VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

FACULTY OF ELECTRONICS

DEPARTMENT OF ELECTRICAL ENGINEERING

Siarhei Semashka

INVESTIGATION OF THE SELECTIVITY OF THE AUTOMATIC SWITCHES

Master‘s degree Thesis

Electrical Energetics Systems Engineering study programme, state code 621H62002

Modern Electrical Power Engineering specialisation

Electronic and Electrical Engineering study field

Vilnius, 2017

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OBJECTIVES FOR MASTER THESIS

......………..No. ....
Vilnius

For student **Siarhei Semashka**

Master Thesis title: Investigation of the Selectivity of the Automatic Switches

Approved on 9th of November, 2015 by Dean‘s decree No. 401el.

The Final work has to be completed by 29th of May, 2017

THE OBJECTIVES:

Perform a review of the selectivity analysis methods. Examine what is more suited to specific structures of networks. Compare all the ways a particular network and check the effectiveness of selectivity. Investigate limitation of widely used time-current protection coordination method and develop complex comprehensive approach for selection a proper tripping discrimination technique. Perform research on specific switches experimentally. Perform analysis of the results and present conclusions.

Consultants of the Master Thesis: ……………………………………………………………….……………………

....……..............
(Title, Name, Surname)

Academic Supervisor .... Dr. Ričardas Masiulionis
(Signature)

Objectives accepted as a quidance for my Master Thesis

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(Student‘s signature)

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(Student‘s Name, Surname)

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Elektros energetikos sistemų inžinerijos studijų programos baigiamasis magistro darbas

Pavadinimas **Automatinių jungiklių selektyvumo tyrimas**

Autorius **Siarhei Semashka** Vadovas dr. **Ričardas Masiulionis**

Kalba

	lietuvių
X	užsienio (anglų)

Anotacija

Darbe yra tiriamas žemos įtampos automatinių jungiklių selektyvumas. Tyrimo reikalingumas grindžiamas poreikiu tobulinti dabar plačiai naudojamos technikos laiko-srovės selektyvumui užtikrinti.

Pasiūlytos rekomendacijos parinkti tinkamą elektros tinklo apsaugos schemą. Išnagrinėtas nuosekliai sujungtų automatinių jungiklių suderinamumas tinklo apsaugai. Remiantis teorinėmis ir eksperimentinėmis žiniomis pateikti patobulinimai. Pirmiausia, trumpojo jungimo srovių vertėms rasti buvo išbandyti automatiniai jungikliai su laiko-srovės selektyvumu, turintys šiluminius ir elektromagnetinius atkabiklius, bei su srovės selektyvumu. Tada buvo atliktas kompiuterinis modeliavimas specializuota programine įranga ir patikrintas jos tinkamumas elektros tinklo apsaugos įrangai parinkti. Sudarytas algoritmas su rekomendacijomis siekiant užtikrinti selektyvumo veikimą iš nuosekliai sujungtų automatinių jungiklių. Darbo pabaigoje pateiktos darbo išvados ir siūlymai.

Darbą sudaro: įvadas, literatūros apžvalga, eksperimentų dalis, simuliacijos dalis, išvados ir pasiūlymai, literatūros sąrašas.

Darbo apimtis – 72 p. teksto be priedų, 29 iliustr., 48 bibliografiniai šaltiniai.

Prasminiai žodžiai: selektyvumas, apsaugos priemonių derinimas, žema įtampa, automatiniai jungikliai.

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Electrical Energetics Systems Engineering study programme master thesis.

Title: **Investigation of the Selectivity of the Automatic Switches**

Author **Siarhei Semashka** Academic supervisor **dr. Ričardas Masiulionis**

Thesis language

☐ Lithuanian

☐ Foreign (English)

Annotation

This paper investigates such characteristic of low-voltage automatic switches as selectivity. The core of the research is based on providing evidence about the necessity of improvement of a widely used time-current technique. The recommendation for choosing a proper protection coordination scheme was proposed. Protection coordination of two circuit breakers connected in series is observed. The proposed improvements are evaluated based on theoretical and empirical backgrounds. Firstly, circuit breakers with time-current based on thermal-magnetic release and current selectivity are tested in order to obtain selectivity. Then, the simulations are conducted in order to check the eligibility of specialized software program for investigation of protection coordination among low voltage automatic switches. Finally, conclusions and recommendations are presented.

Structure: introduction, literature review, experiment, simulation, conclusions and recommendations, references.

Thesis consist of: 72 p. text without appendixes, 29 pictures, 48 bibliographical entries.

Keywords: Selectivity, protection coordination, low-voltage, automatic switches.

VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

Siarhei Semashka, 20150245

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Faculty of Electronics

(Faculty)

Electrical Energetics Systems Engineering, EEIfmc-15

(Study programme, academic group no.)

DECLARATION OF AUTHORSHIP IN THE FINAL DEGREE PROJECT

June 1, 2017

I declare that my Final Degree Project entitled "Investigation of the Selectivity of the Automatic Switches is entirely my own work. The title was confirmed on the 9th of November, 2015 by Faculty Dean's order No. 401el. I have clearly signalled the presence of quoted or paraphrased material and referenced all sources.

I have acknowledged appropriately any assistance I have received by the following professionals/advisers: dr. Ričardas Masiulionis (Vilnius Gediminas Technical University) and Prof. dr. Grzegorz Benysek (University of Zielona Góra).

The academic supervisor of my Final Degree Project is dr. Ričardas Masiulionis (Vilnius Gediminas Technical University) and Prof. dr. Grzegorz Benysek (University of Zielona Góra).

No contribution of any other person was obtained, nor did I buy my Final Degree Project.

(Signature) (Given name, family name)

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I am very thankful to the Department of Electrical Engineering, Faculty of Electronics, Vilnius Gediminas Technical University (VGTU) and Department of Electrical Engineering, Faculty of Computer, Electrical and Control Engineering, University of Zielona Góra (UZ) for the developing the modern knowledge in Electrical Energy System Engineering. I would like to express my utmost gratitude to my MSc. supervisor at VGTU, Dr. Ričardas Masiulionis, for supervision and valuable guidance during the entire period of my MSc. studies. I am also very thankful to my scientific supervisor at UZ, Prof. Grzegorz Benysek, for his supervision, his suggestion and encouragement throughout my studying at the University of Zielona Góra as Erasmus+ exchange student. Also I would like to mention Doc. Dr. Voitech Stankevič at VGTU, who supervised the creation and calibration of Hall effect sensor, which was an essential part of conducting the experiment. A special thanks to Prof. at UZ, Ryszard Rybski and Prof. at VGTU Roma Rinkevičienė for the support in obtaining double degree. I would like to express my sincere gratitude to my all teachers at both Universities, especially Head of Department of Electrical Engineering at VGTU, Assoc. Prof Dr. Sonata Tolvaišienė, for her nice cooperation and discussions.

I would like to thank product manager at ABB UAB in Vilnius, Tadas Lideika, for giving an opportunity for use of short circuit stand in order to test ABB circuit breakers with different selectivity techniques.

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Contents

1 Introduction

During the last few decades' demand for electrical energy is constantly rising due to population growth and increasing industrialization. Most of the users are finally fed in low voltage, therefore low voltage automatic switches are very widespread among distribution systems. There are many different kinds of automatic switches, however circuit breakers prevail as apparatuses, which are capable to take in charge of make-on, carrying and breaking current in normal or abnormal conditions such as short circuit.

The quality of protection of electric equipment is based on sensitivity to various kinds of emergencies, the most of all to short-circuit and overloads currents. In order to guarantee optimal economical and functional service of the whole electrical installation the selection of the proper protection system is an essential requirement (Haron et al. 2012: 101–112).

Within the sphere of this analysis, the coordination between the various devices dedicated to protection of sections of installation or specific components should be addressed in order to obtain the following results:

- guarantee safety of the installation and of people in all cases;
- rapidly identify and exclude just the area involved in the problem, without indiscriminate trips which reduce the availability of energy in areas not involved in the fault;
- reduce the stress on components and damage to the area involved;
- guarantee service continuity with good quality power supply voltage;

- guarantee adequate support in the case of malfunction of the protection delegated to opening;
- achieve a good compromise between reliability, simplicity and cost-effectiveness.

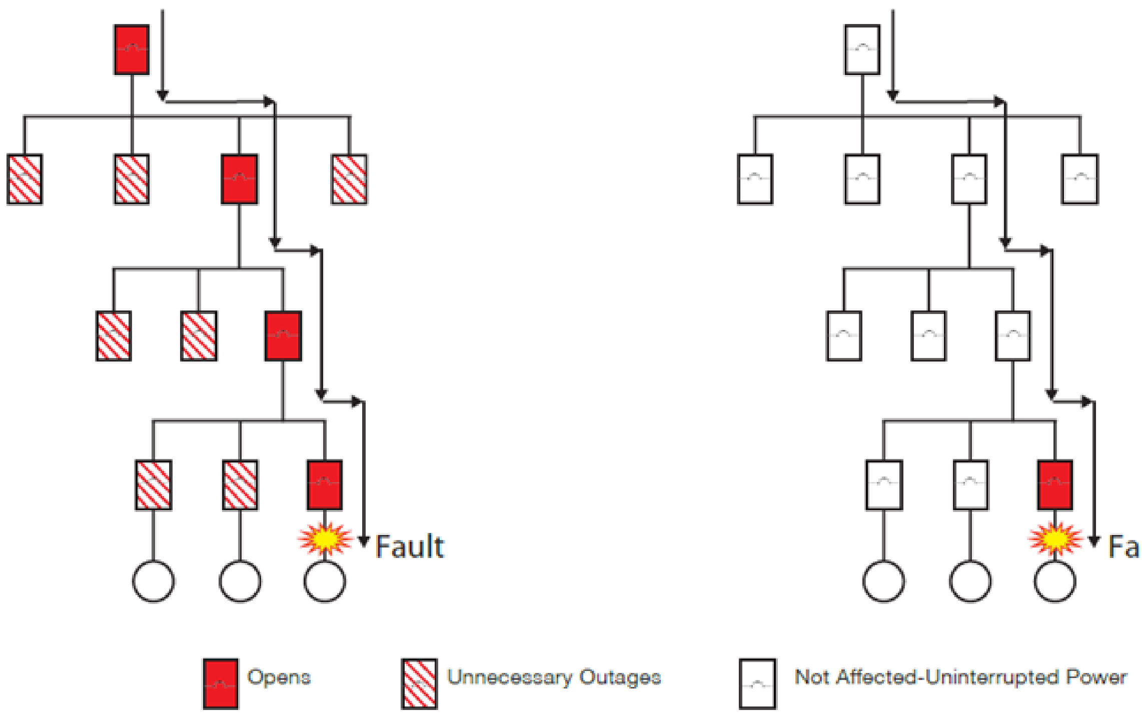
The solutions come from a compromise between these two antithetic requirements – precise identification of the fault and rapid tripping - and are defined according to which requirement is privileged.

