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Connecting Small, Private Independent Hydro Power Plants to Increase the Overall Power Generating Efficiency

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Abstract

In countries, where many small rivers exist, the geography can be used to implement environment-friendly small hydro power plants for the generation of energy. The smaller such hydro power plants are, the higher is the impact of environmental incidents. Usually, there is more than one small hydro power plant located alongside one river, mostly operated by different owners. To increase the overall power generating efficiency of all hydro power plants alongside one river, a good communication- and cooperating concept is needed.

In our work, we propose a system concept and a prototype implementation for several small, private and independent hydro power plants to increase the energy production through a networked intelligent control system. We also show possibilities for avoiding events, which usually induce downtimes of the small hydro power plants. If these events can be minimized in number and duration, the overall energy production time is higher.

Keywords: *small hydro power plants; intelligent control system; cooperation; hydro power;*

1. Introduction

Starting situation: Small hydro power plants act concerning their adjustment and control without integration and consideration of the needs of small hydro power plants in the neighborhood. This is especially the case if they are in the property of different operators. Significant inefficiencies like a lower electricity production are the result. For example at the Alm -– a river in Upper Austria with a length of 48 km –- 55 small hydro power plants exist, operated by more than 40 owners. Although such small hydro power plants are located only with a small distance between each other in the river, they have no connective system which facilitates data transfer for optimizing their performance, respectively enhancing a demand-actuated production of electricity. State of the art are isolated applications without any connection or data-sharing.

1.1. Objectives and innovative content

Aim of our research is the exploration of a novel smart networking system which facilitates the ideal control and collaborative adjustment of small hydro power plants on a river. Therefore the latest data of all hydro power plants arranged in a chain along the river has to be implied. The smart networking system comprises the collection and analysis of the latest data delivered from the small hydro power plants on real-time basis (e.g. performance data, water level, technical parameters on turbines and generators). Smart behavior of the networking system provides control information for optimizing performance and demand-actuated electricity production for the small hydro power plants participating in the smart network.

Also external data such as the amount of rainfalls will be fed into the smart networking system automatically. Such a control and networking system (expert-system) can reduce the costs of hydro power production mainly by reducing downtimes and maintenance expenditures and increasing the reliability of hydro

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power production. Additionally it facilitates a more efficient electricity production out of the river's available water supply by increasing turbine efficiency without harming nature. Smart control systems enhance a remote-control of small hydro power plants which facilitates the rectification of faults, which additionally increases the efficiency of the small hydro power plants. In a first step a detailed concept is prepared which will be used for the development of a prototype in follow-up actions. The project involves real flowing waters and local operators of small hydro power plants. The probing is carried out with the involvement of specific stretches of running waters at established small hydro power plants involving their operators.

Hydro power plants are classified by their average output: small hydro power plants operate at <1MW, medium hydro power plants operate at 1-100MW and big hydro power plants operate at >100MW.

The rest of the paper is structured as follows: section 2 shows related work and state of the art technology. In section 3 we try to figure out, which existing cooperation- and integration concepts for (small) hydro power plants exist. Section 4 describes solution concepts on a hardware- and software level. Possible other increasing in the power generation is analyzed in section 5 and we sum up and close our work in section 6.

2. Related Work

2.1. State of the art

Small hydro power plants cover approximately 9\% of Austria's power demand and are of great significance for the security of supply and regional economy due to their decentralized character. A constant downward trend in electricity trading prices due to market turbulence and high requirements of the EU's water framework directive lead to a threat for the operation of the plants, making considerations of alternative concepts of technology and utilization a necessity.

The main number of small hydro power plants is equipped with outdated control devices -- modernization of these controls alone could increase energy yield for up to 10% [3][9]. Further, small hydro power plant controls are often isolated applications, one reason being the various plant operators along a river. Interconnecting or coordinated control and optimization analogous to big hydro power plant cascades offers great potential, which has not yet been observed. Small hydro power plants which are currently in operation in Austria are equipped with varying types of controls. Digital controls and programmable logic controllers (PLC) are in operation at newer plants, whereas older plants still operate on analogous or mechanical controls, which allow no external access to current data [3].

No safe presumption can be made about the various kinds of controls and their dissemination within the small hydro power plants; however it can be assumed that the majority of plants are using analogous or mechanical controls. According to estimations more than 60% of existing small hydro power plants are equipped with outdated (analogous or mechanical) controls.

In a report commissioned by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety an improvement potential in energy yield of up to 10% only through optimization of plant control is calculated [3], whereas Matz et al. [9] assumes an increase between 1% and 5% of the energy production. Thus, modernization of controls of small power plants alone show significant potential, which can be ascribed to their outdated control equipment.

In order to facilitate the supervision of a plant, new or renewed plants are equipped with remote access in order to allow for transmission of data via a user interface. This allows the plant operator to view current data of the plant and alter them, interfering with the control system. However, data can neither be used for external analyses nor is there a possibility to influence the system by changing certain parameters due to incoming data or externally predefined rules.

2.2. Problem

In contrast to large run-of-the-river power plants, small hydro power plants are prone to experience problems with suspended loads (foliage, branches, waste), which makes frequent flushing necessary (in extreme cases every 15 minutes) in order to keep the power production at a constant. Furthermore, smaller hydro power plants are generally more sensitive and less resilient to flotsam in the water (e.g. Kaplan turbine). Communication between small hydro power plants along the same river is, as opposed to large power plants, not automated.

If, for instance, a diversion power plant has to be shut down due to low water, as a consequence, other power plants also have to shut down as well since they also have too little water available to keep up production (so-called water holes). The diversion plant does not release any water into the headrace channel, which causes backwater as far as the next weir upstream. Only when the headrace channel is full, water is led over the weir to the downstream power plants. In this particular case, plants without automated restart systems have to be manually started again.

