERMAN LV-GRID

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ABSTRACT

The German "Energiewende" poses new challenges for grid operators. Smart Grid systems can be used to avoid the costly expansion of the grid capacity. The present paper illustrates an exemplary investigation of the resulting economic advantage in comparison to a conventional grid expansion.

INTRODUCTION

Massive modifications in the feed-in situation through a growing proportion of decentralised power generation systems as well as an increased penetration of low voltage grids by power-intensive consumers have led to significant changes in the load conditions of low voltage grids (LV-grids) in Germany. This poses new challenges for grid operators. Up to now, power flow in the low voltage grid has been typically characterised by a centralised power distribution, i.e. by a central feed-in via the local substations and by a predictable power consumption of connected consumers. Accordingly, the highest power flows were generally registered at the entry points of the superimposed medium voltage grid, which in the LV-grid would be the local substations. Protection of LV-grids focuses almost exclusively on this crucial point.

The new load situations take the grids to the limits of their capacity. Essentially, this leads to two problems: On the one hand there may be significant local violations to the permissible voltage range when decentralised feed-in within a grid branch exceeds the power consumption of consumers. On the other hand, there may be power flows in the low voltage grid that exceed the resilience of grid equipment, especially of low voltage cables and substation transformers, thus creating internal overload situations that cannot be detected. Today's existing LV grids were not designed to meet current new load and feed-in conditions, which are expected to become more acute in the future. The resulting exceedance of voltage and capacity limits endangers a reliable grid operation compliant with the standards, forcing grid operators to take action [1].

LV-GRID AUTOMATION SYSTEM

In principle there are two approaches to solve the problem: An expansion of grid capacity, i.e. by substituting local transformers with transformers of a higher performance category, as well as expanding the grid, can reduce the occurring problems. However, this is generally associated with high costs. In addition, it must be taken into account that the overload situations described before are limited to a few hours per year. For an optimal operation of LV-grids, another, to a greater degree possible, solution would be to upgrade the grid with automation technology and create a *smart grid*. Hence, the authors of the present paper have developed a decentralised automation system for LV-grids in recent work [2], [3]. The concept of the system is shown in Fig. 1.

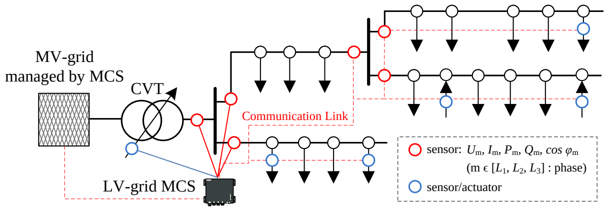

Fig. 1: LV-grid automation system

A few measurement devices (sensors) installed at selected nodes within the LV-grid communicate with the LV-grid monitoring and control system (MCS) and thus enable a cyclic, almost real-time power flow calculation by utilizing a load- and feed-in-prediction method. Controllable actuators can be used for maintaining voltage tolerance bands and grid component utilization rates.

Within a bottom-up-approach, the LV-grid automation system is currently adapted for medium voltage grids (MV-grids) in order to realize the coordinated distribution grid automation system.

As described before, the concept of decentralised grid automation is used to avoid the costly expansion of grid capacity. The system restricts the power flow within the grid to the present grid capacity in case of critical grid states. Thus, connecting additional decentralised power generation systems such as PV systems is made possible. Fig. 2 depicts the power flow and the capacity limits of an LV cable which supplies an agricultural holding plus associated PV system. The virtual extension of the grid capacity by implementing an innovative *active power curtailment* is depicted by the yellow line.

