Practical Experience on Substation Protection and Control Systems

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ABSTRACT

The Romanian Transmission and System Operator (Transelectrica) has developed an intensive process of rehabilitation of the EHV substations including their protection and control systems. This process involves the replacement of old electromechanical relays and the classical control system with digital protections relays integrated in modern control and protection systems. The aim is to achieve upgraded substations with high performance of both primary equipment and its protection and control system. This effort greatly depends on the specification and evaluation of the technical requirements for the protection and control system.

The paper presents some gained knowledge on customer specification of technical requirements for the integrated protection and control system showing also a typical application in a project involving two 220 kV substations in the Romanian Power Grid.

Common practice is to specify three types of requirements: functionality to be achieved, performance requested and all constrains applicable. Functionality basically derives from the single line diagram of the substation. The basic requested protection and control functions are attached to the diagram. Protection functions are specified according to the overall protection system philosophy of the company and for the control system they focus on the operator’s needs. System architecture is given in quite large terms to allow optimization but imposes redundancy, hierarchical control levels, operator equipment and the physical communication medium both in the substation and to the remote control centre.

Performance requirements comprise overall performance (e.g. time synchronization, time response), reliability, availability, maintainability, security and expandability.

Constrains include specifications for the process interface, interface to the National Grid Centre, interface to the remote protection and control maintenance centre as well as some limitations due to existing buildings, roads, preserved structures, etc.
Examples from practical experience in the two substations are included together with some recommendations for further works.

1. Functionality

Essential functionality of the substation protection and control system derives from the single line diagram (SLD) and from details on protection and control functions at bay level and also at substation level. The SLD is mainly decided by the importance of the substation in the grid but also by norms of environment protection, safety labor and security of installations. Single bus-bar, double bus-bar and one-and-a-half circuit breaker are common layouts of today’s substations. There are significant differences in the protection and control system philosophy according to the substation layout and the requirements for protection and control functions should be clearly specified and clearly understood. Thus starting from the SLD and fully define the block diagrams with protection and control functions for each element is a good approach.

As an example a SLD for a small size 220 kV substation is shown in Figure 1. This gives a quick understanding of the primary equipment positions and an intuitive understanding of basic protection and control functions.

![Figure 1. Example of a 220 kV Substation SLD](image)

The diagram implicitly shows some protection functions for the Over Head Lines (OHLs) such as distance protection, directional earth-fault protection, switch-onto-fault or auto-reclosing. For the auto-transformer technological protection, differential protection and distance protection functions are foreseen. The topology shows how primary equipment are connected, which are to be controlled (e.g. circuit breakers - CBs, disconnectors - DSs, earthing switches – Ess) and also suggests some interlocking conditions as well as synchrocheck functionality. Additional extend is given for each element on the block diagram with function allocation.

To complete the functionality some general requirements are usually specified. Hence mechanical, electrical, insulation, cubicle construction and electromagnetic compatibility requirements are added together with testing and commissioning indications. As an example some requirements for the control and protection cubicles are shown below.
For the construction of cubicles the following requirements are mandatory:

- each cubicle shall form a complete enclosure and shall be used for only one primary element
- cubicles shall be of steel sheet
- the cubicles shall have close fitting lockable and lift-off steel doors hinged in such a manner that they may be opened through 150°
- the inner part of each cubicle shall be finished with a metallic surface to secure electrostatic discharge, heat exchange and dispersion
- each cubicle shall have anti-condensation heaters with thermostat control
- cubicles shall be suitable for floor mounting with front access and bottom entrance for power and multi-core cables
- each cubicle shall be suitably labelled for easy identification with the access doors either open or closed and each equipment shall be labelled in customer language

2. Block Diagram and Functions Allocation

Next step is to extend the information contained in the SLD with protection functions allocation, CTs and VTs accuracy suggestions trip/close signals and auto-reclosing logic constrains. For example, Figure 2 shows the protection functions for a 220 kV OHL with two main protection relays, a bay control unit (BCU) and the metering equipment.

Figure 2. Block Diagram for a 220 kV OHL with allocation of functions
Basic requirements for the Main 1 numerical protection relay include the following functions:

- full scheme distance protection with 5 zones, quadrilateral characteristics
- teleprotection interface for remote end relay communications
- switch-onto-fault
- three phase overcurrent and directional earth fault overcurrent protection
- out-of-step protection
- voltage and current circuits supervision
- single and/or three pole auto-reclosing (AR)
- synchro-check and dead line/live bus-bar checking for three pole auto-reclosing and for manual closing
- time delayed overvoltage protection
- fault locator
- disturbance and event recording.