Most common challenge is to capacity to discriminate between untypical but tolerable situations and fault conditions within its competence zone in favor of avoiding unneeded trips which result unjustified outage of a sound part of the installation. Such cases are depicted in the Figure. 1.1. At the same time, circuit breakers must trigger as fast as possible to curb harm for the apparatus.

The definition of selectivity or protection discrimination is given by the IEC 60947-1 Standard "Low voltage equipment – Part 1: General rules for low voltage equipment". Over-current discrimination: co-ordination of the operating characteristics of two or more over-current protective devices such that, on the incidence of over-currents within stated limits, the device intended to operate within these limits does so, while the other(s) does(do) not (Rainin et al. 2012: 237–242).

In a nutshell, selective coordination is an electrical system design practice that improves reliability. The methodology increases uptime by limiting power outages to the branch of an electrical system where a fault appears without knocking out other areas of the grids. When a problem occurs, the closest overcurrent protective unit opens, either a breaker or a fuse, ensuring that any faults do not cascade upstream (Ma et al. 2012: 1460–1466).

Proper discriminating tripping, besides limiting an outage to the shorted or overloaded branch circuit, facilitate investigation causes of faults, identification of underrated or overloaded equipment, and applying corrections. Power can typically be restored faster than when upstream breakers are tripped, mainly if a panel board has been taken down (Rainin et al. 2010: 587–592).



a) Lack of Coordination; b) proper Coordination

Figure 1.1 – Illustrative example of a) absence and b) presence of actual selectivity (Schneider Electric 2011).

Very important terms such as partial and total selectivity must be addressed for thorough investigation. The definitions of the total selectivity and partial selectivity are given in the same Standard IEC 60947-2 “Low voltage Equipment – Part 2: Circuit-breakers”. Basically, total protection discrimination preserved when there is selectivity for any overcurrent possible value in the installation (Rainin et al. 2012: 237–242).

Most of existing technologies of protection discrimination in practice offer only partial selectivity which leads to unjustified outage of an unaffected branches of installations. Protection coordination is one the basic objectives of the modern power networks.

The purpose of this paper is to provide comprehensive approach to choosing an effective method of selective coordination of such protection devices as low voltage circuit breakers.

1.1 Investigation of the selectivity of the automatic switches

There are three main reasons why an investigation of the discrimination of protection devices is attractive:

- A situation of partial selectivity when there is only selectivity up to a certain I_S current value is dominated in operational practice. In other words, if the current exceeds pre-defined I_S level, the selectivity between the two circuit-breakers will no longer be guaranteed.
- Properly designed, discriminative tripping provides one more line of defense, besides backup generators and uninterrupted power sources, against unplanned power outages, which might provoke significant downtime losses for business enterprises.
- Interlock of instantaneous protection on the grid-side switch, in order to obtain correct selectivity coordination between grid-side and feeder-side circuit breakers is frequently used method. While this does provide required discrimination of up-stream and down-stream protection devices, it cannot be characterized as the best instantaneous coordination solution since immediate response does not exist on both breakers (Valdes et al. 2010: 593–602).

1.2 Scope and organization of this thesis

In Chapter 2, some background on existing protection schemes in low voltage grids is given. First of all, the concepts of "overload zone" and "short-circuit zone" are introduced. Then widely used time-current selectivity circuit breakers with thermal-magnetic release is analyzed. Limitations of such protection coordination are revealed and explained. In addition, current, energy, time and zone selectivity are reviewed in order to establish a strong theoretical framework for practical recommendation.

In Chapter 3, the experiment with two circuit-breakers connected in series are describes. Detailed explanation covers operational principal of examined short-circuit stand. Four different cases such as time-current and current selectivity coordination schemes with and without single phase load are studied.

The effectiveness of two investigated protection coordination schemes is tested in Chapter 4 by means of ABB DOC software. The choice of program for simulation is grounded on the fact that equipment which was used for conducting the experiment produced by ABB company. Explicit description of software and simulation part of the performed test is provided.

Complex approach to selection of tripping discrimination in low-voltage grids is developed in the Chapter 5. Presented flowchart aims to facilitate selection optimal protection coordination in turns of reliability and cost effectiveness.

The Chapter 6 provides with the summary and conclusions of the investigation. Also the recommendations of current thesis are analyzed and presented to the reader.

2 Literature review

A lot of materials were dedicated over the last several years on the concept and details of selective coordination in low voltage grids. The basic theoretical approach to the concept of protection discrimination remains constant, while the application in the design of business, public and industrial facilities is quite complicated.

2.1 Impact of grids configuration on the protection coordination techniques

Micro-grids are becoming increasingly attractive to electrical networks due to growing presence of distributed generation capacities. One of the main concern associated with the implementation of micro-grids is to choose a suitable protection strategy which is able to protect them in both modes of operation, that is, the grid connected mode and autonomous (or islanded) mode (Mirsaeidi 2014: 1–10).

Even though micro-grids have provided numerous benefits for the costumers, there are some technical challenges which require to be met for the engineers. Micro-grid protection and its entity is one of them. The protection of the traditional distribution networks is designed in accordance with the large short- circuit currents and the unidirectional power flow, whereas such protection strategy cannot be regarded in order to protect active distribution networks such as micro-grids (Fox 2010: 1–9). It is owing to the fact that when a short-circuit takes place in the microgrid with widespread proliferation of inverter-based distributed generation sources, operating in islanded mode of operation, they are not able to contribute sufficient currents to the total short-circuit current. It is because of the fact that inverters have a low thermal overload capability, restricting their maximum output current to about 2..3 times the rated current. Hence, in order to protect micro-grids in both grid-connected and islanded mode of operation, innovative protection schemes should be utilized (Wei et al. 2011: 692–697).

In addition, usually only unidirectional power flow is considered, while the direction and amplitude of short circuit currents could vary. In fact, operating conditions of micro-grid with distributed generation are constantly changing because of the intermittent micro-sources (wind and solar) and periodic load variation (Laaksonen 2010: 2910–2918).

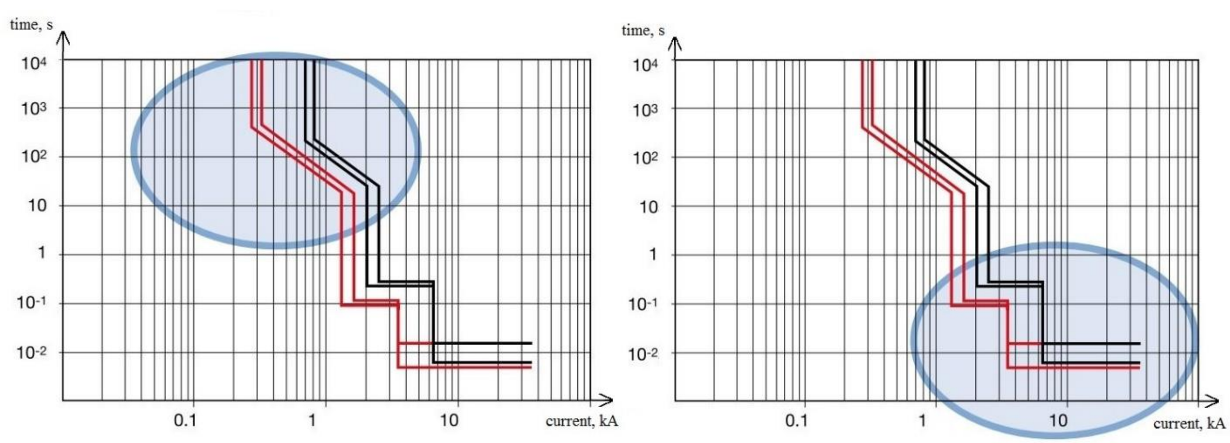
However, due to the fact that overwhelming majority of consumers are still connected in radial manner, the main focus will be on selectivity of low voltage radial-type grid-connected systems. Next sub-chapters will be dedicated to description available protection coordination techniques.

2.2 Overload and short-circuit zone concepts

First of all, in order to analyze the discrimination protection mechanism, the concepts of “overload zone” and “short-circuit zone” must be presented. Figure 2.1 illustrates the main features of these sectors.

Comparing time-current characteristics of two or more overcurrent protection devices on a single graph is the traditional method for determining selective coordination. The relative position of individual device tolerance bands on a time-current curve can illustrate the degree of coordination and it is common for the instantaneous trip characteristics to overlap one another.

"Overload zone" indicates the range of current values, and as a result the relative part of the circuit breaker trips curves approaching the rated current of the circuit-breaker itself with lower than 8..10 times of its value for the C-type of protection curve (Kennedy et al. 2016: 1308–1317). Here the non-instantaneous component takes place, where protection device responds with a time delay. This component includes the long-time and short-time portions of the breaker's time-current curve. Thermomagnetic releases and L protection for electronic releases usually employed for dealing with "overload zone". Clear separation of the ampere rating or long-time pick-up between breakers in series connection obtains non-instantaneous coordination in reliable manner. Non-instantaneous coordination is a simpler matter when working with electronic trip devices due to the narrower tolerance bands they possess in comparison with thermal-magnetic automatic switches (Electric 2014: 1–28).