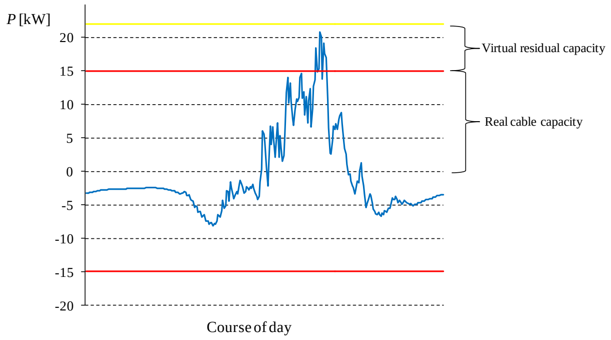

Fig. 2: Power flow and virtual extension of the grid capacity

The economic advantage of presented smart grid system in comparison to conventional grid expansion has been investigated. This advantage has been demonstrated in an extensive case study for a rural German low voltage grid. The concept and the results of this case study will be presented in the following chapters.

ECONOMIC EVALUATION – AIM AND CONCEPT

The aim of the economic evaluation is the net present value (NPV) comparison of the investment in decentralised smart grid approaches as described above to the conventional expansion of the existing grid capacity. In a first step, forecasts of the supply task in 2020, 2030, 2040 and 2050 are made for the considered grid. These forecasts allow a derivation of total load scenarios for every observation year. Now the need for a conventional expansion of the grid capacity on the one hand and the need for (additional) hardware components of the automation concept on the other hand can be determined for each of these scenarios. Here, established grid planning criteria are used to ensure an operation of the grid compliant with the standards. The results of the individual analyses are then fed into a dynamic capital budgeting, so that an economic evaluation of investment alternatives is possible.

Forecast of future supply tasks

During a grid planning process the established planning criteria such as, for instance, Tolerated Voltage Rise / Drop (TVR / TVD) or Tolerated Capacity Utilization (TCU) are primarily applied to two worst case scenarios:

1. Maximum feed-in / minimal load (MaxF / MinL)
2. Maximum load / minimal feed-in (MaxL / MinF)

Since a lot of German LV-grids are characterized by a growing proportion of decentralised power generation systems such as PV systems, scenario #1 becomes the scenario relevant for design (cf. Fig. 3).

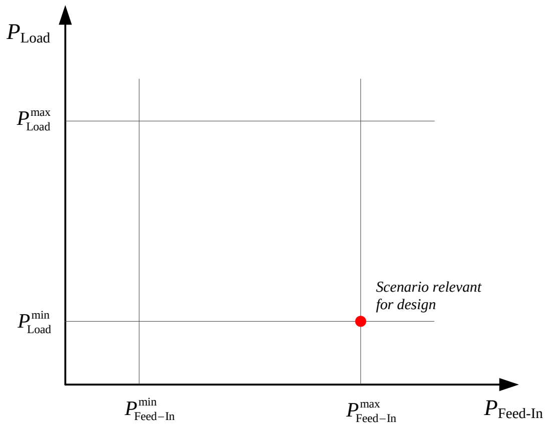

Fig. 3: Load / Feed-In scenarios relevant for design [1], [4]

Thus, the forecast of future PV penetrations is the most important task to estimate the future supply tasks in Germany.

At first, the installed PV capacity in the target year 2050 has to be forecasted. Therefore the overall PV potential of the considered grid has to be combined with the degree of PV penetration used for green field planning purposes. Thereafter the progress of the installed PV capacity in the period between 2014 and 2050 can be narrowed by a natural function of growth [5].

$$P_{inst}\left(t\right)=P_{inst}^{Initial}+\frac{P_{inst}^{Target}-P_{inst}^{Initial}}{1+e^{(-1)\cdot\left(\frac{10}{Target-Initial}\right)\cdot\left(t-\frac{Initial+Target}{2}\right)}} \qquad (1)$$

In a final step, the resulting PV capacities in 2020, 2030, 2040 and 2050 have to be allocated to the consumption nodes of the considered grid.

Conventional grid planning

The need for conventional grid expansions has to be determined for each of the observation years. Therefore the planning criteria TVR = 3% and TCU = 100% are applied to scenario #1 (MaxF / MinL). As a result of this analysis the need for additional LV-cables and for MV-/LV-transformers of a higher performance class is listed over the course of time until 2050. This need is combined with an exemplary price structure of conventional grid equipment (cf. Table 1).

