CT SATURATION EFFECTS ON PROTECTION IN TRANSMISSION SUBSTATIONS

Anamaria IAMANDI[1], Nicoleta ARGHIRA[2], Ioana FĂGĂRĂȘAN[3], Sergiu Stelian ILIESCU[4], Roxana - Alexandra ISTRATE[5]

Digital technology facilitates the improvement in reliability of the protection system by introducing IEC 61850 standard along with digital communications. The correct and safe operation of protection equipment strongly depends on the accuracy of measurements received from current transformers (CTs). The accurate scale of secondary current depends on the proper operation of CTs considering its technical characteristics, secondary load and system conditions (short circuit level, system reactance and primary time constant). The aim of this paper is to study the influence of digital equipment along with IEC 61850 process bus on CT saturation. The practical implementation and validation was done on three Romanian transmission substations for three different short circuit network conditions. Best protection and measurement operation is obtained for the digital protection relay as the transformer core saturates later than in the case of the classical electro-mechanical equipment; in 2 of the 3 investigated substations, CT does not even saturate.

Keywords: digital substation, protection equipment, digital current sensors, CT saturation

1. Introduction

The main pillars that led both utilities and vendors to approach digital substations designs are the increased need to provide interoperability between multivendor equipment, to improve the safety, reliability and availability of assets and to meet the challenges of decarbonizing the power sector. The IEC 61850 standard ensure data interoperability between different Intelligent Electronic Device (IED) vendors using Substation Configuration Language (SCL) to define data configuration syntax. IEC 61890-2/2LE describes the signal acquisition and

[1] PhD Student, Faculty of Automatic Control and Computers, University POLITEHNICA of Bucharest, Romania, e-mail: anamaria.iamandi@upb.ro
[2] Conf., Faculty of Automatic Control and Computers, University POLITEHNICA of Bucharest, Romania, e-mail: nicoleta.arghira@upb.ro
[3] Prof., Faculty of Automatic Control and Computers, University POLITEHNICA of Bucharest, Romania, e-mail: ioana.fagarasan@upb.ro
[4] Prof., Faculty of Automatic Control and Computers, University POLITEHNICA of Bucharest, MO – ASTR, MC – AOSR, Romania, e-mail: stelian.iliescu@upb.ro
[5] PhD Student, Faculty of Energy Engineering, University POLITEHNICA of Bucharest, Romania, e-mail: ialexandraro@gmail.com

digitization chain from conventional/non-conventional instrument transformers to IEDs. In a fully digital substation the signal is digitized next to primary equipment and sent to all IEDs using digital communication network [1]. Digital communication network is an ethernet network based on fiber optic. The IED's operating decision and alarm signals are sent as Generic Object Orientated Substation Event (GOOSE) messages, defined in IEC 61850-8-1 standard. Furthermore, using IEC 61850-8-1 Manufacturing Messages Specification (MMS) is ensured data exchange between IEDs and Human Machine Interface (HMI).

The interest of digital technology in substation protection and control systems has grown among the utilities. Following are presented different project developed by authorities around the world to evaluate the benefits of introducing digital technology:

- The Scottish Power Energy Networks has developed the Future Intelligent Transmission Network Substation (FITNESS) project to evaluate the interoperability between multivendor equipment based on IEC 81850 [2]. In [3] it is observed the results dissemination regarding Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR) configuration under CT saturations and different equipment or communication infrastructure failure considering FITNESS architecture.
- The French TSO, Réseau de Transport d'Électricité (RTE), has launched the project "Poste Intelligent" to evaluate the reliability and security of digital technology [4].
- The Tennessee Valley Authority (TVA) has integrated IEC 61850 standard within several substations. In [5] it is presented a report of a 500 kV digital substation project in which evaluates the full integration of IEC61850 standard within IEDs.
- The Romanian TSO, Transelectrica (TEL) aims to develop a pilot project of a fully digital substation, by applying the concepts and technologies from "Smart Grid Company Policy 2018-2027" and Technical Policy regarding asset digitalization within TEL [6].