"Overload zone" = In< 8..10In "Short-circuit zone" ≥ 8..10In

Figure 2.1 – Illustrative example of "Overload" and "Short-circuit" zones (A. division of A. S. p. A. L. V. B. ABB SACE 2011)

By “short-circuit zone” one means the ranges of current values, and therefore the relative part of the trip curves of the protection device, which are more than 8..10 times of the rated current (Monadi et al. 2015: 1578–1593). In this case, circuit breaker opening is initiated without any intentional delay.

In this section a protective response provides the desired fastest protection in the presence of higher-level fault currents. Magnetic protection for thermomagnetic releases or protections S, D and I for electronic releases are usually employed in this zone (Tian et al. 2016).

In the overload zone with the protections in play, time-current type selectivity is usually realized. Further sub-chapter focuses on major features as well as limitation of this widely used method.

2.3 Time-current selectivity based on thermal-magnetic release

In general, the protection against overload have a definite time characteristic, whether they are made by means of a thermal-magnetic release or by means of function L of an electronic release.

Consider Figure 2.2, which plots typical tripping coordination between upstream (A) and downstream (B) circuit breakers. This type of protection coordination is mostly used due to its low price and relative reliability. It is a common knowledge, that time-current curves (TCC) for over-current protective devices show how long it will take the device to operate under overcurrent conditions. These curves are typically developed by conducting interruption tests on sample devices at various overcurrent levels – overload and fault currents (Gopalan et al. 2014: 222–228).

The protection coordination issue can also be formulated as constrained non-linear programming problem (NLP) to minimize the sum of operating time of primary relays. The overcurrent relay has two decision variables, time multiplier setting (TMS) and plug setting (PS). The operating time of relay is a function of TMS, PS and current seen by relay. The operating time of is given by Equation 1.

$$t_{op} = \frac{\alpha \cdot TMS}{\left(\frac{If}{PS}\right)^{\beta} - \gamma}, \tag{1}$$

where If − fault current, α, β, γ − the constants representing the overcurrent relay characteristic in a mathematical form.

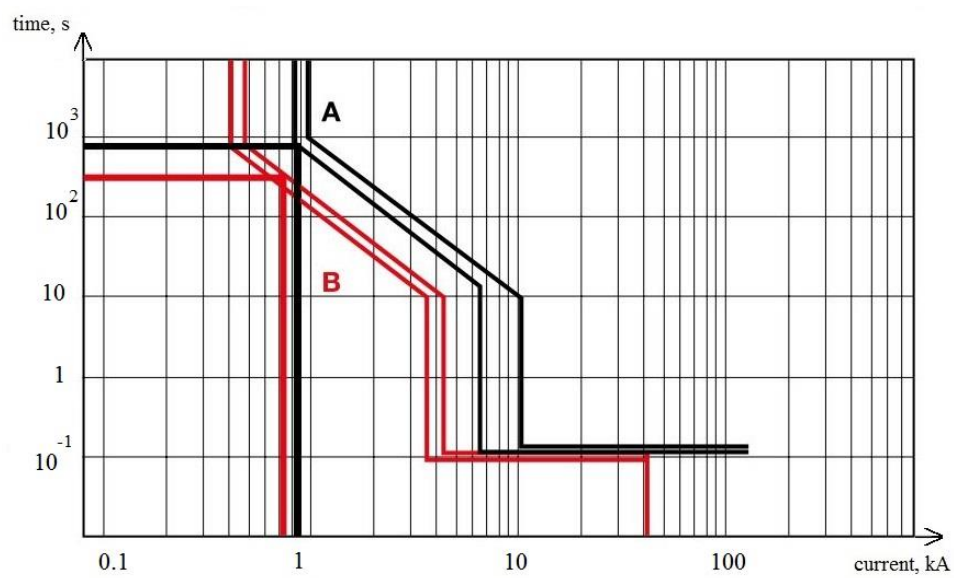


Figure 2.2 – Time current curves of circuit breakers with thermal-magnetic release (A. division of A. S. p. A. L. V. B. ABB SACE 2011), where “A”–upstream automatic switch, “B”–downstream automatic switch.

It is assumed that inverse-definite minimum time (IDMT) type overcurrent relays are used. α, β, γ constants for normal IDMT characteristic are considered as 0.14, 0.02 and 1.0 respectively as per IEEE standards. However, from a practical point of view, time-current curves are easier for usage and more visual.

The time-current protection technique has several critical flaws. In most cases achieving selective coordination comes at the cost of increasing circuit breaker frame size and changing circuit breaker type from a molded case to an electronic trip type with higher short time settings (Tendayi et al. 2016: 1457–1465).

Both solutions could result in an increase in total clearing time of protective devices during an arcing fault, thereby causing in arc flash incident energy (Schneider Electric 2013b). The TCC does not take into account dynamic nature of impedance imposed by arc and transient components what only adds insult to the injury. The Figure 2.3 indicates this feature.

Also instantaneous coordination performance of two breakers in series is not necessarily determined by evaluating the relationship between their time current curves (Abdel-ghany et al. 2015: 113–122). In many cases, the time current curve analysis under-predicts the actual instantaneous coordination capability.

The reason for this disparity lies in the fact that a breaker's time-current curve is established by testing the individual breaker with a current source.

When two breakers are in series, however, the dynamic operation of the downstream breaker influences the fault current that the upstream breaker experience as the load-side breaker begins to open. This interaction tends to be more pronounced when the downstream breaker's instantaneous trip is faster than the upstream breaker's. The true current limiting nature of breakers that have this property is often not reflected in manufacturer's published time-current curves, again contributing to the discrepancy between instantaneous coordination predicted by time-current curve analysis and actual performance (Kui et al. 2007: 453–458).

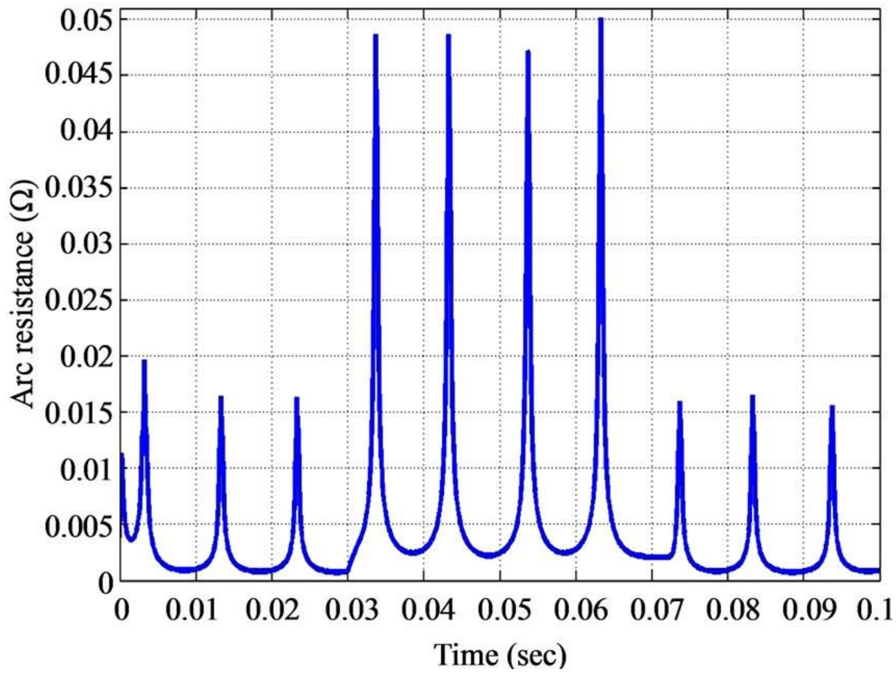


Figure 2.3 – Dependence of arc resistance from time and length (Moghadasian et al. 2011: 47–55).

The typical waveform of a short circuit is given in the Figure 2.4. However, in practice, the majority of molded-case circuit-breakers have more or less marked current-limiting characteristics. Under short-circuit conditions, these circuit-breakers are extremely fast (trip times within a few milliseconds) and opens when there is a strong asymmetrical component (Li et al. 2009: 2977–2988). It is therefore not possible to use the time-current trip curves of the automatic switches, obtained with symmetrical sinusoidal types of wave forms, for the coordination study (Relays et al. 2015).

Moreover, the provided by manufactures TCCs are obtained under specific conditions: standalone operation, given ambient temperature, symmetrical sinusoidal wave form, which do not take place in real fault situation (Wang et al. 2011: 2712–2716).

