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Use of Existing Current and Voltage Measurement Transformers in Digital Substations.

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ABSTRACT

The paper deals with the use of existing current and voltage measurement transformers together with signal digitizers in digital substations. The requirements to the signal digitizers are presented and the recommendations for adaptation of the measurement transformers to the digitizers are given. It is shown that until digital current and voltage measurement instruments with the necessary functional specifications are available at an acceptable price such a solution is cost-effective and reduces the risks in the implementation of a digital substation.

Keywords: digital substation, current measurement transformer (CT), voltage measurement transformer (VT), merging unit (MU).

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INTRODUCTION

Current and voltage measurement instruments in substations are the primary sources of information. Nearly all other monitoring, control, protection and diagnostic functions depend on their reliability and accuracy. Current transformers (CT) and voltage transformers (VT) have had a long evolution and now are technically advanced devices: they are sufficiently accurate, reliable and durable which is confirmed by their failure-free operation in many power systems over a long time [1].

On the other hand there is an obvious intention to reduce the capital and operational costs and to improve the accuracy.

In practice the development of reliable, easy to use and inexpensive digital high voltage current and voltage sensors is a relatively complicated task by itself which takes a significant amount of time and effort. As a sensible option it is proposed to use existing CT and VT of the traditional design or with a minor modification together with merging units (MU) for this purpose. This significantly reduces the technical and financial risks, the commissioning time shortens by a few times, no changes of the operational infrastructure (regulations, service procedures, equipment for calibration testing etc.) are necessary. Of course the appearance of MU in the signal transmission line from a CT (VT) makes the reliability somewhat lower so a set of technical measures has to be anticipated to compensate for this [2, 3, 4].

It is proposed that in the power facilities having CT and VT with a small lifetime the transformers are left unchanged and are in addition equipped by MU. After the end of the lifetime the CTs and VTs should be replaced by modernized CTs and VTs or by digital ones (DCT and DVT). The advantages of this are a short time of the implementation of a digital substation (DSS) and an improvement of the accuracy of the current and voltage measurements in the normal and transient modes by a factor of 2-3 [5].

In the power facilities having CT and VT with a big lifetime and in the construction of new power facilities two options are possible:

CTs and VTs are replaced by modernized CTs and VTs and are in addition equipped by MU.

The use of modernized CTs and VTs is a compromise provisional solution resulting from the need to replace CT and VT from one hand and the absence of DCT and DVT on the market from the other hand. In this case the technical risk is minimal as the design and the production technology of the modernized CTs and VTs change insignificantly. Compared to traditional CT and VT the following advantages are expected: a further improvement of the accuracy, a reduction of the cost value, extended functional capabilities.

CTs and VTs are replaced by DCTs and DVTs.

In this case no MU is necessary because DCT and DVT have a built-in optical interface according to the IEC 61850 standard. This option is advisable for the CTs and VTs which are worn out, for a new construction or a reconstruction [6].

However the results of the development of purely digital CT and VT directly connected to the process bus of a digital substation cannot be yet considered successful due to the following reasons:

1. DCT cannot provide both a wide dynamical range and a high accuracy, one has to select either one or the other, therefore the number of CT units cannot be less than that in existing substations.
2. A CT (VT) set is expensive, the price amounts to a few million rubles for one three phase set.
3. The accuracy of DCT depends on the optical wavelength, the properties of the optical fiber line and the characteristics of the polarizer.
4. Large dimensions of the electronic module (480x380x135 mm): for 3-4 CTs per feeder a complete panel is needed to run their secondary circuits to the relay cabinet so the total number of panels could be about 10-15. This results in a significant increase of the size of the relay cabinet and a rise of the capital costs for the implementation of a digital substation compared to traditional ones.
5. A high power consumption of the electronic module (50 W): for an average digital substation the total power consumed by the electronic modules amounts to 2-3 kW which is greater than the consumption

of the microprocessor units combined in an existing substation. In addition the capacity of the substation batteries has to be increased.
6. The absence of connectors along the optical fiber from the primary sensor to the relay cabinet which means that in the case of a break of the fiber at any point it may be necessary to put the feeder out of service in order to replace the entire fiber. In addition to this special welding equipment and specially trained persons are needed for the welding (termination) of the fiber.
7. The lack of information about the stability of the characteristics: a degradation of the characteristics of the laser, sensibility of the optical fiber and optical analyzers is possible with time [7].