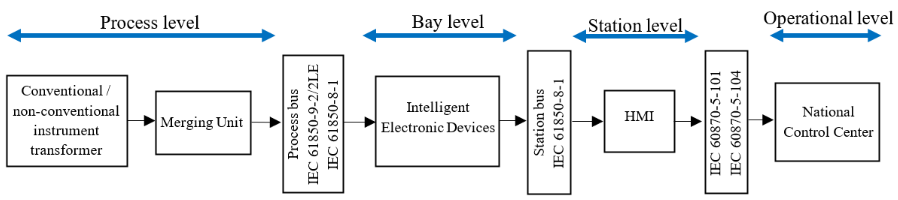


Fig. 1. Generic architecture of a digital substation

Fig. 1 designed the generic architecture of a digital substation, which includes:

- Process level: Merging Unit, IEDs, Control Circuit Breaker, primary equipment (conventional/non-conventional instrument transformers, circuit breaker – CB, disconnectors, etc.);
- Process bus network via IEC 61850-9-2/2LE Sampled Values and IEC 61850-8-1 GOOSE messages through which the IEDs and MUs equipment subscribes to published data;
- Bay level: IEDs - digital protection equipment, control equipment, metering system, teleprotection system;
- Substation bus network via IEC 61850-8-1 MMS to allow data exchange between bay level and station level (HMI, SCADA);
- Station level: HMI, SCADA gateway, data concentrators, etc.;
- Operational level: National Control Center.

In addition, another important aspect related to digital substations are both cyber security risks [7] and cyber security requirements [8]. Furthermore, digital substation strongly contributes to energy sector decarbonization policy by facilitating the integration of renewable energy resources with reduced inertia and low fault currents [9]. Digital protection equipment are designed to detect and eliminate faults with low current values, with a high degree of reliability and security. The aim of this paper is to study the CT saturation considering digital protection equipment, IEC 61850-9-2/2LE process bus and merging unit equipment. Current measurement faults can affect the proper operation of the protection system, thus solutions for considering CT saturation are considered in designing the substation protection system. The reduction of inrush current of the transformer is proposed in [10] for solving some saturation issues. Detection of CT saturation is validated for a bus differential protection in [11]. Modern substation measurements with fiber-optic current sensors with a Faraday principle appeared lately and they do not saturate [12]. Still, the majority of substations use classical current transformers and CT saturation detection is to be adequately studied. This study proposes an algorithm for CT saturation evaluation and its effects on classical and digital protections, independent of the protection function. This paper is divided into 4 sections. Section 2 presents the paradigm of protection systems in transmission substation and the behavior of main protection function during conventional CTs saturation. Section 3 presents the entire chain from signal acquisition to system operation in a digital substation considering both conventional CTs and digital sensors. Section 4 studies the influence of digital technology on CT saturation considering different system conditions (short circuit level, system reactance, primary time constant).

2. Protection functions used in transmission substations and CT saturation influence

Protection systems consist of protection equipment, generally redundant, equipped with main protection and backup protection to ensure high-speed fault clearance and fault extension prevention. In addition to main protection and backup protection, digital protection equipment includes many additional protection functions designed to increase the reliability and security criteria. Main protection must ensure high-speed tripping in case of a fault located in any point of the protective zone. Backup protection may be performed „local, substation or remote" [13], been ensured by time delayed protection function, breaker failure protection function (50BF according to American National Standards Institute's code – ANSI's code) and busbar differential protection function.

ENTSO-E recommends for European TSO's EHV substation to be equipped with a redundant protection scheme, which is formed by a main protection equipment and a backup protection equipment, or with a fully redundant protection scheme, formed by 2 main protections equipment. The two protection scheme must act independent and simultaneous by each other. In [14], there are given some guidelines for overhead transmission lines (OHLs), power transformers and busbars. The protection schemes in [14] are not restrictive, as TSOs can complete them in accordance with their experience and their national grid codes. In Fig. 2 is presented a typical single line diagram of a transmission substation while in circles are highlighted the main protection functions with which is equipped. The numbers in circles represent the protection functions code, according to ANSI's code.

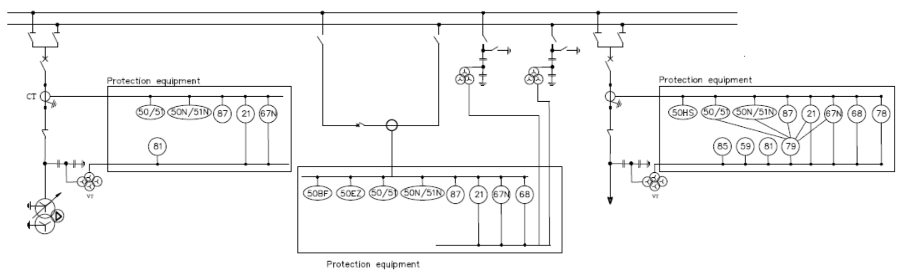


Fig. 2. Main protection function used in a transmission substation

The CT saturation may lead to protection equipment operation delays or to unwanted trips. Following is presented the way in which the CT saturation influence the operating decision of protections functions.