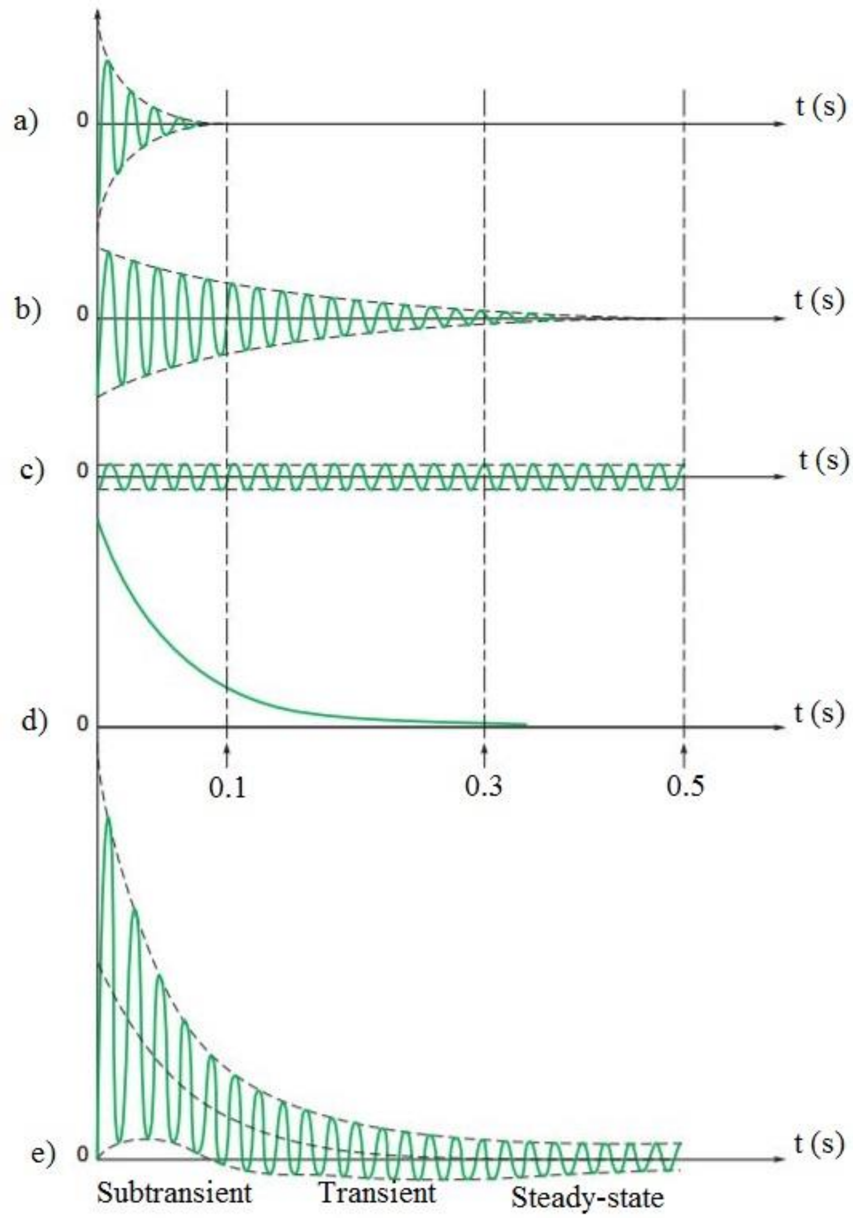


Figure 2.4 – Representative waveform of the total short-circuit current and of its components: a) subtransient reactance (X''_d); b) transient reactance (X'_d); c) synchronous reactance (X_d); d) aperiodic component; e) resulting waveform of typical 3-phase short-circuit current (Metz-Noblat et al. 2005).

Based on presented investigation, it can be concluded that the widely used time-current selectivity must be modified or replaced in some cases for compliance with stricter reliability requirements.

2.4 Current selectivity

This type of selectivity is based on the observation that the closer the fault point is to the power supply of the installation, the higher the short-circuit current is. It is therefore possible to discriminate the zone the fault occurred in by setting the instantaneous protections to different current values(Laaksonen et al. 2014: 1486–1493).

Total selectivity can normally be achieved in specific cases only where the fault current is not high and where there is a component with high impedance interposed between the two protections (transformer, very long cable or a cable with reduced cross-section, etc.) and therefore a great difference between the short-circuit current values (study Figure 2.5).

This type of coordination is therefore used above all in the distribution terminal (low rated current and short-circuit current values, and high impedance of the connection cables). The time-current trip curves of the devices are normally used for this study (Kamel et al. 2013: 1555–1566).

Summing up the investigation, the following traits can be concluded.

Advantages:

- Simplicity in realization;
- Low cost implementation.

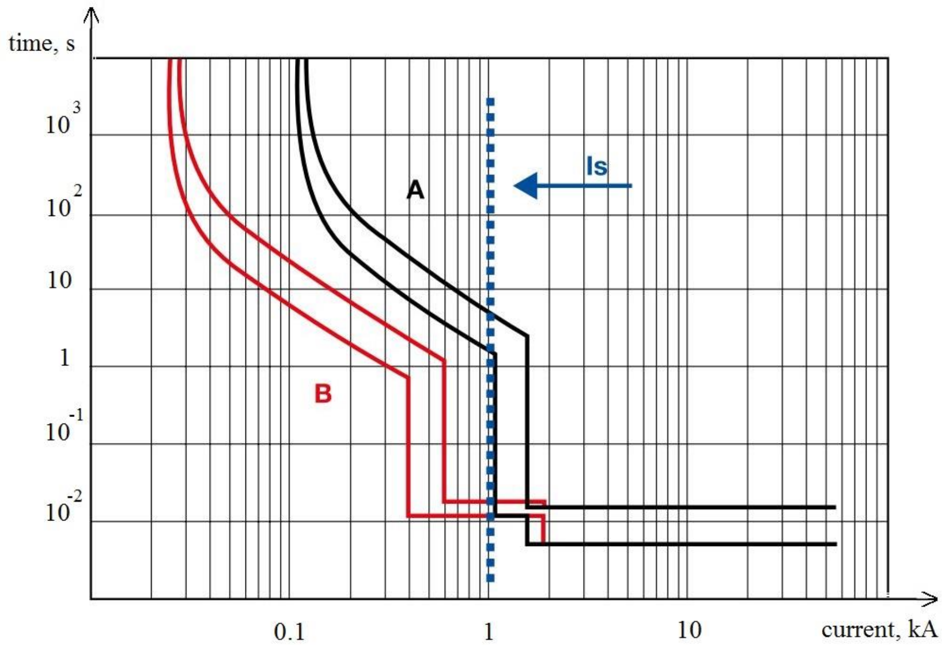


Figure 2.5 – TCCs of circuit breakers with current selectivity (A. division of A. S. p. A. L. V. B. ABB SACE 2011), where “A”–upstream automatic switch, “B”– downstream automatic switch, Is – ultimate selectivity value.

Drawbacks:

- Relatively low level of ultimate selectivity current, which often make selectivity only partial;
- Rapid increase of overcurrent setting level for the protection devices.

2.5 Time selectivity

This type of selectivity is an evolution of the previous one. In this type of coordination, apart from the trip threshold in terms of current, a trip time is also defined: a certain current value will make the protections trip after a defined time delay, suitable for allowing any protections placed closer to the fault to trip

(Salomonsson et al. 2009: 1045–1053). Figure 2.6 gives an example of such technique.

The setting strategy is therefore to progressively increase the current thresholds and the trip delays as one gets closer to the power supply sources. In other words, level of setting directly correlates to the hierarchical level. The delayed trip thresholds must take into account the tolerances of the two protection devices and the effective currents which circulate in them (Ates et al. 2016: 378).

The difference between the delays set for the protections in series must take into account the fault detection and elimination times of the device on the load side and of the inertia time or overshoot, of the device on the supply side.

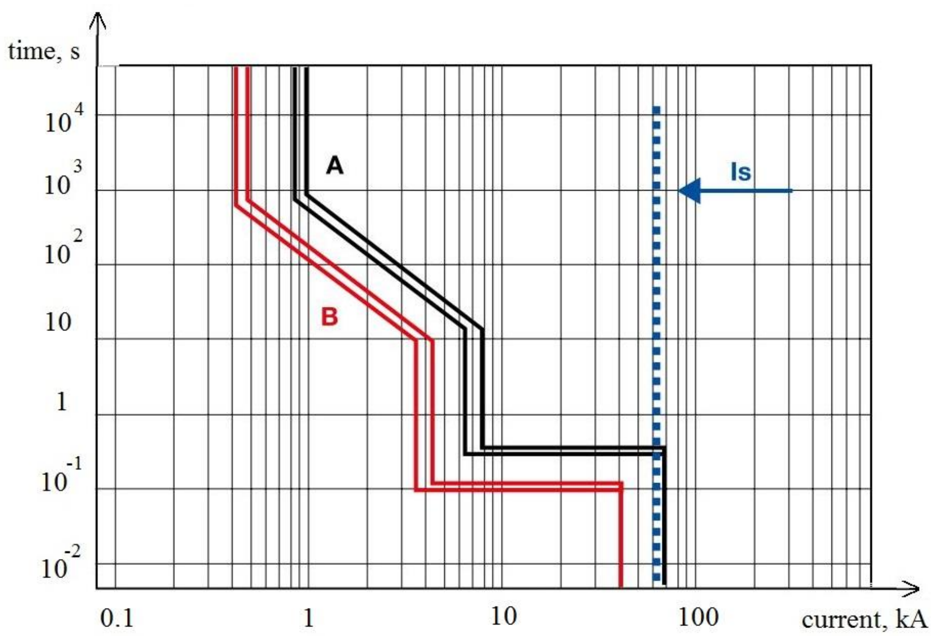


Figure 2.6 – TCCs of circuit breakers with time selectivity (A. division of A. S. p. A. L. V. B. ABB SACE 2011), where “A”–upstream automatic switch, “B”–downstream automatic switch, Is – ultimate selectivity value.

As in the case of current selectivity, the study is made by comparing the time-current trip curves of the protection devices. It is a type of selectivity which can also be made between circuit-breakers of the same size, equipped with electronic releases with delayed protection against short-circuit (Basak et al. 2012: 5545–5556).

Based on presented concepts, the following upsides and downsides could be concluded.

Advantages:

- Simplicity in realization;
- Low cost implementation;
- Possibility of achieving high selectivity current limits;
- Redundancy of supplying functions.

Drawbacks:

- High level of trip times and energy levels let through by protection devices which are close to the source.

2.6 Zone selectivity

This technique, known as well as Zone Selective Interlocking, is a logical extension of waveform recognition for the situation where the downstream breaker is not current limiting. In general, zone selectivity is made by means of dialogue between the current measuring devices (Schneider Electric 2012).

It can be realized in two ways:

- the measuring devices send the information linked to the current setting threshold having been exceeded to a supervision system and the latter identifies which protection has to intervene (Walker 2013: 814–824);

- when there are current values higher than their setting, each protection sends a lock signal by means of a direct connection or a bus to the hierarchically higher level protection and, before intervening, checks that a similar lock signal has not arrived from the load-side protection. In this way only the protection immediately on the supply side of the fault intervenes. Figure 2.7 presents basic operational principle of presented technique.