Requirements to MU

In all cases of the modernization based on traditional CT and VT an MU appears in the power facility as the necessary connection component between the primary sensor and the other nodes of the control system. MU does not measure the technological value itself but rather digitizes the signals obtained from the primary sensor. Obviously the technical specifications and functional capabilities of MU must be sufficient for the execution of all technological tasks associated with CT and VT. For the combined operation of CT (VT) and MU common requirements to MU and primary sensors have to be produced [8].

Apparently the introduction of MU in the transmission line also results in a few disadvantages:

- an increase of the number of devices in a substation (an increase of the initial costs and the costs of the spare parts)
- a reduction of the reliability (there may be a failure of MU itself or its power supply circuits)

Therefore the maximum use has to be obtained from these devices and technical solutions have to be anticipated to outweigh the disadvantages.

General requirements

MU should be mounted in the terminal box (on the terminal block) of CT (VT) which ensures the minimum length of the wiring and therefore:

- an improvement of the accuracy (no influence of the connection wires)
- an improvement of the reliability (no intermediate terminal blocks and wires, low probability of short circuits, short circuits to ground, breaks)
- an improvement of electromagnetic compatibility
- an improvement of the electrical safety (no high voltage outside MU, no danger for the current circuits to unshort)
- impossibility of external shunting (important with regard to MU for commercial electrical power accounting systems)
- impossibility of connecting CT and VT to MU with the wrong polarity
- minimum additional equipment (no additional cases, bases or support elements are necessary)

In particular with respect to high voltage 110-750 kV CT and VT the requirement of a per-phase MU design follows from this. In addition it is not acceptable to combine redundant MUs in one unit (especially if the MU is used in the relay protection system) [9, 10].

Design

- The general design should be similar to the test modules used at present and the unit should be fixed on the first terminal block from CT (VT) which provides a safe disconnection from the VT circuits and a break-free disconnection from the CT circuits.
- In the base of the module the following terminals should be located: the connection of the signal circuits of the primary sensor, the connection of the ground of the primary sensor.

- In the cover of the module the MU itself, the digital connectors, contactless cover position sensor, sealing point (for MU for commercial electrical power accounting systems) are located. The replacement of MU is done by replacing cover by a similar one by latching the base of the cover.

To assist building-in MU should have minimum dimensions.

The Ingress Protection Rating (IP), EMC and vibration categories of MU should match the corresponding categories of the primary sensors (CT, VT) (see Table 1).

Table 1: The internal components of MU for a CT of the normal mode:

Component	Technical requirements
Input component	Secondary sensor: a current shunt (for CT) or a resistive divider (for VT) ADC overvoltage protection Galvanic separation
ADC	The sampling rate must be appropriate for the functions implemented The bit resolution (not less than 14) is determined by the accuracy class required The number and purpose of the ADC measurement channels: - technological measurement channels: 1…4 (depending on the number of CT/VT taps used) - ADC calibration channels: 2 («0» and «Uref») A built-in reference voltage source (low noise, extended temperature range)
Data processing unit	FPGA: minimum power consumption, minimum dimensions, maximum processing speed, fixed and relatively simple algorithms, improved information security PROCESSING OF THE TECHNOLOGICAL MEASUREMENTS: - preliminary mathematical processing (filtering) - a software compensation of the systematic error (only for «AND») - built-in technological functions (with the production of a GOOSE-signal) DIGITAL INTERFACES: - a service USB port for the initial setup and periodic checks - 2 Ethernet ports (for switchgear and SF6-insulated switchgear – twisted pair, for a switchyard – optical cable) with PRP and PTP: - - technological information: IEC 61850-9.2 (SV), IEEE C37.118, IEC 61850-8.1 (GOOSE, MMS), reading of the MU memory - - service information (self-diagnostics, time synchronization, switching between the TEST/OPERATION modes) - VLAN support - built-in encryption (for CT MUs for commercial electrical power accounting systems) - monitoring of the delivery time of GOOSE to MU (the event of the loss of the process bus is recorded in the internal log of MU) SERVICE FUNCTIONS: - self-diagnostics (with the output of the error code to the digital port) - recording of microoscillograms - the assignment of timestamps to SV and GOOSE being sent (PTP support) - control of the LED - ADC calibration (on two channels: «0» and «Uref») - a SV emulator with the possibility to set the amplitude, phase and mode (TEST mode according to 61850) [11] - information security [12]: - change of the technological software – when the security key is present in the service port - protection of the technological software CONFIGURATION SETTINGS: - CT ratio (protected memory) - correction curve for the compensation of the systematic error - range of the operation with the nominal accuracy - GOOSE production settings (e.g. production of GOOSE when the current goes out of the operating range of CT) - settings of the digital ports (VLAN, IP, passwords etc.) - conditions to start the recording of microoscillograms (for diagnostics purposes, with a duration of 1-10 microseconds)
Transceiver	Transmission range: up to 300 m (switchyard), up to 100 m (SF6-insulated switchgear), up to 10 m (switchgear) Minimum power consumption
Non-volatile memory	- buffered measurement reports (1-2 s) - oscillograms - event log (including service messages) - semi-constant information: CT/VT ratios, correction curve, IP address, manufacturer, serial number, manufacture date, product code
Other components	A discrete input (from the SF6 sensor) An LED mode indicator (operational/non-operational, mains present/absent)
Power supply - o	PoE specific features: - ability to distinguish between the absence of current and a failure of MU - continuous monitoring of operability, instant availability for operation - a switch supporting PoE is needed

Current measurements

Current measurements in the normal mode (for the operational monitoring, telemechanics, accounting) and in the transient mode (for the relay protection) require specific primary sensors and MUs which differ significantly in the functional capabilities and technical specifications. Measurements in the normal mode require a high accuracy (not less than 0.2S) in a relatively small range (0.8…1.1)In while measurements in a transient mode do not require a high accuracy (not greater than 5-10%) but the measurement range have to be much larger (1…50)In [13].

The total number of measurement channels for the relay protection system is determined by the Electrical Installations Code [14] and the standards of technological design and can be up to 4-5.

With regard to a digital substation up to 110 kV the number of independent channels can be reduced to 3 from the following considerations [15]:

- one defective or out of service channel does not limit the functionality of the relay protection system because the protection zones overlap that is there is no "dead zone"
- 3 channels allow one to identify a defective channel by the majority principle.

For 220-750 kV substations the number of channels has to be increased to 4 so that in accordance to the design standards the full functionality of the relay protection system is retained when one channel is put out of service and one channel fails.

Let us determine the number of measurement channels for the normal mode:

- 1 channel is needed for a commercial electrical power accounting system (separate sealed MU serviced according to an individual procedure by a specialized company). As the information in the channels is transmitted as SV (multicast) it can be used for other tasks of the normal mode (process automation system, telemechanics) and in this sense can be considered as redundant
- 1 channel is needed for telemechanics, SCADA, monitoring of the electrical equipment, regime and emergency control automatics, synchronized vector measurements. As the information in the channels is transmitted as SV (multicast) the results can be used both for the accounting of electric power and for technological tasks provided that the accuracy characteristics of the both channels are equal. In this case it is possible to make the both channels redundant to each other and to continuously monitor their differential measurement values (cross-calibration) which increases the calibration testing interval.

A further increase of the number of the channels for current measurements in the normal mode adds very little to the reliability while the total cost and amount of maintenance rise.