Specific issues exist for small so-called diversion power plants, where a portion of a river is channeled into a turbine through a separate canal. There, for instance, the diversion plant has to be shut down due to low water; as a consequence, other subsequent power plants also have to shut down as well since they also have too little water available to keep up production. In this case, plants without automated restart systems have to be manually started again.

Thus, due to the significant differences between large and small hydro power plants, the results cannot be scaled and transferred.

Unfortunately, automated and interconnected solutions, which are used in large hydro power plants, are often neither economically feasible nor practical. Large power plants along European rivers like the Danube, Inn, Traun, Oder and Elbe have been working on interconnected solutions for a while. These solutions access to complex numerical models or water management models in order to control and regulate hydro power plants in a sequence of cascades [4] [11].

In Nestmann and Theobald [11] it is shown that the automation of barrages in a sequence of cascades is of increasing importance. There, on the example of the Rhine and Neckar River the principles and applications of a numerical method used for preparing the parametrization have been developed, also taking account of the various interests of navigation, energy production and flood protection. As an example for a smaller river, Edelsbrunner [4] focused on the small hydro power plants along the Pöls, a river in Styria (Austria) to develop various methods for an optimized flushing management for the river Pöls. To ensure an optimized operation of hydro power plants in a sequence of cascades further solutions are based on forecast models [1][6][9][10]. As a consequence of climate change the water supply and demand will change in the near future. Matz et al. [9] describes the possible effects on water economy and hydro power generation. These changes can be countered through the optimized regulation of hydro power plants among others based on inflow forecasts, while considering the additional functions of the dams. Another model extend their weather forecast models with economic aspects, such as feed-in tariffs [10], while for other operators of hydro power plants the significance of hydrological forecasts is expressed with regards to an economical plant operation [1]. Furthermore, by combining model predictive control techniques with decomposition-coordination methods, Florez et al. [6] develop a control system for a whole hydro power valley.

3. Integration & Cooperation Concept

Big hydro power plants today are already strongly integrated or are at least on the way to integration. Intensive use of information technology for data integration and management, for providing predictions based on historical and real-time data, as well as for the overall control systems is state of the art now at least for big power plants [7][8][14].

Today, interconnection even goes a step further, especially connecting to network partners and power supply companies [14]. Global players such as Voith (Germany) Renewable Energy or Andritz Hydro provide a series of respective solutions. However, the focus of these products is typically a highly integrated single but large scale plant [5][14].

When doing paper research on cooperation of small or micro hydro power plants, most research articles focus on the cooperation between energy producers and the network providers (grid, smart grid, mini grid, etc.) to fulfill the customer's needs [2][12].

Cooperation between the energy producers to increase their efficiency, thus focusing on a different target dimension to be optimized, receives rather little attention. Thalhammer [14], Farina [5], and Stewart [13] provide interesting ideas, concepts and/or algorithms which could be relevant to the basic problem discussed in this paper, but with a strong focus on large scale plants. In the following, we discuss alternative control strategies and further consider the impact on the IT innovation necessary to implement these strategies.

3.1. Control Strategy

With small hydro power plants, the prediction of the feeder stream is one of the most important facts to provide the different forecast calculations, necessary to optimize the controlling of the plant [9]. With our scenario not only climate, weather forecasts, prediction of snow melt, etc. are important factors for the prediction of the feeder stream, but also the behavior of other small hydro power plants upstream. The behavior may be influenced by factors such as the amount of energy which can be delivered, size and level of flood basins, or the need for flushing the trash racks. From a rather theoretical point of view, a series of small hydro power plants which operate on one river can be regarded as a linear system with a defined neighborhood. The neighborhood of one subsystem can be specified as a set of directly affecting subsystems of the whole linear system [5]. The control strategy determines the essential characteristics of how the distributed subsystems (the plants) in such a linear system are controlled. Farina [5] proposes a classification of distributed Model Predictive Control (MPC) based on:

- the information exchange protocol, i.e., non-iterative or iterative,
- the type of the cost function to be optimized, i.e., cooperative or non-cooperative, and
- the topology of the transmission network, i.e., fully connected or partially connected.

We concentrate on two manifestations of such distributed MPCs, but also consider some centralized approach:

1. The Local Control Strategy (LCS) is based on a non-iterative and non-cooperative approach, which allows for only a partially connected topology.
2. The Collaborative Control Strategy (CCS) uses a cooperative approach, which relies on a fully connected topology of the transmission network.
3. The Centralized Control Strategy (CCS) uses information from all partners in the overall system and supplies them with the control details. Each partner has to connect to this central service, which coordinates all partners with respect to defined individual and the overall goals. Cooperation is performed via this centralized service.

3.1.1. Local Control Strategy

With the local control strategy, the control of the individual subsystem relies on data from other subsystems. Thus, they are all data consumers and data providers as well. The control of the individual subsystem however is determined locally, no cooperation with others is considered for this aspect. Farina [5] propose their distributed predictive control schema for linear discrete-time systems, which focuses on non-iterative, non-cooperative, partially connected, to solve this kind of a distributed MPC problem.

At each sampling time it is only the neighbors who either send or receive information about their future reference trajectories, and guarantee that the actual ones lie within a certain range of the reference ones. Then, each subsystem solves its own optimization problems.

To Farina [5] the highlights of their concept is, that (1) it is not necessary for each subsystem to know about the control details of the others, not even their neighbors, (2) information only needs to be transmitted to neighbors, thus only a limited number of communication partners, and (3) the algorithm used is very similar to the ones already applied in industry today.

To optimize the control of a single plant, Matz et al. [9] propose a two-phase method. In the first phase, the plant control is optimized "off-line", i.e., all predictions and decisions are based on historical data only. The second phase also includes the feeder stream prediction based on current, if possible real-time data and/or predictions. With this approach, additional data from the neighbors can be integrated into the individual control.

The neighbor-to-neighbor communication with this strategy also provides some profit to selected partners via decentralized optimization within the linear system even if not all partners in the line are contributing their information.