A. Overcurrent protection

The operating principle of the overcurrent protection consists on supervising the phase current and earth current and transmitting the trip command to the corresponding circuit breaker when the threshold value is exceeded.

Most of the utilities are using the RMS value of the fault current to take the operating decision. In this case, during CT saturation, the RMS value corresponding to the secondary current calculated by the relay will be lower than the real value from primary circuit. This will delay the relay operation until the CT magnetic core returns to unsaturated state. Therefore, it is affected both security and speed criteria of the overcurrent protection.

B. Distance protection

Distance protection (21 according to ANSI code) calculates the impedance measured to the fault location and compares it with the setting value. If the measured impedance is less than the setting value, then the fault is within the protected zone and the relay transmits the trip decision to the corresponding CB.

The measured impedance is calculated using current and voltage measurements received from CTs and voltage transformers (VT) installed on the protected element's bay.

The CT saturation may result in distance relay under-reach, over-reach or to delay the relay operation due to both current magnitude decreasing and to phase shifting current. The influence of the CT saturation on distance relay behavior depends on the relay technology (classical or digital), the operating characteristics (there are widely used MHO and quadrilateral characteristics) and the algorithm used to determine the fault impedance.

For example, distance relay 1st zone is set to ensure instantaneous tripping for 80-85% of the protected zone. Due to CT saturation, the protection relay measures a lower current magnitude than the real one. This causes the distance relay to under-reach because protected zone is decreased, and both the fault impedance is increased. Therefore, the fault is eliminated by the higher protection zone, after the corresponding operating time has elapsed.

C. Differential protection

Differential protection's operation principle is based on Kirchhoff's first law in which the currents entering the protection zone must be equal to those exiting the protection zone. The protection zone is bounded by the CTs location.

Differential protection grading plan is set considering both the CT measurement errors and the CT saturation. CT saturation during an external fault may result in false operation of differential relay due to calculation of a false differential current. Special attention must be given when designing the differential protection scheme for unit transformers. The most severe faults are those located in the proximity of the CT on the high voltage side of the unit transformer, as the faults in this area are characterized by high values of short-circuit currents. Consequently, the CT may saturate and the protection relay will transmit erroneously the block command during CT saturation due to harmonics presence. Normally, the protection relay is set to be blocked only in the presence of harmonics caused by inrush currents. In this case, the malfunction of the differential relay will delay the fault elimination inside the protected zone.

3. Current measurement systems in digital substations

Digital substations cover the entire process from signal acquisition to system operation and facilitates the introduction of IEC 61850 standard communication at process level along with digital current sensors.

Following different architectures of signal acquisition and processing chain are presented, considering different technologies: conventional current transformers and low power instrument transformers (LIPT).

3.1. Signal acquisition and processing chain using conventional current transformers

Signal acquisition and processing chain using conventional CT is realized by using IEC 61850-9-2 standard communication and merging unit equipment.

IEC 61850-9-2 standard introduced the representation process of analog current and voltage signals into digital strings data sample. The digital sampled data streams are available for further processing by digital protection equipment.

Merging unit equipment performs the following operations: process the signals acquired from CTs and synchronize the sampled measured values to a commune time reference. The sample data streams are transmitted from merging unit equipment to digital protection equipment via process bus, as they are equipped with analog and digital interfaces compatible with IEC 600044-8/IEC61850-9-2 standard [15].

Merging units are influenced by the CT behavior during saturation. Their correct operation depends on the accuracy of the received signals, “ratio and phase error compensation” [16].