The integration of MUs for the measurements in the normal and transient modes into one unit is unpractical as in this case the maintenance of the MU for the normal mode depends on the possibility to put the MU for the transient mode out of service from the side of the relay protection system and vice versa [16].

Current measurements in the normal mode

CTs of the traditional design have accuracy classes of 0.5, 0.2, 0.2S. For example for the class 0.2S the following relations between the accuracy and the range are set according to GOST 7746-2001 (Table 2) [17]:

Table.2: Relations between the accuracy and the range

%In	1	5	20	100	120
Maximum current error, %	±0.75	±0.35	±0.2	±0.2	±0.2
Maximum angle error	±30`	±15`	±10`	±10`	±10`

A further improvement of the accuracy of the current measurements in the normal mode is advisable mainly in the range of low currents because in the range of the nominal currents the practical limit has been reached and a further improvement of the accuracy without significant expenses or a fundamental modification of the design of the primary sensor is impossible. An improvement of the accuracy in the range of low currents is advantageous both for commercial electrical power accounting systems and for the diagnostics of the equipment (for example diagnostics of a transformer by the change of Zk, P no-load and P short current in time) [18].

For the operation with such CT MU with the following specifications is needed:

- the accuracy of MU in the measurement ranges defined in GOST should be by a factor of 5-10 higher than that of CT
- SV sampling rate – 256 points/period [19].

An improvement of the accuracy of the current measurements in the normal mode by the combination of a CT and an MU can be achieved in a few ways:

1) Reduction of the error due to a minimum load of the secondary circuit of CT (MU only). This mode is characterized by the minimum possible amplitude error
2) Software compensation of the systematic error of CT in MU: as the impedance of the load Z_2 remains constant from the known formulas of the current error (1) and angle error (2) one obtains:

$$f_{iH} = \frac{33{,}8 \times l_M \times Z_2^{0.6} \times I_{2H}^{1.2}}{(I_1/I_{1H})^{0.4} \times f^{0.6} \times F_{1H}^{1.6} \times S_M^{0.6}} \times \sin(\varphi+\alpha) \times 100 \quad (1)$$

$$\delta = \frac{119332 \times l_M \times Z_2^{0.6} \times I_{2H}^{1.2}}{(I_1/I_{1H})^{0.4} \times f^{0.6} \times F_{1H}^{1.6} \times S_M^{0.6}} \times \cos(\varphi+\alpha) \times 100 \quad (2)$$

where I_1, I_2 - primary and secondary currents, respectively, f- frequency of the current, z_2 – complex impedance of the secondary circuit (including the load impedance), I_{M} - average length of the magnetic core, S_M – effective section of the magnetic core, ϕ – loss angle, α – phase shift between the secondary EMF E_2 and the secondary current I_2.

From the formulas (1) and (2) it is possible to immediately calculate the amplitude and phase correction coefficients for the measured signal value. In a similar way it is possible to make a software compensation of the frequency dependence [20].

To reduce the error it is advisable to calibrate CT and MU together already at the factory because in case of a separate calibration of the primary sensor (CT) and MU their errors sum up.

3) Use of MU together with a CT tap switch (only for new CTs and CTs adapted for the operation in a DSS). Usually a CT has several taps of the secondary winding which allow one to select the transformation coefficient desired without a modification of the CT. The availability of a "smart" MU allows one to implement a selector of the secondary current of the CT so that the selector automatically connects the shunt (ADC) to that tap which has the minimum current and angle error at the given primary current. In this case it is possible to substantially lower the CT error and the error 0.2% is obtained already in the range of (0.3…1.2) In which corresponds to the accuracy class 0.5S according to GOST 7746-2001. The necessary condition for a smooth reconnection in this case is that the tap step should be not greater than 0.3 In, otherwise artificial spikes of the measurement value are possible during the reconnection. Naturally the function to switch the range should be anticipated in the FPGA module.