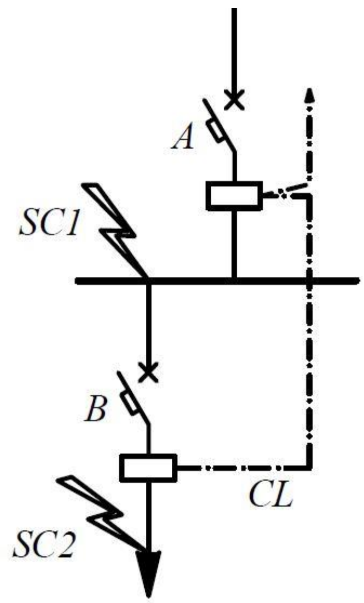


Figure 2.7 – Operational principle of Zone Selective Interlocking scheme, where "A"–upstream automatic switch, "B"–downstream automatic switch, "SC1" and "SC2" – location of the short-circuit, "CL" – communication link between protection devices.

Compared with coordination of the time type, the need to increase the intentional delay as one moves towards the power supply source is no longer necessary. The delay can be reduced to the time needed to exclude the presence of a possible lock signal coming from the load-side protection.

This is a type of selectivity suitable for radial networks and, when associated with the directional protection, also suitable for meshed networks.

Based on presented review, the following conclusions can be drawn.

Advantages:

- Reduction of the trip times;
- Suitability for meshed systems with bi-directional power flow;
- Possibility of achievement high selectivity levels.

Drawbacks:

- High cost implementation;
- Complexity of installation;
- Necessity of auxiliary supply.

2.7 Energy selectivity

Coordination of energy type is a particular type of selectivity which exploits the current-limiting characteristics of molded-case circuit-breakers. This protection discrimination based on circuit-breaker let-through breaking energy (I^2t), not only by current value.

The phenomena are mainly dynamic, therefore proportional to the square of the instantaneous current value, and are heavily dependent to the interaction between the two pieces of apparatus in series. Therefore, the energy selectivity values cannot be determined by the end user (Lu et al. 2007: 370–377). The manufacturers make tables, slides-rules and calculation programs available where the ultimate current selectivity values of *Is* under short-circuit between different combinations of circuit-breakers are given. This is illustrated in Figure 2.8. These values are defined by theoretically integrating the results of tests carried out in compliance with what is indicated in Annex A of the IEC 60947-2 Standard.

			Supply s.	S290		S500			
	Char.			D		D			
		I_{cu} [kA]		15		50			
Load s.			I_n [A]	80	100	32	40	50	63
S200L	C	6	6..8	T	T	1.5	2	3	5.5
			10	5	T	1	1.5	2	3
			13	4.5	T		1.5	2	3
			16	4.5	T			2	3
			20	3.5	5				2.5
			25	3.5	5				
			32		4.5				
			40						

Figure 2.8 – Example of selectivity table for modular-case circuit breakers based on their Energy protection discrimination (SACE S.p.A 2013).

An energy-based tripping system employs two trip systems working in conjunction – a conventional circuit breaker trip and a specially designed primary trip system. The primary trip system will not trip during the first half-cycle of a fault regardless of the fault current level, another – an electronic unit to determine the duration of the fault and then trips accordingly if the fault has existed too long (Schneider Electric 2013a).

The investigated data indicate that Energy type protection coordination has the following features.

Advantages:

- Possibility of achievement high selectivity levels;
- Possibility of achievement the total discrimination up to the breaking capacity.

Drawbacks:

- High cost implementation;
- Relatively big size of installed protection devices.

3 Experiment execution

This study examines two types of selectivity: time-current with thermal-magnetic release and only current protection discrimination exploiting the single-phase to neutral wire (N-conductor) short circuit. Consider Figure 3.1.

Figure 3.1 – Equipment for conducting the experiment, where 1) – connection point to the power grid of the building; 2) – short circuit stand; 3) – Hall effect sensor; 4) – 2kW electric load (electric kettle); 5) – digital storage oscilloscope; 6) – laptop for data analysis.

During the experiment, the correlation between two low voltage circuit breakers in series was examined. The realization of the experiment was video-taped and now it is publicly available on the YouTube (Semashka 2017).

In order to obtain the real values of short-circuit in the targeted grid, the Hall effect sensor was built in addition to the available short circuit stand. The sensor was laboratory calibrated and connected in series to the exposed to the short circuit phase. The peak current value was catch by oscilloscope, saved and transformed into real value using pre-defined coefficient. In this experiment, each of tripping coordination was tested with and without single-phase static load for more detailed analysis of its influence on the selectivity.

3.1 Operational principal of experimental equipment

Figure 3.2 shows the structure of experimental equipment for making a single phase to ground (N-conductor) short circuit and observing coordination of 2 types of circuit breakers. In order to conduct the experiment is the Short circuit stand (SCS) was built. The first pair of circuit breakers belong to traditional time-current protection scheme, the second – up-stream circuit breaker to current limiting, and down-stream to time-current selectivity. The SCS was connected to the power grid of the building. It should be noticed, that equipment for measuring the value of short circuit is plugged in different switch board in order to avoid tripping a grid-side circuit breaker and disconnecting measuring equipment during the short circuit experiment.

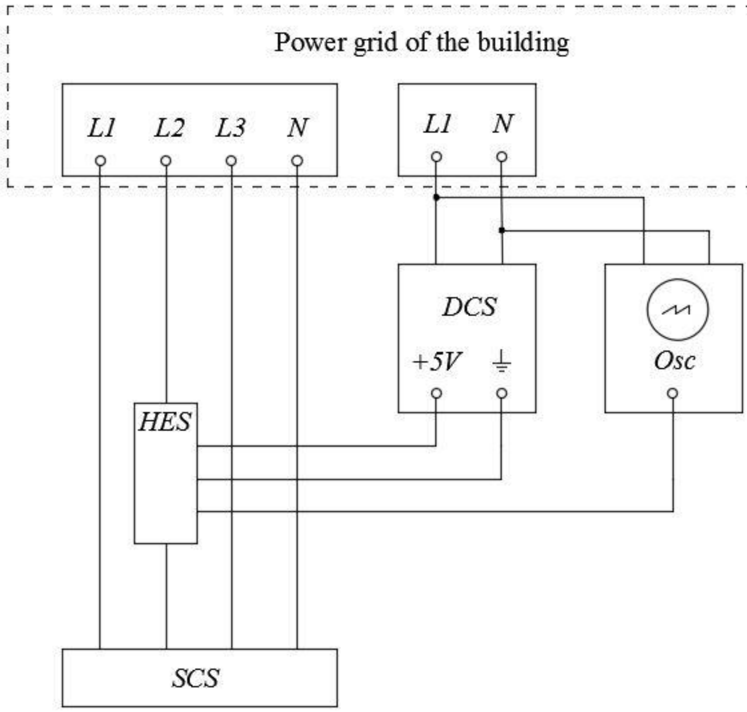


Figure 3.2 – Structure of the experimental equipment, where DCS[1] − direct current power source; Osc[2] − digital storage oscilloscope; HES[3] – Hall effect sensor; SCS[4] – short circuit stand.

A Hall effect sensor (HES) is placed on predetermined conductor between SCS and supplying switch board. A DC power source is used for providing +5V to the HES, and a digital storage oscilloscope (Osc) is installed to gather information from it.

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[1] Б5-30;
[2] Tektronix TPS2012 100/200 MHz;
[3] Study 3.3 subchapter;
[4] Study 3.2 subchapter.

3.2 Explanation of operational principal of short circuit stand (SCS)

The following subchapter deals with the functional concept of studied short circuit stand and describe the procedures must be done in order to execute the experiment. Detailed explanation of the applied equipment is presented. Consider Figure 3.3, which plots an electrical diagram of the short circuit stand. The stand was provided by ABB brunch office in Vilnius, Lithuania.

First of all, SB1 push-button ("NO" − normally open) is used for starting an experiment. SB1 allows to reach contactor KM2 by control supply voltage. While a current goes through the coil of contactor KM2, the contacts of KM2 are closed and provide time relays LR1 and LR2 with control supply voltage simultaneously. SB2 push-button ("NC" − normally closed) is connected in serial with coil of contactor KM2 and N-neutral wire. Therefore, it serves as "reset", which can open the circuit with time relays LR1 and LR2.

LR1 time relay "On-delay" requires continuous control supply voltage for timing. Timing begins when control supply voltage is applied. The green LED flashes during timing. When the selected time delay is complete, the output relay energizes and the flashing green LED turns steady. If control supply voltage is interrupted, the output relay de-energizes and the time delay is reset. Control input A1-Y1/B1 is disabled when this function is selected.

Time relay LR1 has the following settings: rotary switch for the preselection. of the time range – **10s**; potentiometer with direct reading scale for the fine adjustment of the time delay – **3s**; Rotary switch for the selection of the timing function – "**ON-delay**". Study Figure 3.4 and Figure 3.5