As a rule the Main 1 protection operates on CB trip coil 1 irrespective of which protection function tripped. The teleprotection scheme is usually a permissive one and only distance protection zone one trip shall transmit a permissive signal to remote relay on both physical channels. Receiving of a remote permissive signal causes an instantaneous trip providing the distance protection locates the fault inside over-reach zone two. All instantaneous protection functions trips shall start the auto-reclosing function but time delayed trips from whatever protection functions are not allowed to start the auto-reclosing scheme.

Breaker Failure Protection (BFP) is started by any trip signal followed by an early phase segregated re-trip on both tripping coils of the CB. Should the CB fail to operate then a time delayed and current flow assisted three-pole tripping signal is issued by the BFP on both coils of the CBs supplying the faulted element. A mandatory inter-trip signal to remote line end has to be sent on both physical channels.

The relay shall be mounted in a cubicle along with tripping relays, auxiliary relays, tripping circuits’ supervision relays, test blocks and distinct switches. Typically the BCU may be mounted in the same cubicle.

Basic requirements for the Main 2 numerical protection relay include the following functions:

- full scheme distance protection with 4-5 zones, quadrilateral characteristics
- teleprotection interface for remote end relay communications on both physical channels but on apart telecommunication channels
- switch-onto-fault
- three phase overcurrent and directional earth fault overcurrent protection
- out-of-step protection
- voltage and current circuits supervision
- single and/or three pole auto-reclosing
- synchro-check and dead line/live bus-bar checking for three pole auto-reclosing and for manual closing
- time delayed overvoltage protection
- fault locator
- disturbance and event recording.
The Main 2 protection operates on CB trip coil 2 irrespective of which protection function tripped. The teleprotection scheme is a permissive one and operates similar to that described for Main 1 protection except of operating on separate telecommunication channels but on both physical ones. The auto-reclose scheme is similar to Main 1 protection except the AR dead time that is somewhat longer.

The relay shall be mounted in a distinct cubicle from Main 1 protection, along with tripping relays, auxiliary relays, tripping circuits’ supervision relays, test blocks and distinct switches.

Derived also from the SLD are the requirements for the numerical BCUs. As an example a BCU is supposed to include measuring, monitoring, control, interlocking, local display and communication features. Some applications require to also adding other functions as auto-reclosing or synchro-check for CB manual close. Measurement of all three phase-to-ground voltages and all three-phase currents is self-understood. Then active, reactive power or phase-phase voltages or frequency shall be calculated and locally displayed and shall be transmitted to the Substation Control System (SCS). Monitoring functions usually include single point data, faulty state data, double point data and data regarding the device itself. Examples of single point data consist of protection functions status, e.g. auto-recloser on/off and operating mode (single-pole and/or three-pole), teleprotection interface on/off, protection selected setting group or synchro-check selected device. Data regarding protection functions operation such as faulty phase, protection zone or even fault location are examples of data included in the faulty state data. The class of double point data is primarily intended for survey of CBs, DSs and Ess. Control features consist of the ability to switch on/off the equipment included in the double point class and also to decide on auto-recloser status and operating modes, to switch on/off the teleprotection interface, change the protection setting groups, to decide on the synchro-check device and change its setting group or even to bypass the interlocking conditions. Interlocking conditions derive from the SLD and shall support any switching of primary equipment. Mainly the interlocking function is implemented both at bay level and at substation level. Switching on a CB is always related to synchro-check and as a rule this should be available in the BCU and a protection device.

Attached to the SLD it is recommended to show the trip logic diagram. Tripping coils assignment to Main 1 and Main 2 protection devices or to the BCU as well as the assignment to breaker failure protection (BFP) start and trip underline the protection and control philosophy.

Regarding CT secondary windings as a rule the accuracy is imposed while the accuracy limit factor and rated burden is suggested and shall be confirmed by calculations according to the protection relays and real on site conditions. For VTs the accuracy class is imposed and the rated burden is only suggested and should be concluded be calculations.

3. Integrated Protection and Control System Architecture
Substation integration and automation is a tool that helps utilities to reduce installation, maintenance and operation costs. A consequence of integration of protection and control is also the reduction of expensive hardwiring in the substation and reduction of possible human errors. To achieve this goal exchange of signals among various intelligent devices is a must and this rise the problem of substation network and protocol definition. Definition of the network should contain enough information to understand the requirement but not too detailed as to limit the possible solutions. Two major topologies have to be investigated mainly the multidrop network and star network. In a multidrop network (as shown in Figure
3) A single communication medium connects both protection and control devices that have to share a common protocol and transmission speed. Only a single device at a time can exchange information with the higher order level or another device. All communications have to obey rules that solve or prevent message collisions. If the amount of data traffic or network nodes increase then the performance of the multidrop network decreases. Splitting of the network in two dedicated LANs, one for the substation control system (SCS) and the other for the substation monitoring system (SMS), as suggested in Figure 2 allows to group the specific data for control apart from those intended for parameterization, configuration and monitoring of protection devices. The SCS LAN has to provide full redundancy and for the two 220 kV substations the implemented solution consists of two redundant optical fiber rings.

