INTEGRATION OF PROTECTION, CONTROL, MONITORING AND REMOTE COMMUNICATION INTO ONE INTELLIGENT ELECTRONIC DEVICE FOR SMALL HYDRO-POWER PLANTS

Gunnar STRANNE[2], Urban NYGREN[2], Lars MESSING[2], Magnus CALLAVIK[1 †],
Lennart BALGÅRD[1], Bengt ROTHMAN[1], Per Erik MODÉN[1],
Lennart WIKTORSSON[3] and Mats LINDBERG[4]
1. ABB AB, Corporate Research, 721 78 Västerås, Sweden.
2. ABB Power Technologies AB, 721 82 Västerås, Sweden.
3. Tekniska Verken i Linköping AB, Box 1500, 581 15 Linköping, Sweden
4. Mälarenergi AB, Box 14, 721 03, Västerås, Sweden

ABSTRACT

This paper will briefly describe a new Intelligent Electronic Device (IED) containing integrated control, protection and communication elements for small hydro power plant. This joint project aims to set-up two small hydro pilot installations at two Swedish utilities. The concept requirements and project results will be discussed along with results from a Simulink model of the turbine, generator and station control strategies.

I. BACKGROUND AND REQUIREMENTS

Sweden has 1000 - 1500 small hydro power stations in operation erected during the last century. Due to low electricity prices and withdrawn subsidies during the 1990's small hydro suffered from low profitability. Consequently about 145 power stations were closed down or paused during a ten year period from 1989 to 1999 [1]. During this period no or little investments was taking place. This trend was unwanted, since small hydro is both an excellent distributed renewable energy source as well as a part of the cultural and industrial heritage. However, the recent years electricity prices has raised substantially, on an average from ca. 100 to about 250-300 SEK/MWh and electricity certificates has been introduced to support hydro power units below 1500 kW at an additional price level of circa 250 SEK/MWh. Hence the profit of and .interest in running small hydro has increased and the interest to renovate power stations in operation and starting up new ones have grown.

Still the relative value of electricity produced from a 1 MW station is relatively low, e.g. an annual production of 4 000 MWh a 500 SEK equals to 2 MSEK or *ca.* 5 000 SEK per day. Therefore profitable operation of a small station requires a stable system that is autonomous to a certain extent and runs with few unscheduled maintenance and support visits. Furthermore the systems should have a long life-time with availability of spare parts, rather than a tailor-made system. A change to a standardized solution that is easy to service is preferable.

Even for small hydro-power plants (< 2 MW) a relatively large number of functionalities must be included for efficient control and protection as compared to larger power stations. Functionalities such as voltage control, generator supervision, turbine control, water management, start/stop, excitation equipment and an interface to the operator control central or access via a remote PC are necessary. Generally the requirements to control all these functionalities set a demand for several building blocks to be included in the hydro-power plant control system. These requirements drive the complexities and costs almost to the level of larger hydro-power stations.

† Corresponding Author, Magnus Callavik, ABB AB Corporate Research, 721 78 Västerås Sweden.
E-mail magnus.callavik@se.abb.com. Phone +46(0)21 323226, Fax +46(0)21 323212

Although optimized production is important, the most vital requirement of the station is safe water management and safe protection system. Moreover, if the proportion of distributed versus centralized generation unit connected to the grid will grow in the future, also the role of the distributed hydro power station as a sources for robust grid operation are likely to be further strengthen, which will increase the requirements for protection and interface with the grid. Additionally the storage capacity of small hydro will be an asset for the grid operator when balancing other renewable sources such as wind, which in turn will increase the demand for flexible operation of the power station.

I.1 Objective of this project

The objective of this project is to show how a standardized Intelligent Electronic Device (IED) that can provide autonomous operation and prioritizes safe water management. The IED should be compact and integrated with the control of electrical and mechanical elements including the flow of water, communication, monitoring and protection system for small hydro-power plants. The IED including all of the stated functionalities above are therefore provided in one compact unit that easily may be carried by just one single person.

I.2 Project Set-up

The project is realized together with one equipment supplier, two electric utilities and the Swedish Energy Authority to focus on (1) a solution with the minimum functionalities necessary to operate the station and (2) the most important requirements for reliable and cost-effective operation with the highest possible availability. Prototypes from ABB are planned to be installed in two hydro-power plants owned by participant utilities Mälarenergi AB and Tekniska Verken i Linköping AB.