3.1.2. Cooperative Control Strategy

In contrast to the local control strategy, the cooperative distributed one requires all subsystems to consider the effects of local control actions on them. Furthermore, each subsystem also has to optimize for an objective of the overall system. To achieve the same optimal results for the overall objective as with the centralized control strategy, Stewart et al. [13] propose the use of state and output feedback to improve the overall performance.

The cooperative control strategy is frequently used within one plant, integrating the different systems, to achieve an optimal overall objective [5][13].

3.1.3. Centralized Control Strategy

With the centralized control strategy all subsystems are controlled via a single, centralized service, optimizing towards a centralized controller objective. All systems report to this service and receive their control information from it. While this approach offers many technical advantages, such as one powerful centralized server equipped with strong optimization software, transmission channels only from single subsystems to the centralized service, often organizational objections against one centralized service prevent this solution in practice [13].

The decision on the control strategy is strongly influenced by the fact, whether the subsystem owners trust in the centralized service and in their willingness and ability to consider the individual objectives, too.

With the local strategy, it is always the single subsystem which has full power of control, while you give it up completely with the centralized one. The cooperative strategy asks for additional means such as good negotiation skills, when it comes to considering the effects of local control actions of all subsystems.

With regard to the specific situation of small hydro power plants in our scenario we propose the following approach.

3.2. Consequences for the Almtal Scenario

Further, we discuss considerations on the technical infrastructure, organizational and financial aspects concerning the control strategies, with respect to our scenario. For more than 100 years electricity is produced by hydro power plants on the Alm. Today 55 small and micro hydro power plants of more than 40 owners are operated on 48 kilometers. The currently used control systems go from analog relays over different kinds of PLCs to industry PCs.

3.2.1. Discussion of technical, organizational and financial aspects in the Almtal Scenario

Considerations concerning **technical aspects** thus concern the controls, the network (connection and transmission) and data integration. As there are still several analog relay controlled hydro power plants, many PLCs and some industry computers, many of these systems are not ready to calculate complex control algorithms to optimize energy production, neither for their own system (cp. local control strategy), nor for the cooperative control strategy, which demands to take all models of the other subsystems, i.e. the other plants, into account.

To implement a decentralized technical solution, extensive investment would be necessary with several of the plants, as each would need to implement the optimization algorithms and provide an infrastructure ready to run these sophisticated algorithms, especially complex with the collaborative strategy. It is not only the algorithms, but also the data which is needed from the plants and the optimization results as input for the control system, which are relevant. No data integration has been necessary till now, thus no integration standards, and also no network between the subsystems (power plants). The more complex the topology is and the more data are transmitted for the optimized control, the higher will be the requirements on the system(s) - from the communication infrastructure to IT infrastructure and the optimization algorithms.

Concerning the **financial aspect** it will be important to compare the costs for implementation, long-term operation and maintenance including a quantified estimation of the innovative strength. Thus, implementing the cooperative strategy with a decentralized infrastructure is not realistic with our scenario, as its technical complexity is too high for small operators and the anticipated costs as well.

The main problem with the centralized control strategy is rather **organizational objections**. The partners involved fear to lose control over their own system, when it is centralized, and thus do not accept such a solution [13].

3.2.2. Proposed concept

With respect to the size and the current infrastructure of the subsystems involved in our scenario as well as the anticipated costs of the different solutions, we propose to clearly distinguish between the infrastructure strategy and the control strategy.

Building up a common, centralized infrastructure with connection (and interfaces) from each partner, offers optimized services to all subsystems, regardless of the control strategy which will be implemented. A strong server infrastructure combined with a reliable and secure transmission network is the basis for this architecture. With a common data integration service, data can be collected from different sources and by different interfaces. No local recording is needed. Huge power plants today already integrate different subsystems. Integration on the level of the overall control center is the most effective one there [14].

As all data from all subsystems are available on this common server, all control strategies presented before can be implemented on this basis. In any case the calculation is done on a highly efficient centralized resource and the results are sent back to each subsystem.

We propose to implement the cooperative control strategy, as all data needed is already available and it promises the best fit of optimized results for all partners, which is a good basis for a successful long-term collaboration.

Not only the immediate availability of data and control parameters from the plants as well as reduced network traffic (esp. with the cooperative control strategy) is important benefits. Also, changes to the overall system (e.g., new partner joining or an existing is leaving) can easily be propagated.

Despite all the advantages of this concept, some owners of subsystems may still be bothered by the use of a centralized service. Here it is up to the provider of this common service to build the trust needed to successfully cooperate to provide better results for all partners.

4. Solution Concept & Proposed Implementation

In this section, we propose a solution for the challenges, which arise in the special scenario of connecting different small hydro power plants and we refer to additional ideas and concepts to increase the efficiency of generating energy. There exists a prototype implementation at several hydro power plants, which can be adapted and used for a smart connection. In subsection 4.1. we describe possible hardware, which can be used for the implementation, in subsection 4.2., the functionalities of the used software concept are proposed.