Attention should be paid to the possibility and advantages of the implementation of some technological functions in MU because in this case an opportunity appears to improve the reliability and/or processing speed (the data are processed within MU, there is no need first to transmit the data to a specialized unit for processing and then to an execution unit). Among such functions there may be for example per-phase commercial or technical accounting of the electric power. A prerequisite for this is the reception of SV from both the main and the redundant VT from the process bus switch.

Current measurements in the transient mode (for the relay protection system)

At present the specified CT accuracy for relay protection purposes must be within the 10% error for every mode but in practice the error may exceed 35% depending on the CT design and the amount of the aperiodic component. Therefore the main possibility to improve the CT characteristics is an improvement of the accuracy and linearity of the current measurements in the transient mode which makes it possible to:

- improve the sensitivity of the current and distance protection to remote short circuits (the protection zone is expanded)
- improve the sensitivity and processing speed of the differential busbar protection (as there is no distortion of the current the unbalance current is small and the speed of the response of the protection increases)
- improve the accuracy of the determination of the location of a fault (in some cases)
- stop using zero-sequence CTs and determine 3Io by a calculation (in some cases)

An improvement of the validity and accuracy of the current measurements in the transient mode by the combination of a CT and an MU results from the following:

1) The minimum secondary load of the CT (only MU) results in a greater accuracy limit factor of the primary current (the current at which the CT produces an error less than 10%).
2) CT with a multisection magnetic core is used (the effect of the residual induction is removed, the transmission of the nonperiodic component is removed). A reduced load capability in this case does not matter as the only load of the CT is the MU.
3) A Rogowski coil is used (high accuracy in the range of the nominal and large currents, no angle error due to the absence of a magnetizing current, the absence of saturation, a small effect of the nonperiodic component, no degradation of the characteristics due to the absence of a magnetic core). A reduced load capability in this case does not matter as the only load of the CT is the MU. Special design measures are necessary to reduce the influence of the currents of the neighbouring phases to the measurement results.

For the operation with such CT MU with the following specifications is needed:

- the accuracy of MU in the measurement ranges defined in GOST should be not worse than 3-5%
- the rate of SV samples output to the process bus – 80 points/period
- the frequency of the interrogation of the primary sensor by ADC – not less than 1 MHz (for diagnostic microoscillograms)

Attention should be paid to the possibility and advantages of the implementation of the following functions in MU:

- some technological functions (for example current protection) because in this case an opportunity appears to improve the reliability and/or processing speed (the data are processed within MU, there is no need first to transmit the data to a specialized unit for processing and then to an execution unit)
- recording of microoscillograms for diagnostic purposes (current spikes for the determination of the location of a fault of an aerial line, diagnostics of the cable by the charge current during the application of the voltage, transformer excitation current, subtransient electrical motor current).

Voltage measurements

At present the most accurate measurement instruments for the phase voltage 6-750 kV are a measurement transformer and a capacitive divider. The accuracy class of 0.2 has been achieved in practice. This class provides voltage measurements with a voltage error of 0.2% and an angle error of 10` in the range of (0.2…1.2) Un according to GOST 1983-2001 [21].

A further improvement of the voltage measurement accuracy is advantageous both for the normal mode (commercial electrical power accounting systems, monitoring of the state of a transformer by the change of Zk, P no-load and P short current) and for the transient mode (the "dead zone" of the relay protection system is reduced, overvoltage spikes can be detected, the accuracy of the determination of the location of a fault of an aerial line is improved).

For the implementation of a DSS in a substation with traditional electromagnetic VT the following clarifications should be made [22]:

- the magnetic core has a reduces section (the load– only MU), the mass and the cost is reduced
- winding correction is not necessary.