Table 1: Exemplary price structure of conventional grid equipment [1]

Equipment / Procedure	**Price per unit of measure**
MV-/LV-transformer $S_r \leq 400$ kVA	18.50 €/kVA
MV-/LV-transformer $S_r > 400$ kVA	15.00 €/kVA
Walk-in substation	15‘000.00 €/unit
LV-cable NAYY 4x120 SE	8.50 €/m
LV-cable NAYY 4x150 SE	10.50 €/m
Laying of cables: unpaved ground	40.00 €/m
Laying of cables: paved ground	60.00 €/m
Laying of cables: bitumen walkway	85.00 €/m
Laying of cables: driving surface	100.00 €/m
Annual operating costs LV-cable	540 €/km

It is necessary to cover this price structure with a constant increase. An increase of 1.5% per year is close to reality.

Grid planning considering smart grid systems

Decentralised smart grid approaches provide an alternative to conventional grid expansions in the considered grid. Based on the identified need for conventional grid equipment the basic equipment and possible extension of the smart grid system have to be determined. Essentially, this involves hardware components such as remote measurement units, actuators to execute the possible control interventions and corresponding communication links. The total load scenarios for every observation year are examined individually to that effect. Since the used hardware components offer a maximum useful life of 20 years, a regular exchange of the components within the observation period must be considered in addition.

Active power curtailment is one element of the control intervention portfolio of a smart grid system. This curtailment causes compensation payments to the operator of the PV system which have to be considered within the economic evaluation as well. First of all, the admissible rated power of a PV system which can be connected to the present grid without causing any boundary violations has to be determined. In the following, this admissible rated power can be used to calculate the energy amount that cannot be fed into the grid due to active power curtailments. The area limited by the admissible rated power on the one hand and the annual duration curve of a PV system on the other hand identifies this energy amount (cf. Fig. 4).

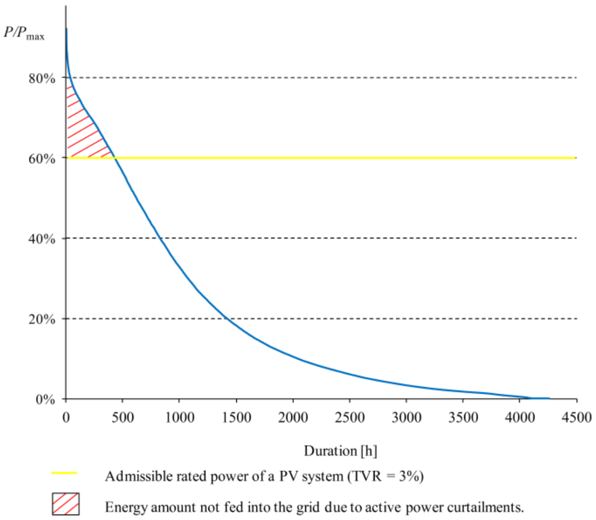

Fig. 4: Annual duration curve of a PV system [1]

This identified energy amount depends on the underlying TVR. Since a smart grid system will not execute a control intervention in case of a violation of the conventional planning criterion TVR, but only in case of a violation of the permitted voltage range of ±10% according to EN 50160, TVR = 4% and TVR = 5% can be postulated as moderate alternative scenarios in comparison to TVR = 3% (worst case) to determine the admissible rated power.

Beside the hardware components (basic equipment, extension, exchange) and the compensation payments for energy amounts not fed into the grid due to active power curtailments the following additional cost components should be considered as well when evaluating smart grid systems:

- Rotational function tests
- Compensation payments for higher grid losses
- Unavoidable grid expansions

CASE STUDY IN A RURAL LV-GRID

The described method for investigating the economic advantage of decentralised grid automation in comparison to conventional grid expansion was applied to a typical rural LV-grid in Frankfurt/Main (Germany). The grid is characterized by its long lines, its simple grid structure and an enormous PV potential. In the grid there are several agricultural properties which exhibit six PV systems with 216 kW_p of installed power. The grid was equipped with components of the described LV-grid automation system for field test purposes during the research project “iNES – Smart Distribution Grid Management”.