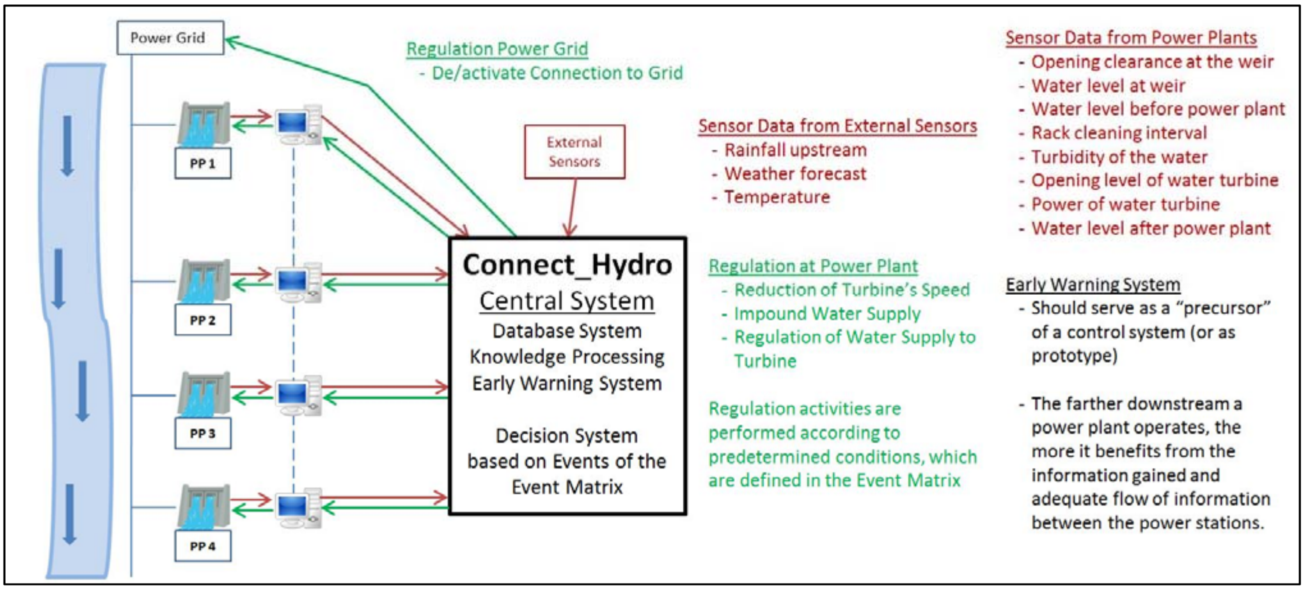

Fig. 1. Overview of the technical concept in the project "Connect_Hydro"

4.1. Technical & Hardware Level

At present, most small hydro power plants in Austria with less than 500kW power are operating isolated from the hydro power plants upstream and downstream. They neither provide data for hydro power plants alongside the river nor use data from these power plants or any other source. Many of these power plants have not even remote control access due to obsolete control techniques and the often close-by living owners, who take care of their respective hydro power plants.

In order to find out whether real improvement can be achieved by connecting single small hydro power plants the current situation has to be examined. Therefore data from different small hydro power plants alongside the river "Alm" is collected and analyzed regarding increasing electrical power and decreasing maintenance effort.

If there is room for improvement by connecting single small hydro power plants a simple approach has to be developed, which allows small hydro power plants with various technological standard to benefit from this connection at low cost. This includes specifying an instrument for collecting data from small hydro power plants and providing them with control instructions on the one hand.

On the other hand a central unit is required to unify the collected data from the participating power plants and other sources and to create useful information for the individual small hydro power plants. The single small hydro power plants are connected by the central unit, which may also take responsibility for additional tasks, for instance producing data for an early-flood warning system.

4.1.1. Different initial situations in controlling the small hydro power plant

One main problem of setting up an overall communication system is having different states and types of devices, which are used for controlling the parts of the small hydro power plant. These can be relay control stations, small or large programmable logic controllers (PLC), or industrial computers.

When implementing a control system with external logic, the following steps must be considered: (1) Gathering data from several different small hydro power plants, (2) Transfer the gathered data to the external logic, (3) Send the control recommendations back to the small hydro power plants.

4.1.2. Data Logging in the small hydro power plant

Currently a solution prototype is installed at several stations. Data is gathered from three places in the small hydro power plants. The data is sent to the central server via C++ implementations. Connection to the server respectively the data transmission operates via TCP/IP.

Components of the central server:

- Evaluation software: data from the sensors is received and stored/inserted into a database via a JAVA-application
- Database: responsible for data storage (MySQL)
- Web-Interface: visualization of the stored data via PHP and JavaScript

The following parameter are gathered at the small hydro power plants: opening clearance at the weir, water level at weir, water level before and after power plant, rack cleaning interval, turbidity of the water, opening level of water turbine, power of water turbine.

For every parameter, the following information is gathered (since 2016, about 18 million database entries):

- Logger ID (loId, int(11)), Logger IP (loIp, varchar(45))
- Logger Time (loLoggertime, int(11)), Logger Timestamp (LoTs, datetime)
- Logger Port (loPort, char(2)), Logger Value (loValue, double), Logger Device ID (loDeviceId, varchar(20))

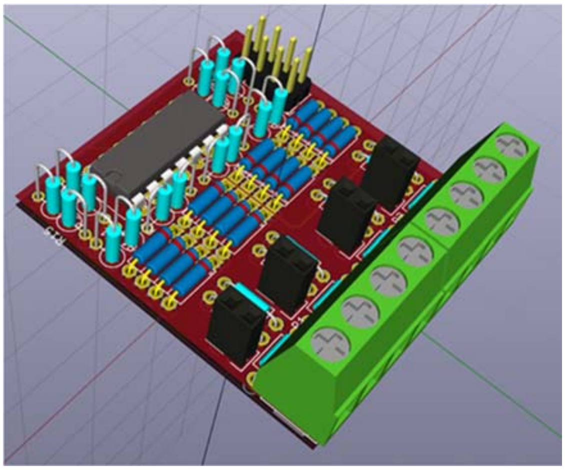

Fig. 2. Hardware for Data Logging

4.1.3. Components of the networking unit

Criteria of selecting the components are price, robustness, programmability, connectivity, availability, power consumption, interfaces, type of signals, compatibility with existing power plant controls, size.