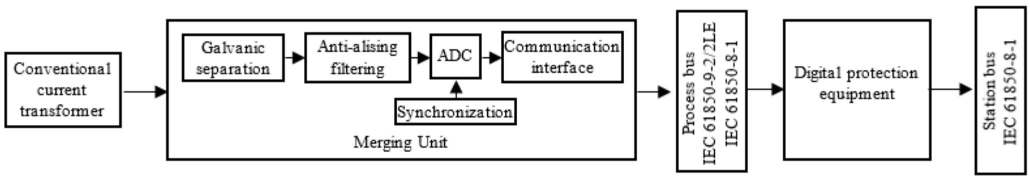


Fig. 3. Signal acquisition and processing chain using conventional CTs

In Fig. 3, merging units perform the galvanic separation of the input currents from the primary circuit. Following, the input currents are filtered using anti-aliasing filtering [17], converted from analog to digital sampled values and sent to process bus using communication interface. Digital protection equipment acquires digital data strings from process bus using communication interface, execute the logical algorithm and send the operating decision using communication interface.

3.2. Signal acquisition and processing chain using LIPT

LIPTs started to be used in transmission substations as microprocessor-based relay are widely used together with digital technology. In full digital substations signals are digitized close to primary process. The main benefits of using LIPT are high accuracy, wide range of measurement, reduced secondary power and reduced cooper wires.

IEC 61869-6 [18] presents a simplified diagram of digital current sensors. In the simplest form, a digital current sensors assembly is formed by an "outdoor part" – the sensor, and an "indoor part" – the merging unit equipment. The "outdoor part" and the "indoor part" are communicating with each other via a communication link. There are two main architecture configurations used when designing a digital substation with LIPT: the acquired signal is processed and transformed to digital using merging unit (Fig. 4) or using current sensor (Fig. 5). In Fig. 4, the signal is filtered, transformed to digital and time synchronized using merging unit equipment. Following, using merging unit's communication interface is sent to digital protection equipment via process bus using IEC 61850-9-2/2LE communication protocol.

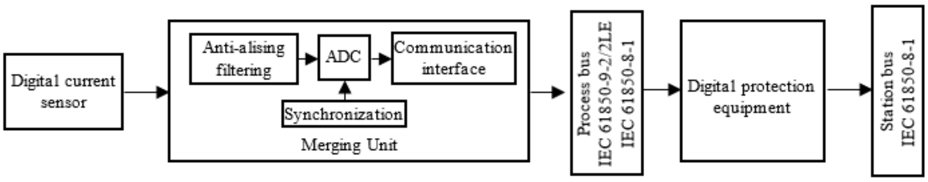


Fig. 4. Signal acquisition and processing chain using LIPT

In Fig. 5, the signal provided by the LIPT is filtered and sent to merging unit using a proprietary communication protocol. The merging unit equipment makes the conversion to IEC 61850-9-2/2LE and sends the digital data strings to digital protection equipment via process bus.

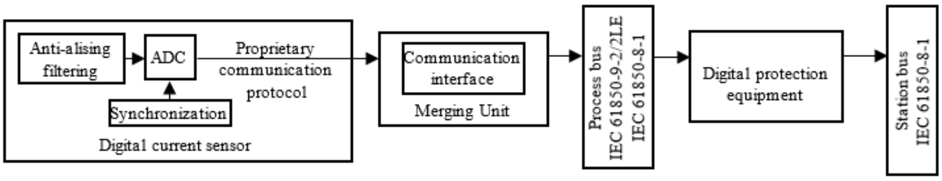


Fig. 5. Signal acquisition and processing chain using LIPT and proprietary communication protocol

4. CT saturation study on the Romanian transport substations

Following is studied the behavior of CT during saturation and how the protection equipment's operating performances are affected. There are considered three transmission substations from RPS equipped with conventional CT.

4.1. CT saturation detection algorithm

The correct and safe operation of protection system depends on CT ratio, measuring accuracy and the CT saturation's degree during a fault in primary circuit. It is recommended to power utilities to study the CT saturation from the design phase of the substation, considering power system conditions, technical characteristics of the CTs and protection equipment's characteristics which are to be installed.

The effects of CT saturation are studied with the following proposed methodology:

1. Identification of **CT technical characteristics** from Factory Acceptance Test report: *ratio*, *secondary load* – S_{2n} [VA], *accuracy class [-]*, *Accuracy Limit Factor* – ALF [-], *winding resistance* – R_{CT} [Ω], *secondary rated resistance* – R_n *[Ω]*, *secondary rated reactance* – X_n *[Ω]*, *saturation voltage* – E_k *[V]*;
2. Determine the **power system condition**: *symmetrical primary fault current* – I_{3f} *[kA], system ratio – X/R [-], primary system time constant –* τ *[s];*
3. Identification of **protection equipment** *secondary load –* S_n *[VA]* and *the operating time –* t_{op} *[ms]* from technological specifications guaranteed by manufacturer;
4. Determine the **secondary circuits load** needed to connect the protection equipment to CT – S_{wire} *[VA];*
5. Evaluation of **CT saturation behavior** and influence on the protection equipment, [19].