Star network topologies include a series of point-to-point connections between a central node and existing devices. Usually the central node device is a communication processor that is in charge with communication to all the devices. The communications occur in parallel and this allows for higher rates of information refresh. The communication processor collects, organizes and transmits data to the substation master and this results in an increased performance. Using of more communication processors for instance for each substation voltage levels and accordingly allocating the existing devices results in a clear and reliable substation network.

Choosing one of the two topologies has to be carefully analyzed based on substation size, importance, number of bays, and number of equipment in each bay and by estimating the communication necessities in the system. Standard protocols are preferred to reduce locking up risk on a single manufacturer.

The communication to the National Grid Center (NGC) uses the standard protocol IEC 60870-5-101 and this is a must as the existing control system at NGC is based on this.
Typically two independent physical paths are requested to provide full redundancy. The media is the optical fiber included as a rule in the ground wire of the OHLs.

4. System performance

The system performance requirements refer to overall performance, reliability, availability, maintainability, security and expandability.

Overall performance states typically the requirements for time synchronisation, SCS time response at substation human-machine interface (HMI), achievement of full functionality even in case of a single failure and request for intensive self-checking. For the SCS of the two substations the time response to refresh status was expected to be less than 2 s, while refresh of analogue values was expected to be less than 5 s. Under field operation the observed times were much lower than required in the specifications.

The reliability of the system is expressed through the mean time between failure (MTBF) and shall be calculated based on reliability of the individual system components. Frequently the requirement is MBTF > 8760 h.

The system availability (A) shall be high enough, typically A > 99.9% and is put into practice by adequate equipment redundancy and extensive use of functions tests such as data acquisition function check, control function check or scan function check. An alarm should be issued whenever a device failure occurs. Automatic switchover operations of redundant equipment shall be logged and reported.

As a rule the mean time to repair index is used for specify the requirement for maintainability. To achieve a value lower than 1 h the specifications ask for spare parts. The total amount of spares shall consider the time to repair and the return time to operational conditions.

The SCS shall avoid potentially dangerous or unstable situations and a single component failure shall not result in a system black-out. The system shall provide some security also for human operator errors.

The requirement for an open integrated system with distributed functions is mandatory and it is the heart of the expandability obligation. Some conditions are imposed but in such a manner to allow optimization. Among the imposed conditions we mention: system open architecture, mandatory use of standards for design, configuration, and manufacturing, standard communication protocols. Future system extensions shall require minimum re-arrangement of existing equipment and software resources, modifications shall not degrade system reliability, availability and security and the overall time shall be acceptable.

5. System constrains

Systems constrains include specifications for process interface, interface to the NGC control system, including the remote protection maintenance centre but also some limitations due to existing buildings and structures in the substation. Connections to the secondary windings of the CTs, VTs and DC power supply impose the protection and control equipment analogue interface characteristics and decide on the power supply features. For example in one of the two substations the rated secondary current is 5 A, while for the second one it is 1 A. The DC power supply existing in the substations is 220 V dc and all protection and control equipment are supposed to provide this voltage level also for binary inputs.

To connect the substation to the exiting NGC control system imposes the use of a certain communication standard as already mentioned. There is also a constrain regarding the communication to the remote protection maintenance centre that imposes the communication protocol.
Local field constrains were encountered in one substation due to the preserve of the existing control room building that imposed the location of equipment, room size had also introduced some limitation and the cable ducts had to be designed accordingly.

6. Conclusions
Upgrading of transmission substations include both primary and secondary equipment replacement to achieve high performance. Substation integrated protection and control systems help utilities to optimize installation, maintenance and operation costs.

Customer specification of technical requirements for the integrated control and protection system is a sensitive point to achieve the desired performance. Imposing of some requirements but in the same time allowing for optimization is the important challenge.

It is a lesson learnt to specify three types of requirements: functionality to be achieved, performance requested and all constrains applicable. Functionality basically derives from the single line diagram of the substation and it is the base for control and protection functions requirements. Protection functions have to be specified according to the overall protection system philosophy and the control system function requirement shall focus on the operator’s needs. Clear and sometimes in depth description of the protection philosophy is both a challenge and a must. System architecture shall be given in quite large terms to allow optimization but in the same time should impose for an integrated open system providing redundancy, hierarchical control levels, certain operator equipment and for physical communication medium both in the substation and to the remote control centre.

Performance requirements in terms of overall performance, reliability, availability, maintainability, security and expandability permit to guide the project to the utility needs.

Foreseen constrains as interfaces to remote control centre and to remote protection maintenance centre contribute to a better understanding of the field conditions and focus the contractor to enhanced solutions.

References