Example of components of a finished solution/implementation:

- Programmable controllers e.g. Siemens Simatic S7-1200, Mitsubishi MELSEC FX3GE, Advantech Adam 6024
- Industrial computer e.g. Siemens SIMATIC IPC227E
- Mini-PC e.g. Raspberry Pi, BealgeBone Black
- Modules for combination e.g. Arduino Ethernet, Atmega, Arduino Nano, Atmega328, Enc28J60

Example of components for a self-construction solution:

- Printed curcuit board (self-implemented)
- Microcontroller e.g. ATmega328P
- Ethernet e.g. Enc28J60
- Others e.g. operation amplifier (LM324), electro conductors (Elko 100μ), voltage linear regulators (LM7805CT)

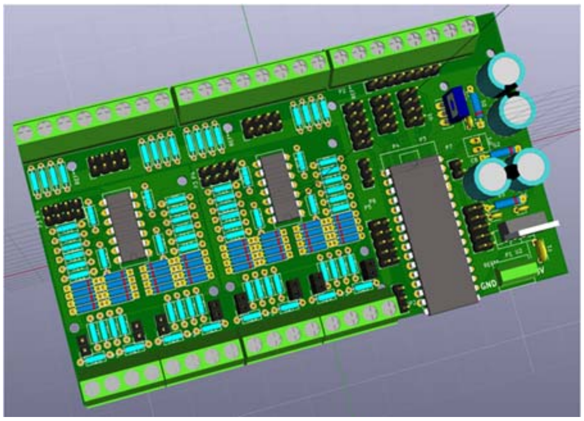

Fig. 3. Hardware for the Networking Unit

4.1.4. Components/tasks of the central server

- Central communication component between the small hydro power plants (insert data from power plants into the database, send control information from database/system to the power plant)
- Data Storage (relational database, converting measured data to real values)
- Rule-based component (manage rules \& if-then-relations, generate control information based on data and rules)
- Self-learning component (automatically improving rules, based on benchmarks)
- User interface (web/app; manage users, rights, rules, assets, messages; visualization of facilities and parameters)
- Coupling with early-warning-system (e.g. via web service, water levels, weir opening, disturbances)
- Notification system (e.g. via sms or email, necessary for the facility operators)

4.2. Software Level

At the software level, we propose a central system, which is a combination of a "Database System", a "Knowledge Processing System" and an "Early Warning System", that announces alarms/alerts based on the "Decision System", which is based on the events of a particular, for this application scenario developed event matrix. The overall communication- and regulation-schema can be seen in figure 1.

Data from sensors at the power plants is gathered as well as sensor data from external sources and stored in the central system (mentioned in section 4.1.4.), mainly in the database. From this database, the knowledge processing system can learn, based on the events defined in the event matrix, e.g. how several sensor data combinations and occurrences will lead to which events (e.g. much rainfall upstream obviously can lead to a flooding of the power plants).

Based on the knowledge in the system, it is possible to predict harmful occurrences (e.g. a flooding of a power plant can damage the active turbines), to make decisions (e.g. to prevent damaging the turbines, they should be deactivated when a flooding is predicted) and give signals either to the early warning system (e.g. message to the owner/operator of the small hydro power plant that it is recommended to deactivate the turbines) or a installed regulation system (e.g. which automatically can deactivate the turbines).

The workflow of the prototype is processing the input- and historical data from the database, mapping it to the events in the event matrix, correlating with previous events and knowledge from the knowledge processing system.

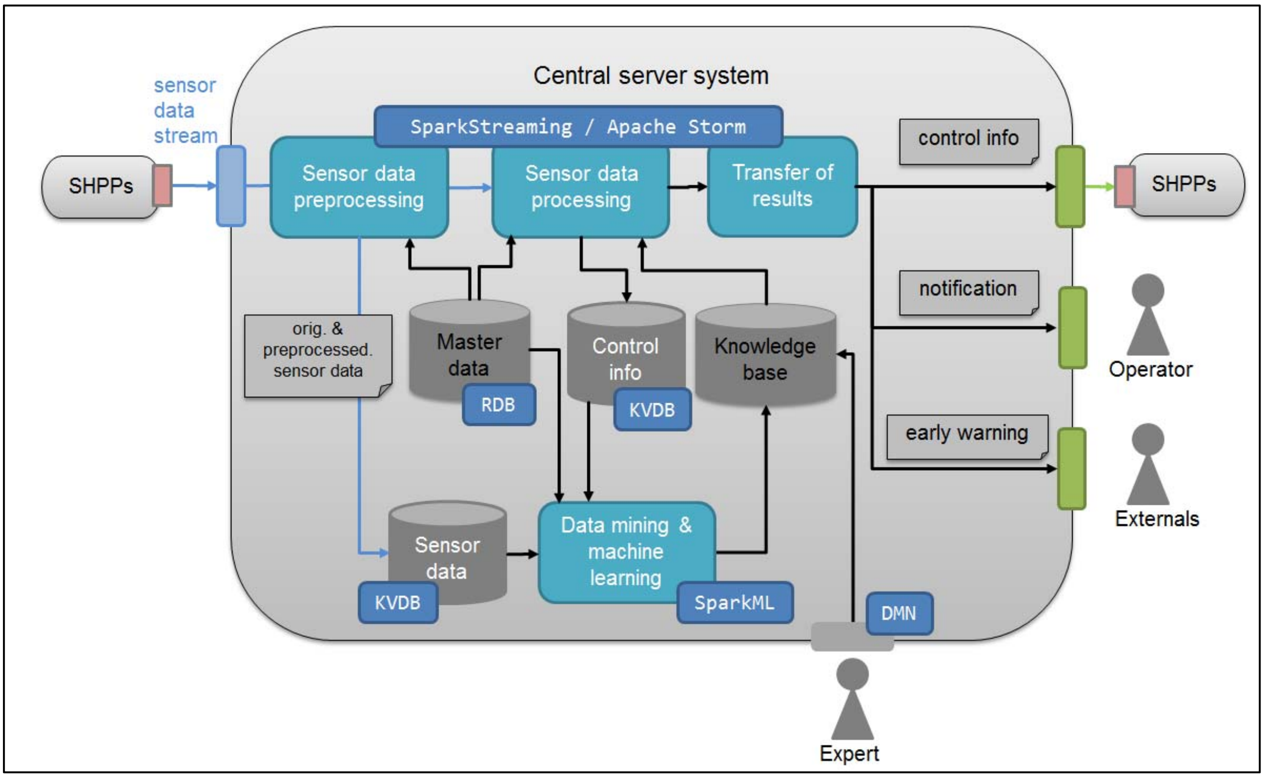

Fig. 4. Structure of the Central Server System including Technology Aspects
SHPP = Small Hydro Power Plant | RDB = Relational Data Base | KVDB = Key-Value Data Base | DMN = Decision Model and Notation

4.2.1. Database & Data Model

In this subsection, the Data-Model is described self-explanatory by the extended Entity-Relationship-Diagrams in Figures 5-8 which was implemented in the project.