I.3 Description of the power stations for pilot installation

The final prototype concept will be installed in two power stations. One pilot is going to be installed at the Surahammar power station owned by Mälarenergi AB. This power station was erected 1927 and is rated at 1.0 MW, cf. the turbine in Figure 1A. The second pilot installation is aimed at Slattefors power station owned and operated by Tekniska Verken i Linköping AB. Slattefors was erected 1962 rated at 0.9 MW, see Figure 1B. Both stations have one Kaplan turbine with a synchronous generator.

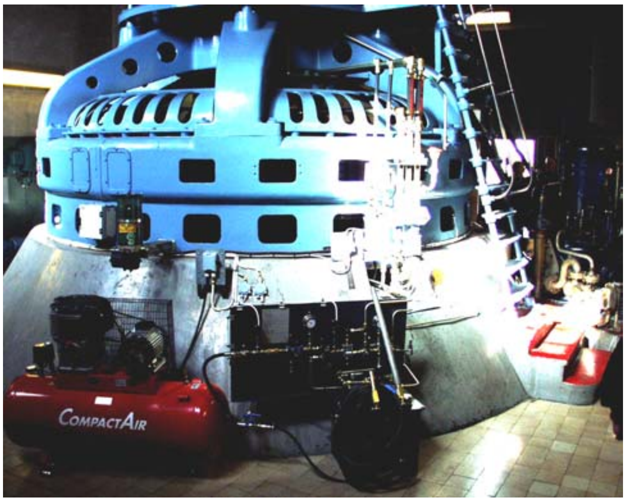


Figure 1A and B. **A LEFT) Mälarenergi's generator at Surahammar power station.**
B RIGHT) Tekniska Verken's Slattefors power station building

II. THE MICROHYDRO™ CONCEPTUAL APPROACH

The approach is to integrate station monitoring, turbine and generator control functionality into one commercial high performance protection and control IED. Voltage and current signals that are used by the protection unit are also made available to the control system without additional wiring. Integration of functionality into one unit is considered as a key to improve the cost performance.

Communication on the other hand is a technology field with fast development. Therefore the communication module is a separate unit, which therefore can be replaced more often than the control and protection device. It is suggested to use a communication block, based on the IEC 61850 standard, with optional remote communication techniques to a remote PC or the operator control room. In the future it is anticipated that several hydro-power stations in a common watercourse would have the installed IED's to provide an optimized electricity production by regulation an optimum flow of water through the system.

Figure 2 A and B. **A, LEFT) Example of front panel of existing control and protection system at Surahammar hydro power station**
B, RIGHT) Example of new station control and protection system

Using modern control and power electronic equipment it is foreseen to decrease the size of the installation of the control, protection and communication equipment substantially. In Figure 2 the front row of control system for the Surahammar station is compared to the size of a new system with similar functionality.

II.1 The flexible control and protection package

The configuration flexibility of the relay terminals enables protection of any generator and in particular systems according to the Microhydro concept where even more functions are required to be integrated into one common platform. A Generator Protection Guide describes the applications of individual protection functions and how they are implemented in the ABB 500-series of relay protection terminals [2]. Typical setting guidelines for each protection function are included.

The terminals can be ordered for different mounting arrangements (i.e. 19" rack, flush, semi-flush, wall mounting etc.). The 500 series terminals use a microprocessor based modular platform hardware. More than 25 000 such terminals have been delivered worldwide and installed in power networks with rated voltage up to and including 750kV. The main properties of the modular protection and control terminals are;

- ◊ The protection and control terminal is fully numerical device (i.e. based on micro-processor technology) with low power consumption in the measuring circuits
- ◊ Great flexibility which easily adapts to user's practice regarding;
  - o Protection functions to be included
  - o Number of current and voltage inputs required (i.e. 10 or 20 analogue inputs)
  - o Number of binary optocoupler inputs required
  - o Number of contact outputs needed

Customer requirements for tripping and external signaling, as well as needs for light emitting diodes (LEDs) to locally indicate status of the unit, starting of protection function and tripping etc. are easily met. Protection and control functions are available as standard/optional software modules and presented to the user as functional blocks. Each individual protective terminal can be provided with built-in, multicolor 18-LED panel module for visual indicators. Additionally 40 seconds, integrated disturbance and event recorder can be provided for monitoring/recording of up to 10 analogue and 48 binary signals per terminal. Alarms for the following operating conditions can be provided as voltage free contacts, local LED indication or remotely via communication:

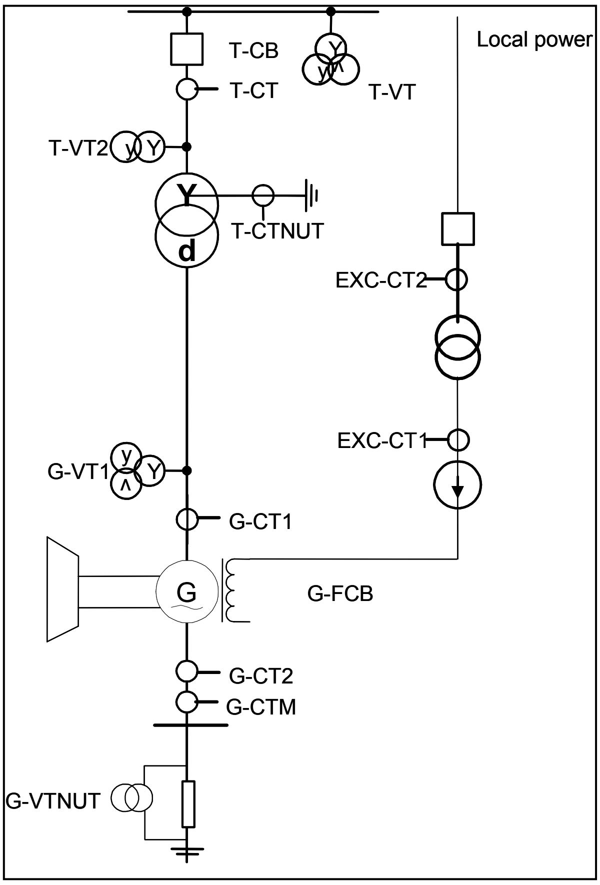
- ◊ Generator frequency deviation (frequency outside pre-set band around rated i.e. ±0,5Hz)
- ◊ Generator voltage deviation (voltage outside pre-set band around rated i.e. ±5%)
- ◊ Generator loaded/not-loaded
- ◊ Generator negative sequence over-current or over-voltage alarm
- ◊ Generator over-excitation alarm
- ◊ Generator loss-of-field alarm
- ◊ Generator reverse power alarm
- ◊ VT fuse failure alarm
- ◊ Loss of injection voltage for rotor earth fault protection

II.2 Protection Method

Generators are designed to run for a large number of years at a high load factor and also to permit certain incidences of abnormal operating conditions. The synchronous machine and its auxiliaries are continuously supervised by monitoring devices to reduce the exposure to abnormal operating conditions to an absolute minimum. Despite monitoring, electrical and mechanical faults sometimes occur, and the generators must be provided with protective relays that quickly initiate disconnection of the machine from the system in case of a fault and when necessary initiate the complete shutdown of the generator.

No international standard exist regarding the needed configuration of the protective schemes for different types and sizes of generators. Manufacturers provide recommendations and there are guides given by various organization Standards. The protective scheme configurations may vary from country to country and also between power companies in the same country. There are also different needs to consider depending on the specific machine construction. For those reasons the generator protective schemes are flexible.

In the Microhydro concept the generator and the step up transformer are protected by common equipment. There are also back-up protections for faults outside the protected zone. In practice, there are many mechanical and thermal protection devices that help avoiding damage to the power-generating unit. Their output signals typically come to the protection panel as potential-free contacts or mA or voltage signals and incorporated in the overall tripping and alarming scheme via inputs to the terminal.



Protection functions available (ANSI Device No)

◊ Generator differential (87G)
◊ Generator restricted EF (87GN)
◊ 2-stages, 80% stator EF (59N), 3Uo internally calculated
◊ CB failure protection for generator breaker
◊ Loss of excitation (40)
◊ Reverse power (32) with minimum setting of 3%
◊ Stator thermal overload (49S)
◊ 4-stages, 3ph over and under voltage protection (59 & 27)
◊ 2-stages, over and under frequency protection (81O & 81U)
◊ Overexcitation (V/Hz) protection (24)
◊ Negative sequence overcurrent protection (46)
◊ Undervoltage with overcurrent seal-in (27/51)
◊ Turn-to-turn (generator split star point overcurrent) protection
◊ Generator 3Ph overcurrent protection

Optional protection functions available

◊ Rotor EF, AC 50/60Hz injection via RXTTE 4
◊ 95% stator EF (59N) connected to generator neutral point VT
◊ 80% stator EF (59N) connected to generator open delta VT1 winding
◊ Rotor thermal overload for static excitation (49R)
◊ 3ph overcurrent protection (50/51) for excitation transformer
◊ 3ph overcurrent protection (50/51) and earth-fault protection (50N/51N) for auxiliary transformer

Figure 3. Typical single line diagram for generator-transformer unit and list of available protection functions.