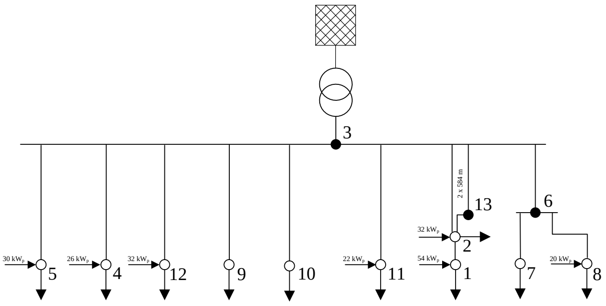

Fig. 5: Investigated rural LV-grid in Frankfurt/Main

The results of the PV forecast for the investigated grid are shown in Fig. 6. Accordingly, the installed PV capacity in the target year 2050 amounts to 425 kW$_p$.

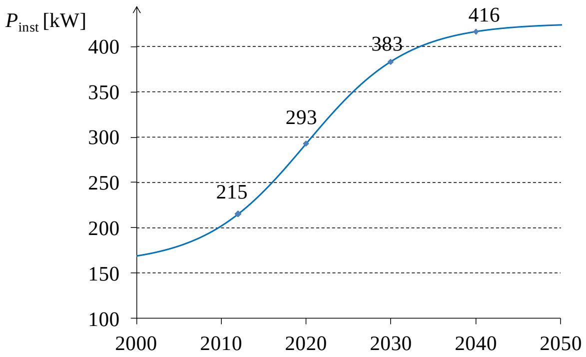

Fig. 6: PV forecast for the investigated LV-grid [1]

The depicted PV capacities in 2020, 2030, 2040 and 2050 were allocated to the consumption nodes of the considered grid. In the following the need for a conventional expansion of the grid capacity on the one hand and the need for (additional) hardware components of the automation concept on the other hand were determined for each observation year and combined with the underlying price structures. Moreover, the energy amount that could not be fed into the grid due to active power curtailments was calculated (cf. Fig. 7).

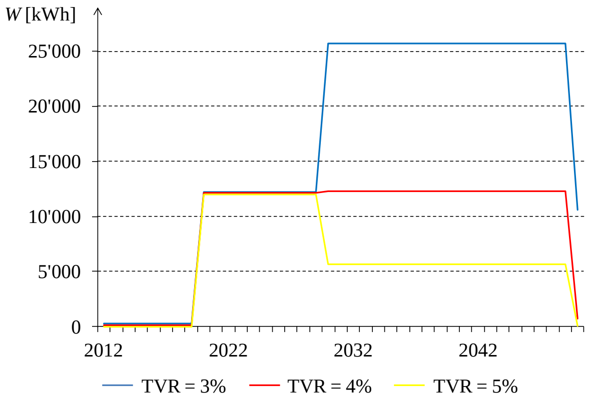

Fig. 7: Course of energy amount not fed into the grid [1]

The results of the individual analyses were then fed into a dynamic capital budgeting, so that an economic evaluation of investment alternatives is possible. Table 2 shows the results of the net present value calculation for the investigated rural LV-grid.

Table 2: Payments per investment alternative [1]

Investment alternatives	**TVR**	***NPV*$_{2014}$**	**Savings**
Conventional grid expansion	3%	35’723 €	0%
Decentralised grid automation	3%	27’699€	22.46%
Decentralised grid automation	4%	23’877 €	33.16%
Decentralised grid automation	5%	22’020 €	38.36%

The profitability of an investment decision in favor of the described smart grid system is clearly visible. Even when considering the worst case scenario (TVR = 3%), significant cash flow advantages over the conventional grid expansion arise.

OUTLOOK

The manual evaluation of the economic advantage of smart grid systems is very extensive and requires a high level of expertise. Thus, future investigations should be executed software-assisted. A corresponding research project is already initiated.

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