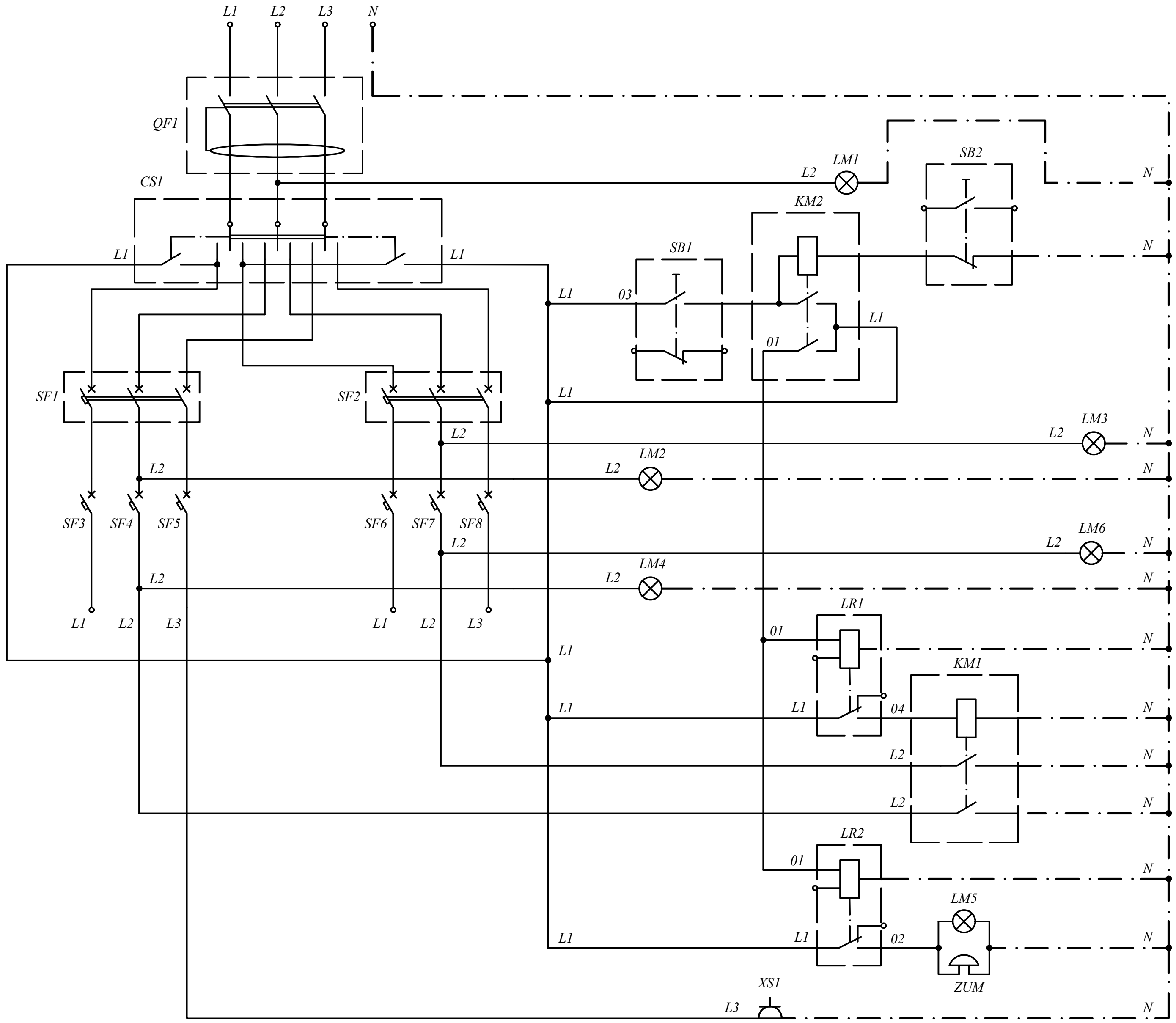

Figure 3.3 - Circuit diagram of the Short circuit stand (SCS)

Explanations:

QF1 − ABB F204 AC / 25A, 30 − residual current 4-poles device;

CS1 − ABB OT63F3C / 63A − manual change-over 3-poles switch;

SF1 − ABB SHU S751/3 DR E25 / 25A − selective 3-poles circuit breaker;

SF2 − ABB S203 / 25A − 3-poles circuit breaker with inverse time-current characteristics;

SF3..SF8 − ABB S201 / 16A − single-pole circuit breaker with inverse time-current characteristics;

LM1..LM6 − ABB CL2-506R − pilot light;

LR1 − ABB E234 CT-MFD − electronic time relay;

LR2 − ABB E234 CT-TGD − electronic time relay with the function pulse generator;

KM1..KM2 − ABB ESB 20-20 20A − single-phase contactor;

SB1..SB2 − ABB E215-16-11C / 16A − pushbutton;

ZUM − ABB SM1-230 − bell transformer;

XS1 − ABB Italian P30 standard M1173 − single-phase modular socket.

Figure 3.4 – LR1 time relay “On-delay” function description (ABB STOTZ-KONTAKT GmbH 2007a).

LR1 time relay controls contactor KM1. While the supply voltage is applied to a contactor’s coil, after adjusted time relay his contacts close the circuit between

Figure 3.5 – LR1 time relay view with control panel settings explanations, where 1) − rotary switch for the preselection of the time range; 2) − potentiometer with direct reading scale for the fine adjustment of the time delay; 3) −rotary switch for the selection of the timing function; 4) −indication of operational states; 5) − circuit diagram. (ABB STOTZ-KONTAKT GmbH 2007a).

a line L2 and N-neutral wire, consequently creating a single phase-to-ground short circuit. LR2 time relay with pulse generator function and its view with control panel settings are provided in Figure 3.6 and Figure 3.7. LR2 time relay is connected in serial with LM5 pilot light and ZUM bell transformer. Thus after adjusted time LM5 light up and the ZUM bell rings.

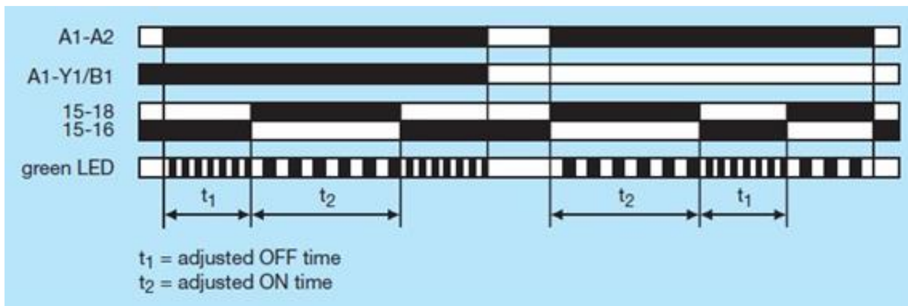

Figure 3.6 – LR2 time relay with pulse generator function description (ABB STOTZ-KONTAKT GmbH 2007b).

LR2 time relay requires continuous control supply voltage for timing. Applying control supply voltage, with open control input A1-Y1/B1, starts timing with an ON time first.

Applying control supply voltage, with closed control input A1-Y1/B1, starts timing with an OFF time first. The ON & OFF times are displayed by the flashing green LED, which flashes twice as fast during the OFF time. The ON & OFF times are independently adjustable. If control supply voltage is interrupted, the output relay de-energizes and the time delay is reset.

Meanwhile the control supply voltage is applied to the LR2 time relay with function pulse generator, as it is mentioned earlier. Time relay LR2 has the following settings: potentiometer with direct reading scale for the fine adjustment of the ON time – **0,5s;** rotary switch for the preselection of the time range of the ON time –

10s; potentiometer with direct reading scale for the fine adjustment of the OFF time – **2;** rotary switch for the preselection of the time range of the OFF time – **1s.**

The short circuit must be eliminated by either down-steam (consumer-side) or up-steam (grid-side) circuit breaker. In that case pilots' lights LM2 and LM4 will be light off (or LM3 and LM6 according to position of CS1 manual change-over switch). For the presentation of an emergence of short circuit LM5 pilot light will kindle and ZUM bell transformer will ring.

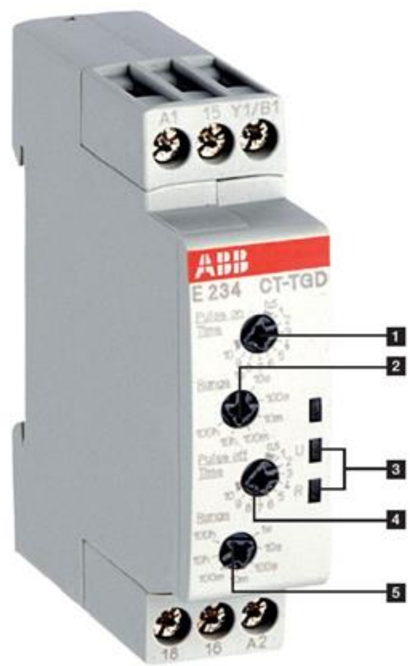

Figure 3.7 – LR2 time relay view with control panel settings explanations, where 1) − potentiometer with direct reading scale for the fine adjustment of the ON time; 2) − rotary switch for the preselection of the time range of the ON time; 3) − indication of operational states; 4) − potentiometer with direct reading scale for the fine adjustment of the OFF time; 5) − rotary switch for the preselection of the time range of the OFF time (ABB STOTZ-KONTAKT GmbH 2007b).

All listed above equipment was installed in accordance with the manufacturer’s installation instructions and tested under normal conditions.

3.3 Hall effect sensor implication

Peak current measurement requires employing such device as Hall effect sensor. The Hall effect is an ideal sensing technology. The Hall element is constructed from a thin sheet of conductive material with output connections perpendicular to the direction of current flow. When subjected to a magnetic field, it responds with an output voltage proportional to the magnetic field strength. The voltage output is very small (μV) and requires additional electronics to achieve useful voltage levels. When the Hall element is combined with the associated electronics, it forms a Hall effect sensor. The heart of every Micro Switch Hall effect device is the integrated circuit chip that contains the Hall element and the signal conditioning electronics (Anon 2012).

In order to apply Hall effect for accurate measuring of short circuit current, it was needed to create a sensor, which based on described above principal (study Figure 3.8).

Linear current sensors monitor the gauss level of the magnetic field created by a current flow, not the actual current flow. The current being measured is passed through a flux-collecting core that concentrates the magnetic field on the Hall effect sensor. The waveform of the sensor voltage output will trace AC or DC waveforms of the measured current. The through hole design electrically isolates the sensor and ensures that it will not be damaged by over-current or high voltage transients. It also eliminates any DC insertion loss.

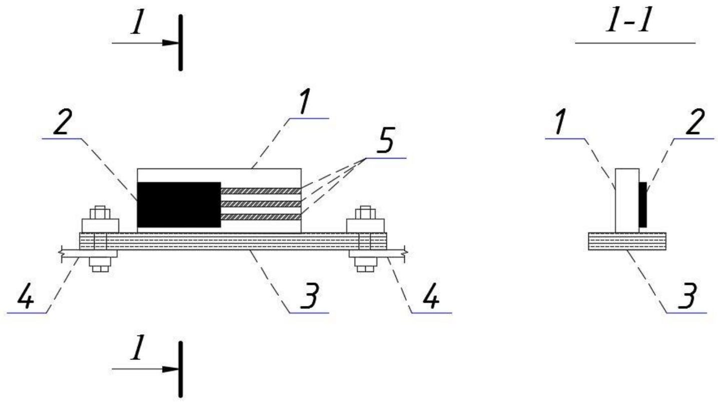

Figure 3.8 – Structure of experimental Hall effect sensor, where 1 − wooden prop, 2 – SS495A2 Basic Honeywell solid state Hall effect element (probe), 3 – cupper bus, 4 – power line conductor, 5 – contacts of the Hall effect probe.