The flowchart from Fig. 6 summarizes the methodology presented above.

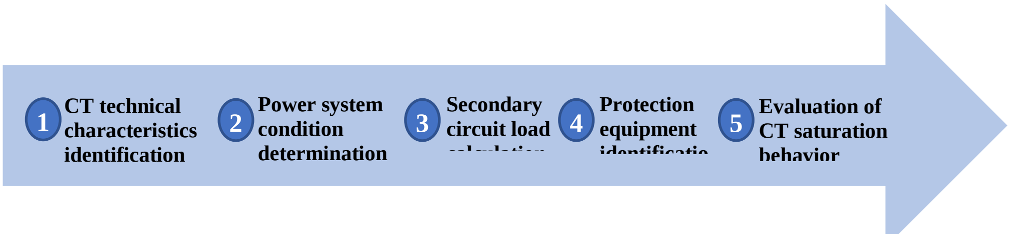


Fig. 6. The proposed methodology to study effects of CT saturation

4.2. Study on real data

A. Scenario definition

The aim of the case study is to observe the behavior of CTs during saturation in different power system conditions. In order to have a broader perspective, there are studied three 220 kV transmission substations located in different points of RPS – Fig. 7.

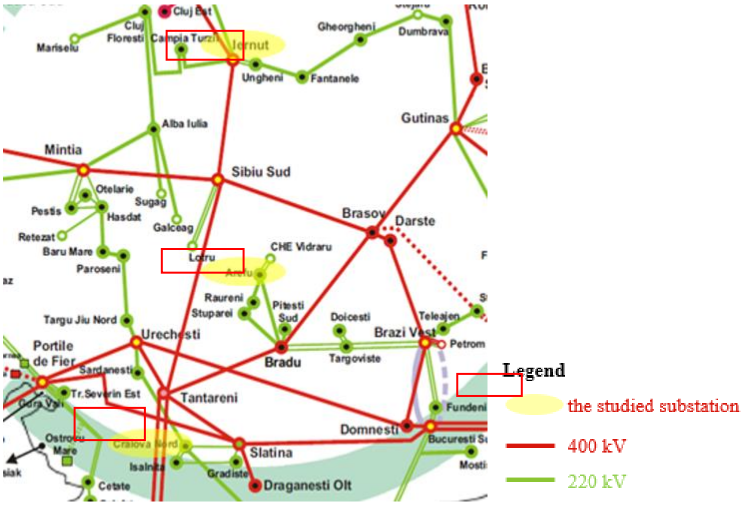


Fig. 7. Framing the studied network area

The studied substations were considered in different locations of the network to have different power system conditions (different short-circuit level, system reactance and primary system time constant) and, therefore, to have a better perspective of their influence on CT saturation. In the selected case-study, the power system conditions are strongly influenced by the proximity of large scale generating units and the interconnections with 400 kV transmission lines. Malfunctions of the protection system in these important substations would be highly detrimental for operation and stability of the power system, thus the selection of this scenario. For each studied substation, it is considered the case of a conventional CT mounted in an overhead transmission line (OHL) bay.

The following study was performed in the hypothesis of neglecting the influence of remanent flux. The proposed methodology in chapter **4.1.** is applied for the 3 substations.

B. Intermediate computations

Table 1 depicts the protection and secondary circuit data, as well as the CT computed results for steps 1-3.