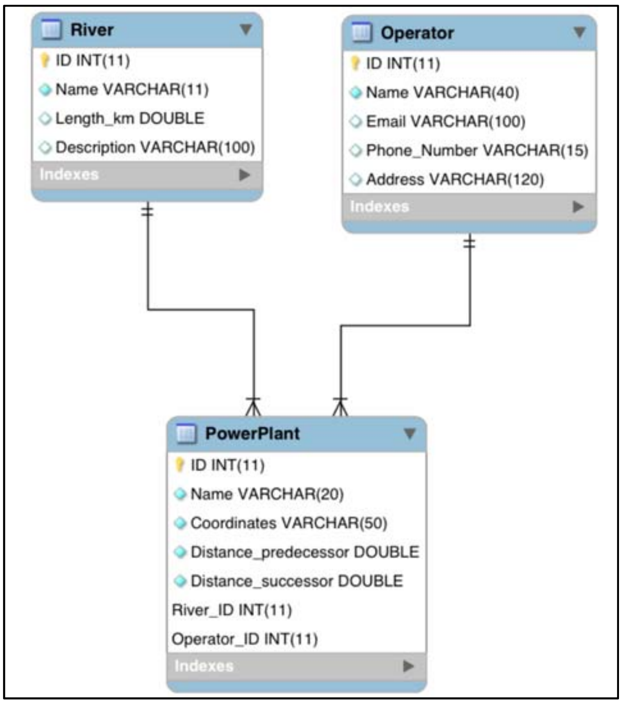

Fig. 5. Power Plant Operator River Relation

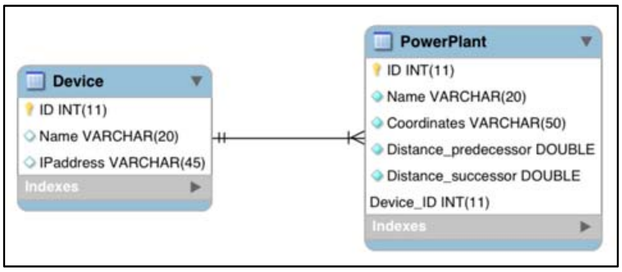

Fig. 6. Power Plant Device Relation

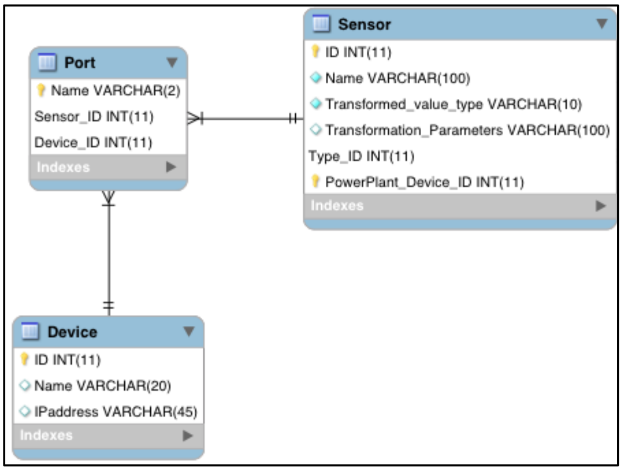

Fig. 7. Device Port Sensor Relation

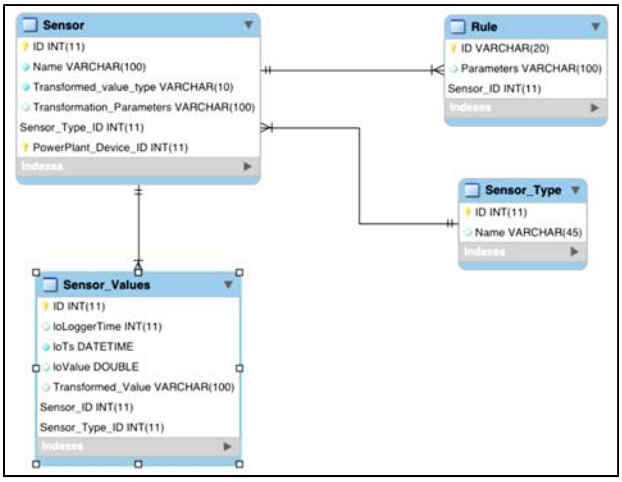

Fig. 8. Sensor Relations

5. Potential Analysis & Economic Evaluation

As already described, a prototype implementation has been installed at three hydro power plants on the Alm – river in order to gather and analyze data on site over a period of almost one year. Thus, it was feasible to observe and evaluate critical events such as dredging works and throttling of the water throughput to derive an increased energy production through a networked intelligent control system. In the special case of the observed hydro power plants on the Alm – river an enhanced energy production of about 3% was quantified for a period of one year, which is the general result of reduced downtimes.

To get an idea of the market for such intelligent control systems also a potential analysis for the federal state of Upper Austria and Austria has been done in terms of how many hydro power plants are appropriate for such intelligent solutions. For this field of application it was essential to filter those power plants which meet following criteria:

- Plants without intelligent control system
- No (pumped) storage power stations
- Maximum power of the plant >10kW and <10MW
- Number of plants on a river >1 hydro power plant
- Mixed ownership structure

Based on data from preliminary projects, such as Tichler et al. [15] as well as on statistical data (Statistics Austria, E-Control Austria, Small-Scale Hydropower Austria Association) for Upper Austria 660 and for Austria 2.200 hydro power plants have been identified. Assuming the same increased energy output rate through intelligent solutions as on the stations with a prototype (3%) leads to an energy surplus of 15GWh in Upper Austria and 96GWh in Austria. For the federal state Upper Austria the increased energy output corresponds to 0.15% of the total hydro power generation there (incl. large-scale hydro power), whereas for Austria a share of 0.25% has been quantified.