When the current is passed through a measuring or load resistor, the output becomes a voltage that is proportional to the primary current being measured. DC, AC, and impulse currents can be accurately measured and waveforms duplicated. This fact allows us to calibrate Hall effect sensor (HES) using DC power source for gauging momentary AC single phase to ground short circuit current.

The data obtained is consistent with the major trends of linearity of an analog sensor output. This is illustrated in Figure 3.9 and Equation 2 represent the desired formula:

$$\psi = \frac{\Delta I}{\Delta U} = \frac{50 - 10}{|-2{,}5098 - (-2{,}4813)|} \approx 1403{,}51 \left(\frac{A}{V}\right) \qquad (2)$$

where $\Delta I -$ difference between max and min of applied DC current, $\Delta U -$ difference between max and min of obtained voltage on Hall effect sensor.

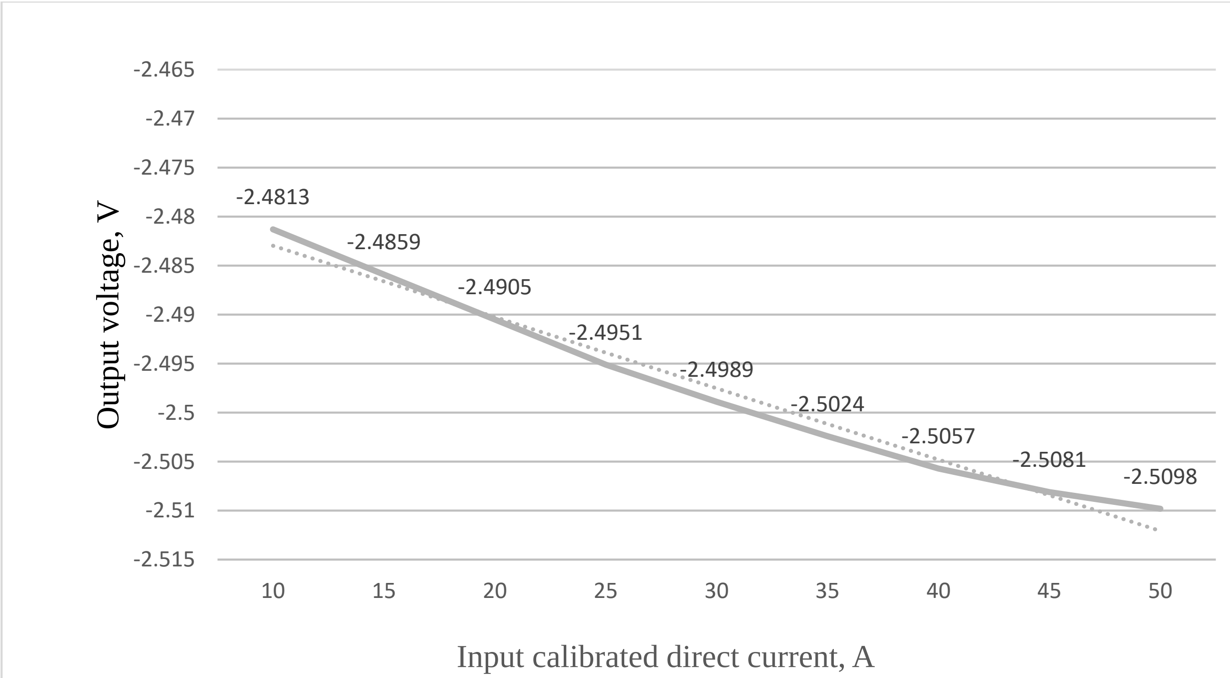

Figure 3.9 – Dependence of the output voltage on the Hall effect sensor from calibrated direct current.

The calibration was performed by calibrated power supply SM 120-50 Delta Elektronika as a DC source and Fluke 8846A G-1/2-digit precision multimeter for voltage drop measuring (Saravanan et al. 2014: 2018–2022).

As a result, the calculated current to voltage ratio will be further used for short circuit current computation.

3.4 Experimental data acquisition

3.4.1 Time-current selectivity coordination scheme without load

The first experiment was carried out in the electrical circuit, which consist of two time-current types circuit breakers without any load.

The tested circuit consist of one up-steam three phase circuit breaker and one down-stream one phase circuit breaker, which would be exposed to the single-phase to neutral wire short-circuit.

Consider Figure 3.10, which represent maximum value of current during one phase to N-conductor short circuit without load.

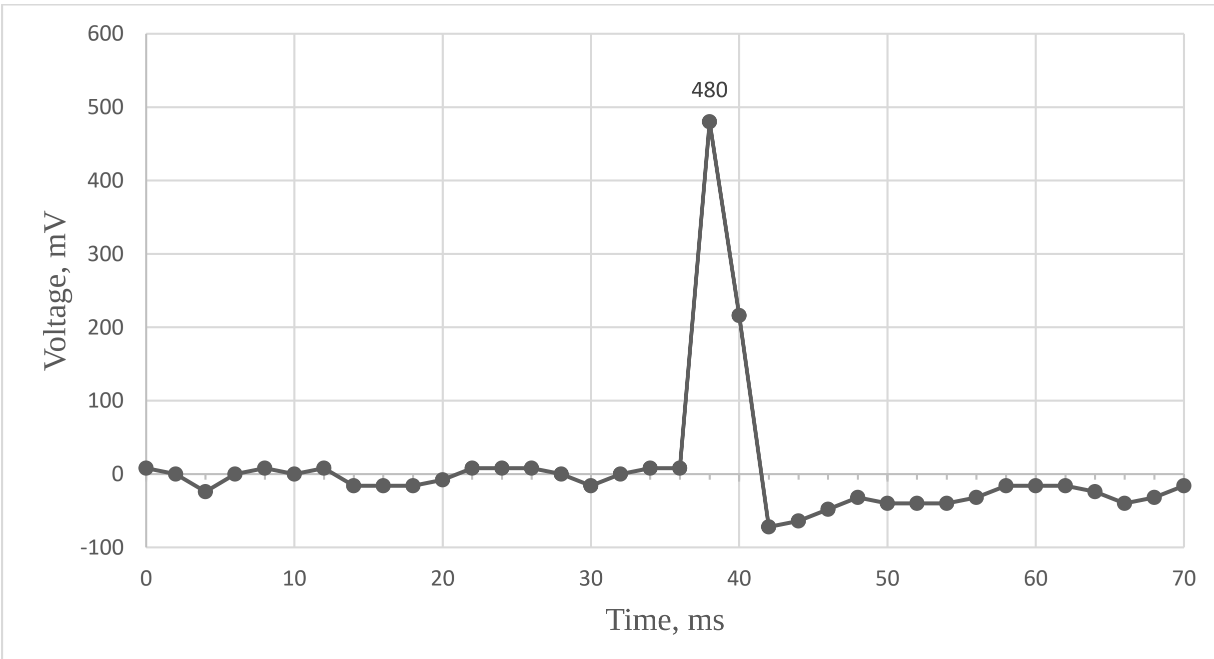

Figure 3.10 – Obtained dependence of Hall effect sensor' voltage on time during the experiment without correct protection coordination without a load.

Based on the screenshot of the oscilloscope, which is approved by Excel datasheet, and calculation in Equation 2 the peak short-ciruit current I_{nsnl} without selectivity and without load can be found as follows:

$$I_{nsnl} = U_0 \cdot \psi = 0{,}48 \cdot 1403{,}51 \approx 673{,}68\ (A), \quad (3)$$

where U_0 − output voltage from Hall effect sensor caught by the oscilloscope during the experiment, V; ψ − current to voltage ratio.

The procedure of execution of the experiment was video-taped and can be publicly available on YouTube (Semashka et al. 2017b).

Regardless the fact that the clearing time of described scheme was within 15 ms, which satisfies the existing regulations (Nfpa 2015: 104), both automatic switches tripped simultaneously, therefore the protection discrimination was not preserved.

3.4.2 Time-current selectivity coordination scheme with load

The results of the second experiment describe the single-phase to N-conductor short circuit' value and its clearing time. The model comprises two time-current types of circuit breakers: up-stream three phase and down-stream one phase circuit breakers. Also one-phase load is connected. An electric 2kW kettle is used as a load for the phase, which would be exposed to short-circuit.

Consider Figure 3.11, which represent maximum value of current during single phase to neutral wire short circuit with load.

Based on the screenshot of the oscilloscope, which is approved by Excel datasheet, and calculation in Equation 2 the peak short-ciruit current without selectivity and load can be found as follows:

$$I_{sl} = U_0 \cdot \psi = 0{,}352 \cdot 1403{,}51 \approx 494{,}04\ (A) \tag{4}$$

where U_0 − output voltage from Hall effect sensor caught by the oscilloscope during the experiment, V; ψ − current to voltage ratio.

The procedure of execution of the experiment was video-taped and can be publicly available on YouTube (Semashka et al. 2017a).