II.3 Control and Monitoring

The functionality required for the control of a small hydropower station is provided by function blocks as illustrated in the block scheme in Figure 4. The scope includes:

◊ control of the water level – with various modes of operation
◊ normal operation at specified power, water flow, or guide vane opening
◊ logic for the timing of start and stop sequences
◊ synchronization including required speed control as well as the actual closing of the breaker
◊ control of a gate, the guide vanes, and the runner blades by means of binary increase/decrease signals for each actuator (normally acting on hydraulic valves)

It does not include the direct control of the exciter, but it does include provision of the orders to the excitation control to perform voltage control (during synchronization, until the breaker is closed) or control of either reactive power or power factor (during normal operation). Concerning the water level, the following modes of operation are provided:

◊ Continuous level control – The level is controlled by varying the flow through the gate as well as the turbine, but using the gate only when the required flow is higher than the turbine can accept at the moment
◊ Intermittent operation – When the water level approaches the upper and lower limit, the turbine is automatically started and stopped, respectively.

◊ Level control to within limits - Normally the turbine runs at the preferred operating point. When the water level reaches a limit, level control becomes active in order to get it back inside by means of varying the turbine flow and if necessary also the flow through the bypass gate.

The function blocks have a number of parameter settings that allow adaptation to the particular power station. In addition to that, one can configure the exact conditions to be included in the start sequence by adding simple logic function blocks as required. Apart from automatic start and stop as in intermittent operation, it is of course possible to manually give start or stop orders, and to adjust set point values and limits that govern operation.

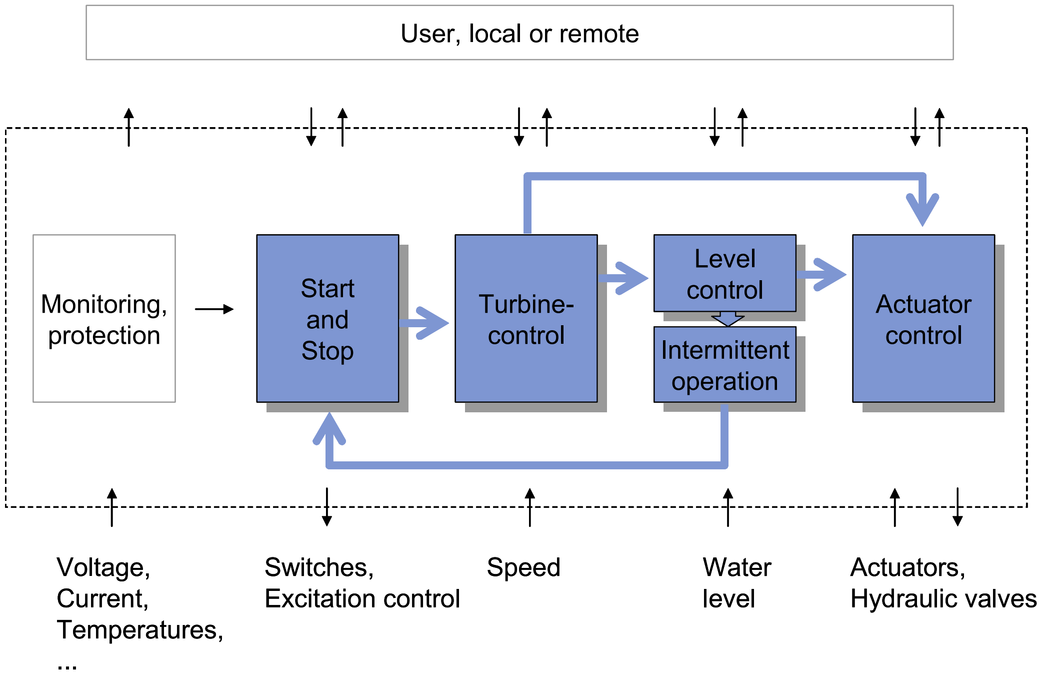


Figure 4. Microhydro interfaces

II.4 Communication Hierarchy

The communication box is intended to work as gateway between the station networks and a WAN to enable secure remote control. Some extra server functionality must be added to enable a local graphical HMI using just a standard web browser as display. The Web browser could be installed in a permanently mounted touch screen or alternatively on a laptop that the user has when visiting the station. For electrical protection reason this network is based on optical Ethernet to provide galvanic insulation. The communication solution uses three networks for three purposes:

i. A station network that can be designed as standard office network to enable easy connection to miscellaneous devices, e.g. local HMI panel, web cameras and other types of Ethernet connected devices. The station network is based on Ethernet (CAT5 RJ45) and TCP/IP.
ii. WAN based on Ethernet and TCP/IP to enable connection to an as wide as possible range of communication ways between the station and control center. This network is used to connect the station to remote control center through a public or private network, e.g. GSM or rented phone lines. This network serves as protection firewall and is VPN built.
iii. IEC61850 network. Real-time network used for connection to and between IED's to the remote control center or the local HMI.

II.5 Excitation

The Microhydro concept should be applicable independent of the turbine and generator equipment used, e.g. both for asynchronous generators without excitation as well as for synchronous generators with excitation. Since small hydro stations have been installed over a period of more than 100 years, many various types of excitation equipment exist in the stations today. Old synchronous generators usually have a rotation device for excitation driven by the mains shaft, a separate turbine or motor. Brushes and other equipment in these solutions may demand extensive maintenance and could discontinue operation. More recent installations usually have static power electronic excitation equipment. The rotating converter has sometimes been kept and sometimes been bypassed in recent overhaul. Brushless systems are uncommon in small hydro applications in Sweden, although these systems would be welcomed to limit maintenance.

The vast number of different solutions that exist today does not make it possible to set one standard excitation solution. The conceptual aim is to provide one solution with an integrated approach and one solution with a clean interface to the excitation hard and software.

II.6. Model of the station and turbine control

As a means to verify the intended control solution and illustrate its behavior, an implementation was made in terms of a Simulink model. A reservoir model was added, and simulations were run according to the different modes of operation – continuous level control, level control to within limits, and intermittent operation. Some of these simulations are shown below. Figure 5 shows a case of intermittent operation when the inflow of water to the reservoir remains constant.

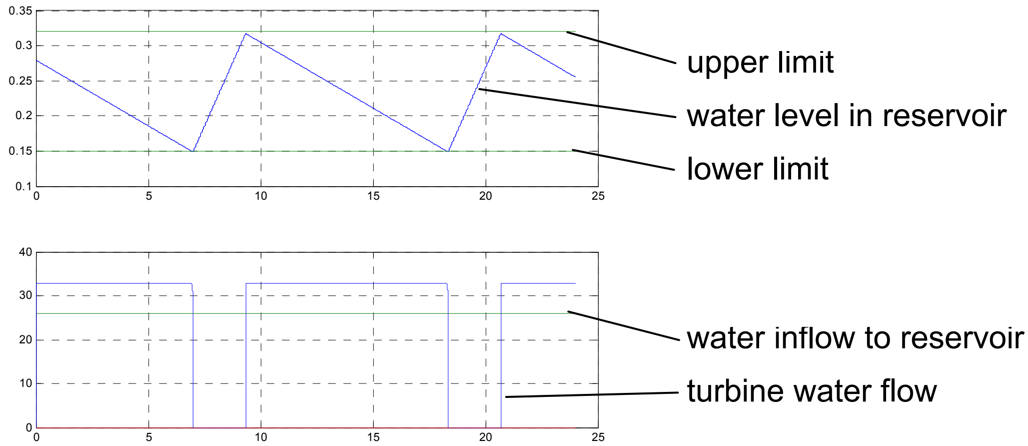


Figure 5. Intermittent operation – turbine at preferred operating level, or closed – the switching governed by the water level reaching its upper or lower limits