Both results, for Upper Austria and for Austria, show a significant portion of an enhanced energy yield, even though an implementation of an intelligent control system in small hydro power plants needs further energetically benefit analysis.

Table 1 shows the main results of the potential analysis for intelligent control systems in small hydro power plants in Upper Austria and Austria.

Table. 1. Results of the potential analysis for Upper Austria and Austria

	Upper Austria	Austria
Suitable small hydro power plants	~ 660 plants	~ 2.200 plants
Ø annual energy output	500GWh	3.200GWh
Increased energy output	15GWh	96GWh

Finally, a broad assessment of intelligent control systems in context of small hydro power plants also covers a cost-benefit analysis. Thus, based on the results of the potential analysis the concept of annuity methodology and learning curves was used to investigate economical values. Since the detailed cost structure corresponds to the three prototypes implemented on the Alm, the principle of learning rates is essential as it serves to estimate the future investment costs of a technology under development [16]. The theory of technological learning is based on the idea that with increasing amounts or units of a given technology the specific costs per unit decline. Thus, a learning rate of e.g. 20% indicates a cost reduction by 20% per unit if the cumulative production is doubled. Among different learning rate concepts the approach of one-factor learning curve (OFLC) is used for the decentralized hardware components (networking unit) at the hydro power stations. These costs cover the expenditures for material, assembling, working time, sensor technology as well as the integration in the existing control system. Based on [16] and [17] a learning rate of 10% is assumed for this evaluation.

The cost-benefit analysis has generally investigated the costs for a centralized system (server) and for the networking units and their implementation as decentralized components. For the networking units at the three test sites and their integration in the control system costs of around 4.400€ per unit were calculated. However, the development costs for the server are the crucial factor for the cost-benefit analysis, since these costs are estimated at 150.000€. Thus, the number of units assuming for a roll-out of the intelligent control system has a deep impact on the economic results as the high costs for the server has to be disbursed to the power plants connected to the server.

Based on the investment and operating costs (range of 20.000-90.000€ for operation & maintenance costs for server, depending on the connected units) the total annual costs for the intelligent control system are calculated for several scenarios. Figure 9 shows the results by applying a learning rate of 10% and the annuity method assuming a discount rate of 3% and a period of observation (=life span of the technologies) of 15 years.