In Table 1, the following equation were used to calculate secondary rated resistance (R_n), secondary rated reactance (X_n) and saturation voltage (E_k):

$$R_n = \frac{S_{2n} * cos\varphi}{I_{2n}^2} \quad (1)$$

$$X_n = \frac{S_{2n} * sin\varphi}{I_{2n}^2} \quad (2)$$

$$E_k = ALF * I_{2n} * \left(\sqrt{(R_{CT} + R_n)^2 + X_n^2}\right) \quad (3)$$

Table 1

Technical characteristics of the conventional CTs

Studied substation	Nominal ratio [A/A]	S_{2n} [VA]	cosφ [-]	Accuracy class	ALF	R_{CT} [Ω]	R_n [Ω]	X_n [Ω]	E_k [V]
220 kV substation A	1200/1	30	0.8	5P	30	5.117	24	18	1026.95
220 kV substation B	1200/1	30	0.8	5P	30	5.117	24	18	1026.78
220 kV substation C	1200/1	30	0.8	5P	30	6.3	24	18	1057.3

The power system condition (step 4) was determined by performing fault simulation in different location for each studied substation: (1) close to CT and protection equipment, (2) on adjacent transmission substation busbar and (3) at 2nd transmission substation busbar compared to studied substation. In Fig. 8 is shown a generic diagram with fault locations.

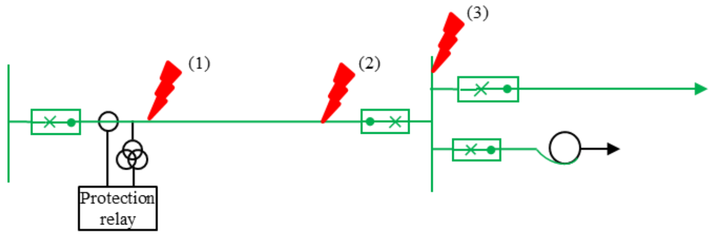


Fig. 8. Generic fault location design for power system condition evaluation

In Table 2, the primary system time constant τ [ms], was calculated using equation (8):

$$\tau = \frac{1}{\omega} * \frac{X}{R} [s] \tag{4}$$

Table 2

Power system data

Studied substation	Fault location	I_{3f} [kA]	X/R [-]	τ [s]
220 kV substation A	(1)	7.66	8.25	0.0263
	(2)	14.71	9.38	0.0299
	(3)	9.28	11	0.035
220 kV substation B	(1)	18.8	8.44	0.0269
	(2)	9.21	6.56	0.0209
	(3)	15.2	9.82	0.0313
220 kV substation C	(1)	18.14	10.61	0.0338
	(2)	18.17	10.74	0.0342
	(3)	13.56	7.66	0.0244

In Table 3 are given technical characteristics of the protection equipment and also cable parameters needed to determine the secondary circuits load for each studied substation.

Table 3

Secondary circuit data

Studied substation	S_n [VA]		t_{op} [ms]		L [m]	s [mm^2]	φ_{Cu} (70°C) [Ω mm^2m^{-1}]	S_{wire} [VA]
	Classical	Digital	Classical	Digital				
220 kV substation A	2.2	0.2	55	20	56	4	0.02121	0.59388
220 kV substation B	2.2	0.2	55	20	52	4	0.02121	0.55146
220 kV substation C	2.2	0.2	55	20	64	4	0.02121	0.67872

C. Results and discussion

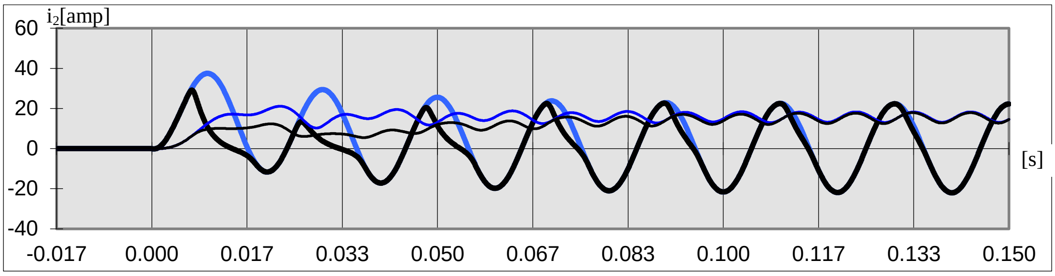
For each studied substation it was studied the CTs behavior considering different loads connected in their secondary windings.

First, it was studied the case of maximum load connected in CTs secondary winding. The CTs saturate in aprox. 6 ms ÷ 25 ms regardless the system condition. The 2nd study was performed considering a load consisting of an electromechanical protection equipment. CTs saturate in aprox. 30 ms ÷ 70 ms, depending on system condition (short-circuit level and primary system reactance). The electromechanical protection equipment operating behavior is affected as the CTs saturate before the electromechanical protection equipment can take the operation decision (minimum 55 ms according to technical characteristics).