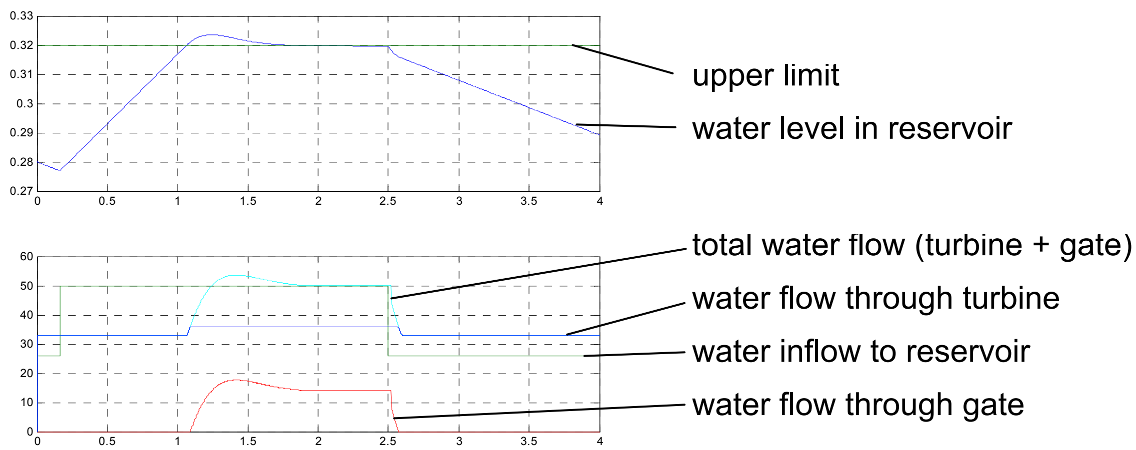


Figure 6. Level control to within limits – turbine at preferred operating level as long as water level is within limits – combined flow through turbine and bypass gate is varied to control the level when so required in order to keep it within limits.

Figure 6 shows a case of level control to within limits, where an artificial step is disturbing the reservoir inflow. In fact, there is first a step up and then a step back down, and during this period the inflow is larger than the maximum flow through the turbine, so the bypass gate has to be opened as well in order to keep the water level at the limit.

The continuous level control case, cf. Figure 7, is applied when there is no reservoir or a very small one. Here, the inflow gets high enough for a short period of time to require opening of the bypass gate. The simulation model was also extended to allow simulation of start and stop of the turbine.

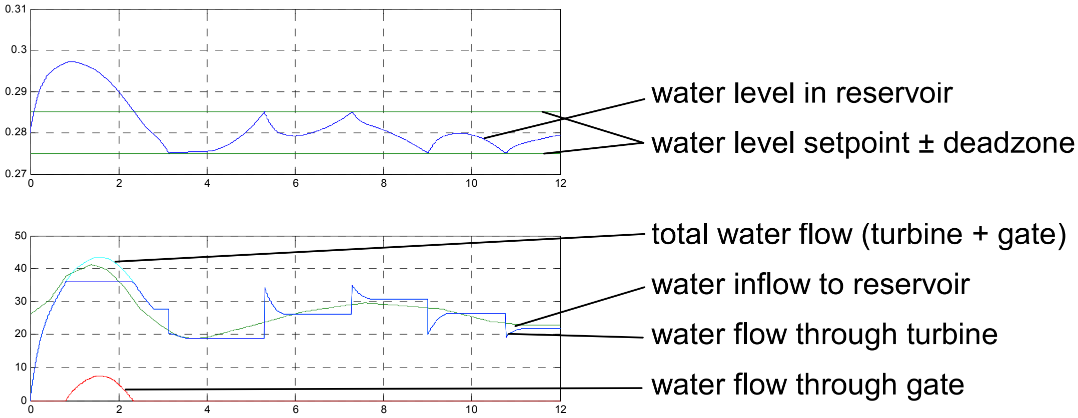


Figure 7. Continuous level control – the flow is varied continuously to control the level to within a small dead zone around the set point, the dead zone enabling the control to come to rest for certain periods of time

II.7 Benefits

	Installation	Operation	Maintenance	Analysis
Completely integrated	50%	20%	20%	10%
Autonomous	10%	10%	10%	5%
New functions	5%	10%	10%	10%
Communication	-	10%	-	50%

With a standardized integrated concept it is foreseen that significant cost savings and benefits can be achieved. An attempt to quantify this is given in Figure 8.

Figure 8. Benefits with a standardized integrated concept

III. ACKNOWLEDGEMENT

Funding for part of this project by the Swedish Energy Agency is greatly acknowledged.

IV. REFERENCES

[1] Widmark, D., Småskalig vattenkraft och kulturmiljövård, Riksantikvarieämbetet, PM 2002:6
[2] ABB Product Guide for RET521 at www.abb.com/substationautomation