In a new construction or full reconstruction with the replacement of VTs a capacitive divider is preferred to an electromagnetic VT due to the following considerations:

- it is less expensive (the difference is especially big for high voltage)
- it has no ferroresonance
- it is less subject to failures (overvoltage spikes do not affect the lifetime)
- it has an extended frequency range
- the reverse transformation from the secondary circuit to the primary one is impossible
- a low load capability and the dependence of the accuracy on the kind of the load in this case do not matter as load is constant and known beforehand (only MU)

The work of a capacitive divider only on MU leads to a few design changes:

- a reduced capacitance of the divider (due to the minimum load): reduced dimensions, weight, cost. The reduction of the dimensions of the divider allows one to build it into rigid insulators, high voltage transformer inputs, cable inputs (a reduction or complete elimination of free-standing transformers)
- no transformer, reactor (minimum and stable load) and anti-resonance filter are necessary so that an internal ferroresonance is excluded, there is neither dependency on frequency nor temperature error, the cost is reduced
- not less than 2 primary sensors are necessary (the optimum is 3 sensors): redundancy/majorization, cross-calibration, an increase of the calibration testing interval, one sensor is for a sealed VT for a commercial electrical power accounting system) [23, 24].

For the operation with the dividers MU with the following specifications is needed:

- the accuracy should be about 0.02% in the range of (0.2…1.2) Un (in order not to introduce a remarkable error into the measurement channel)
- the accuracy should be of the order of 1% in the range up to (1.5…3) Un (depending on the voltage class) for the diagnostics of the high voltage equipment
- the rate of SV samples output to the process bus – 256 points/period
- the frequency of the interrogation of the primary sensor by ADC – not less than 1 MHz (for diagnostic microoscillograms and for the detection of a single phase-to-earth fault in a 6-20 kV network by the level of HF harmonics)
- a storage of the measurement values during the last 5…10 ms (to provide the response from MU during a short circuit in the "dead zone")
- recording of microoscillograms (observation of the time of the appearance of a voltage spike for the determination of the location of a fault of an aerial line, registration of storm and switching overvoltages for the monitoring of the operational life of the high voltage insulation and an indirect monitoring of surge arresters)
- the number of inputs for voltage measurements (excluding 2 calibration inputs): for a 6-35 kV VT – 3 inputs, for a 110-750 kV VT – 1 input (the utilization of a VT with several taps and multi-channel MU is unpractical in this case)
- an availability of discrete inputs for the connection of SF6 density sensors
- an availability of an analog input for the monitoring of the total current of the capacitive divider (the monitoring of the general state of the divider and the state of the grounding)

- MU for a three-phase 6-35 kV VT must contain relay protection functions associated with the monitoring of the frequency (automatic frequency load shedding, frequency-actuated automatic reclosing), voltage (automatic reclosing, automatic switching over to a reserve source, undervoltage protection). The built-in kind of the functions implemented by the help of GOOSE messages results in a higher processing speed and an improved reliability (there are less devices in the circuit)
- a software compensation of the amplitude and angle error (the load is known and constant)

The fact that the only secondary load of VT is MU leads to ideal conditions to minimize the amplitude and angle errors. For three-phase 6-35 kV VTs this also results in symmetrical phase loads which further reduces possible additional errors. In addition a software compensation of the amplitude and angle error is possible when the calibration at the factory is done.

CONCLUSIONS

1. Current and voltage measurement transformers used at present have had a long evolution and are now technically advanced devices. They can be successfully applied in "digital" substations in a combination with signal digitizers. The cost of this solution is significantly lower compared to the use of optical CT and VT offered on the market.
2. In a new construction or full reconstruction of power facilities it is advantageous to use CTs and VTs modified to operate together with signal digitizers. The modification makes it possible to substantially improve the characteristics of the current and voltage measurement channels as well as reduce the total cost.
3. The development of fully digital current and voltage measurement instruments with advanced technical specifications, inexpensive and easy to use is a relatively complicated task which has not been solve so far. The use of existing CTs and VTs at this stage allows one to master all other technologies of a DSS until the proper digital measurement instruments are available. This results in a substantial reduction of the technical and economical risk in the implementation of a DSS.

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