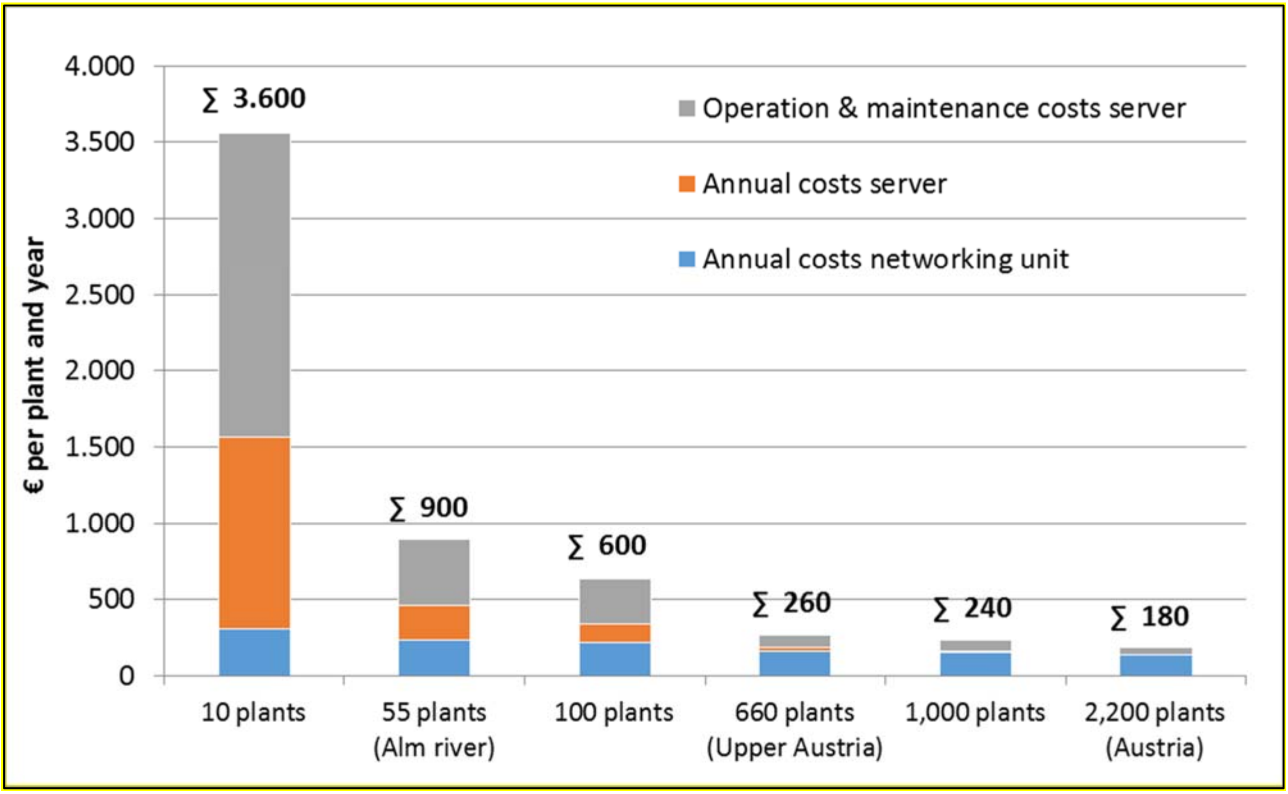

Fig. 9. Total annual cost per plant

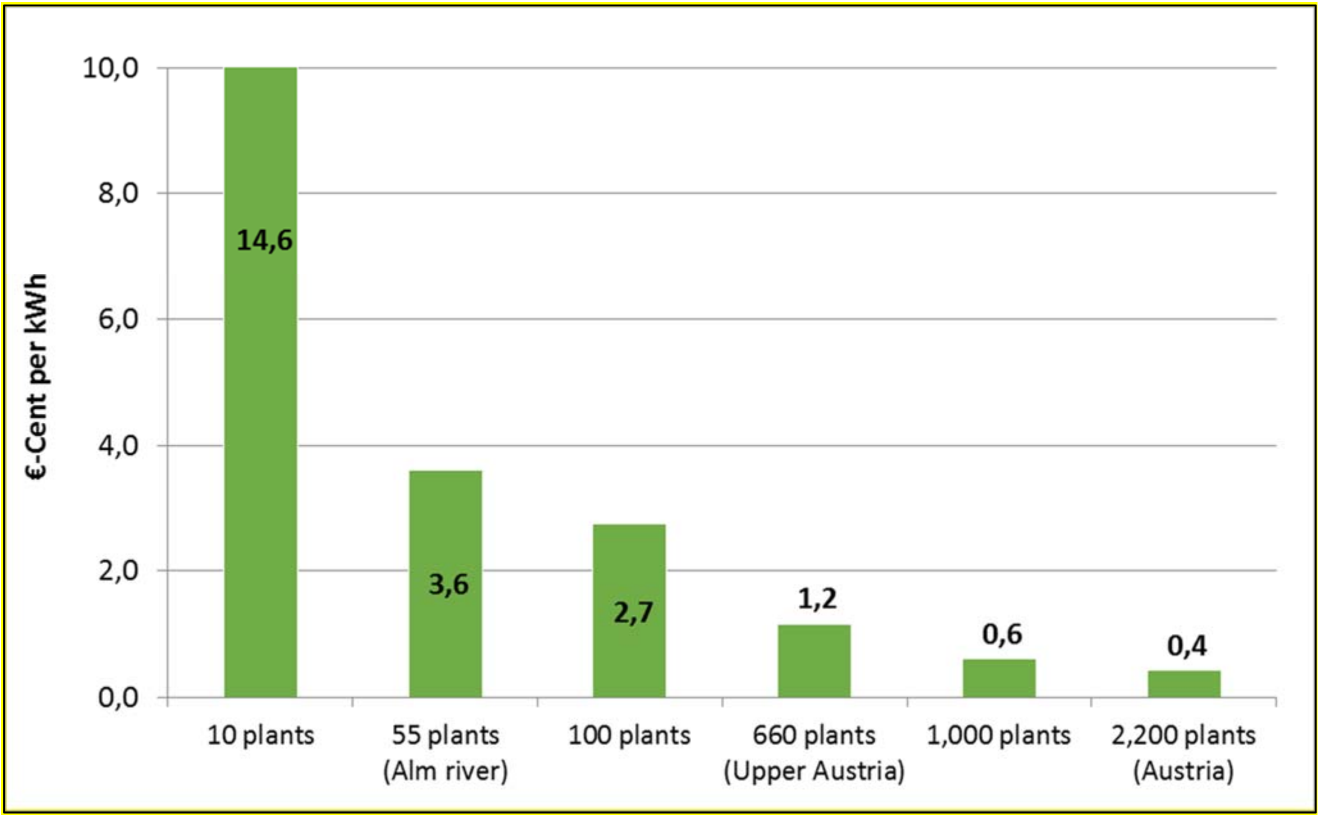

Fig. 10. Electricity generation costs

As shown, the annual costs decrease steadily by an increasing number of networking solutions, which is due to the applied learning rate but also due to the server costs to be allocated to more and more systems. Whereas, for the case of 55 units, which corresponds to the total number of hydro power stations at the Alm, 900€ of yearly costs per plant are calculated. These costs will drop to 180€ per year in the case of the Austrian potential for such solutions (2.200 plants) would be realized.

Finally, the previously quantified total annual costs are set in relation to the increased energy output (as shown in table 1) in order to quantify the electricity generation costs. Figure 10 illustrates the calculated generation costs depending on the number of implemented system solutions.

Due to the fact of a large value for the annual costs per unit in the case of 10 plants, high specific generating costs were calculated as well. Considering more than 50 or 100 installed intelligent control systems result in significantly lower costs which can be seen as a competitive result compared to other measures to increase the efficiency of hydro power plants [18].

6. Conclusion & Future Work

We showed possible cooperation concepts for connecting independent, private and small hydro power plants together for increasing the overall power generating efficiency as well as a prototype implementation on a hardware and software level. We also gave a short example scenario to show the potential of increasing the power generating efficiency by connecting several small hydro power plants alongside the same river by using provided (sensor) data.

The main aspect of increasing the overall efficiency in this scenario is the reduction of the power plants downtime caused by damaged turbines.

There is no recent literature about possible efficiency increase by connecting small hydro power plants - so the need for research and projects in this area is necessary. We expect promising results from the current and follow-up projects in this research field.

Our calculation predicts an increase of 2-5\% in the overall energy production, when a smart connection between the small hydro power plants is established.

The first benefit in connecting the small hydro power plants is the reduction of downtimes, the second benefit is the reduction of operating costs, e.g. when the water supply gets slit up with sand, the turbines must be turned off (to avoid damage) and the water inlet has to be excavated, which is a highly cost intensive procedure, compared to the profit you receive from a running turbine.

Another point of view will be the cooperation between different power plant owners. To enable a connected control, it will be necessary for some owners to reduce their water-throughput (upriver) to avoid e.g. damage at other power plants (downstream). How can you motivate these owners to reduce their productivity for the benefit of downstream power plant operators?

The current project is a first research step to evaluate the possibilities in this domain. Follow up projects will be used to concretize further options on increasing the power generating efficiency through a smart connection of small hydro power plants.

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