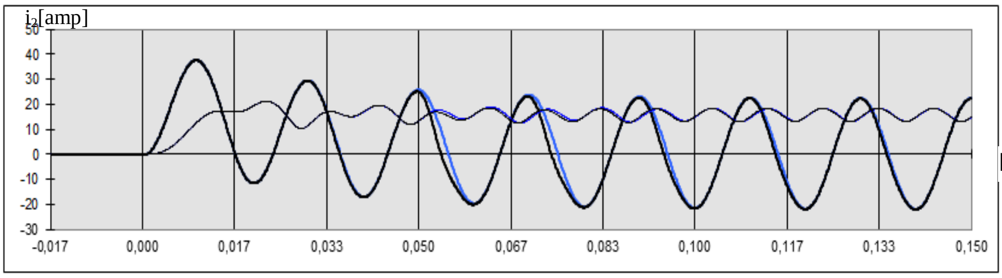
The 3rd study presumed a digital protection equipment connected in CTs secondary winding. In this case, CTs saturation appears just in the case of the substation C and in the event of high short-circuit values. Even if the current transformer saturates, this does not affect the correct operation of the digital protection because the tripping decision period (20ms) is shorter than the saturation time (50 ms).

Following, to have a better perspective of the CT secondary winding response, there are given a graphical representation of CT behavior for 220 kV substation B considering short-circuit simulated in point (1) and different secondary loads: maximum load (a.), load corresponding to an electromechanical protection equipment and load corresponding to digital protection equipment.

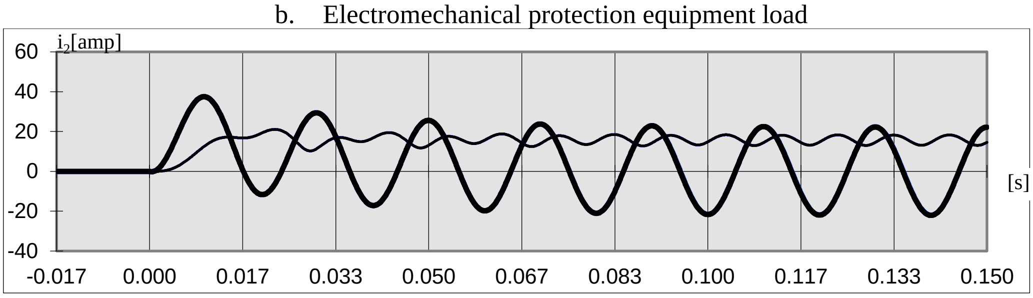
In Fig. 8, the blue line represents the ideal secondary current variation in time while the black line represents the real secondary current in time, $i_2(t)$. The secondary current values are plotted both as instantaneous values and as rms values.



a. Maximum secondary load



b. Electromechanical protection equipment load



c. Digital protection equipment load

Fig. 8. Simulation results for 220 kV substation B, fault location (1) considering different secondary load

The entire study case simulation results are summarized in Table 4.

Table 4

Simulation results

Studied Substation	Fault location	Magnetic core saturation time [ms]		
		Maximum load	Electromechanical protection equipment load	Digital protection equipment load
220 kV substation A	(1)	25	-	-
	(2)	6	70	-
	(3)	10	-	-
220 kV substation B	(1)	7	48	-

	(2)	11	-	-
	(3)	8	50	-
220 kV substation C	(1)	7	32	50
	(2)	7	30	48
	(3)	9	-	-

5. Conclusions

The current paper studies the conventional current transformer behavior considering different system condition and different secondary loads: maximum load, load corresponding to an electromechanical protection equipment and load corresponding to digital protection equipment. It was observed that CTs core saturate regardless of the system condition when the maximum load is connected in their secondaries. Comparing the simulation results of the two types of protection equipment connected in secondary (electromechanical equipment and digital equipment) it is observed that CTs core saturate fastest in the case of an electromechanical protection equipment.

Best protection and measurement operation is obtained for the digital protection relay: in 2 of the 3 investigated substations, CT core does not even saturate. In the event of the worst system conditions (high short-circuit level and high primary system reactance), the CT also core saturates with the digital protection equipment solution. Still, the digital protection relay has a faster response time than electromechanical protection equipment and the operating behavior is not affected. In addition, digital protection equipment designers have developed different protection functions to detect CT core saturation and to reconstruct the secondary current curve.

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