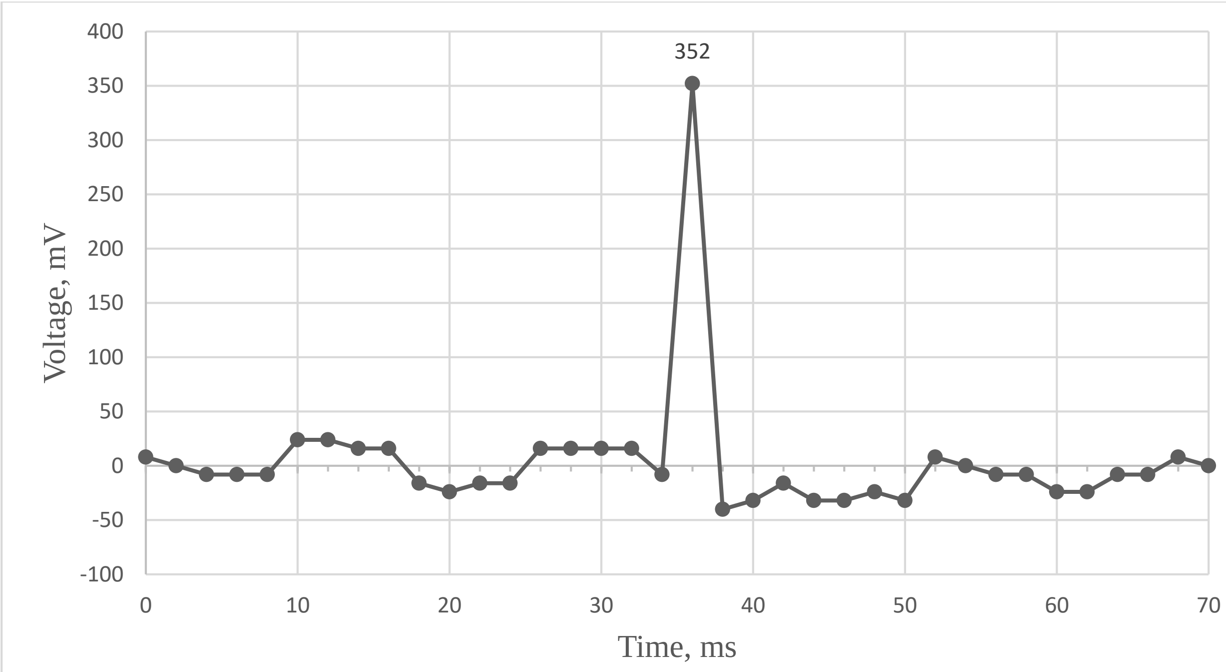

Figure 3.11 – Obtained dependence of Hall effect sensor' voltage on time during the experiment without correct protection coordination with the load.

Regardless the fact that the clearing time of described scheme was within 15 ms, which satisfies the existing regulations (Nfpa 2015: 104), again both automatic switches tripped simultaneously. Based on the results it can be concluded that the investigated protection scheme does not preserve a proper selectivity.

3.4.3 Current selectivity coordination scheme without load

The third experiment was conducted with two types of protection coordination, but without load. The tested circuit consist of up-steam three phase circuit breaker with current selectivity and down-stream one-phase circuit breaker with time-current selectivity.

Consider Figure 3.12, which plot surge of current during single phase to neutral wire short circuit without load.

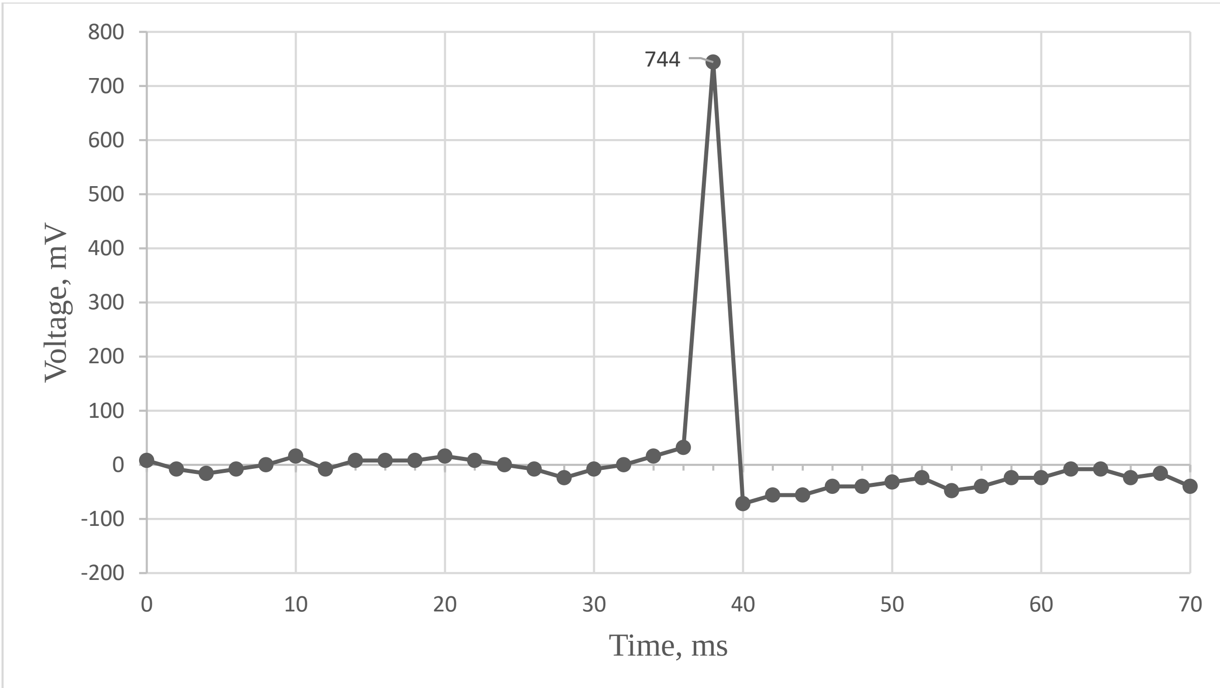

Figure 3.12 – Obtained dependence of Hall effect sensor' voltage on time during the experiment with selectivity coordination without a load.

Based on the screenshot of the oscilloscope (which is backed with Excel datasheet) and calculation presented in Equation 2 the peak one phase to N-conductor short-ciruit current reach the following value:

$$I_{nsnl} = U_0 \cdot \psi = |-0{,}744 \cdot 1403{,}51| \approx 1044{,}21\ (A) \quad (5)$$

where U_0 − output voltage from Hall effect sensor caught by the oscilloscope during the experiment, V; ψ − current to voltage ratio.

During the experiment, only downstream circuit breaker tripped and the upstream automatic switch remains closed. One of such moments was video-taped and now can be accessed via YouTube (Semashka et al. 2017d). That allows to keep a proper protection discrimination scheme. Moreover, the clearing time of described scheme is within 15 ms, which satisfy the existing regulations (Nfpa 2015: 104).

3.4.4 Current selectivity coordination scheme with load

The fourth experiment was conducted with two types of protection coordination with single phase load: up-steam three phase circuit breaker with current selectivity and down-stream 1 phase circuit breaker with time-current selectivity. Electric kettle (2kW) was used as a load.

Consider Figure 3.13, which plot surge of current during single phase to N-conductor short circuit with connected load.

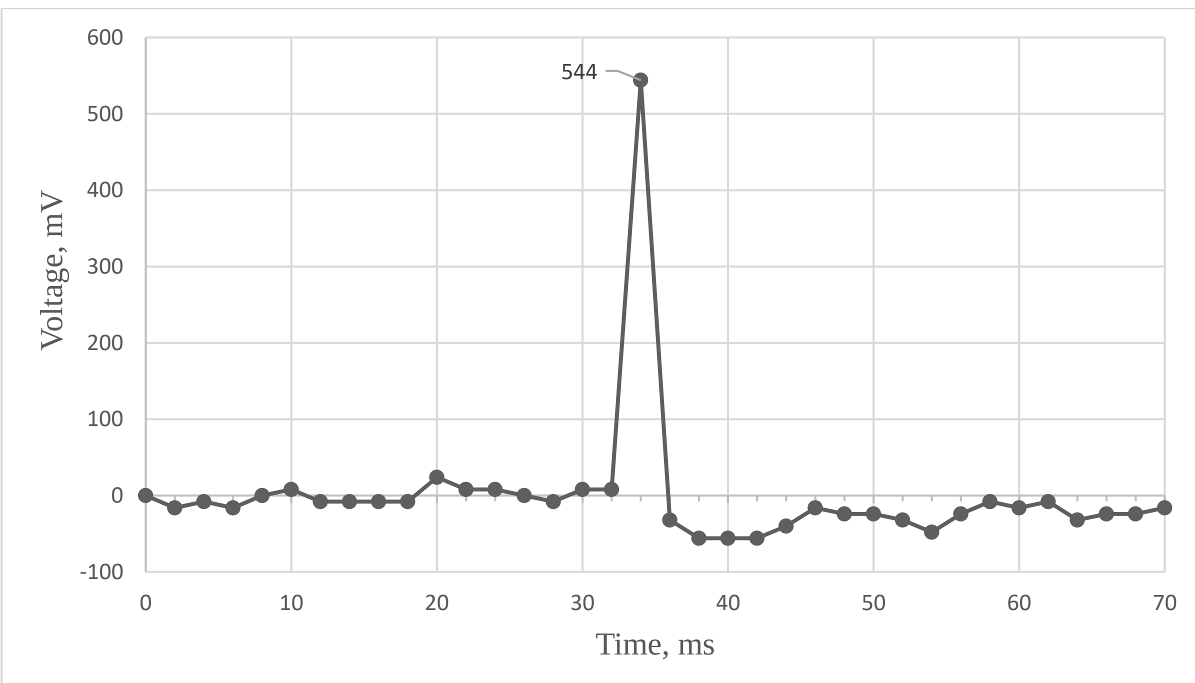

Figure 3.13 – Obtained dependence of Hall effect sensor' voltage on time during the experiment with correct protection coordination with the load.

As we can see on the screenshot of the oscilloscope confirmed with Excel datasheet, the surge of single-phase to neutral wire short-circuit is equal to 352 mV. Based on the This is illustrated in Figure 3.9 and Equation , the target value yields:

$$I_s = U_0 \cdot \psi = 0{,}544 \cdot 1403{,}51 \approx 763{,}51\ (A) \tag{6}$$

where U_0 − output voltage from Hall effect sensor caught by the oscilloscope, V; ψ − current to voltage ratio.

During the test, only downstream circuit breaker tripped, what allows to maintain the proper protection discrimination scheme. One of such situations was video-taped and now it is available publicly on YouTube (Semashka et al. 2017c). In addition, the clearing time is within 15 ms, which is conformed the existing regulations (Nfpa 2015: 104).

3.5 Data analysis

- One phase to ground short-circuit current with load on the exposed phase is lower than current without load in both cases (schemes with time-current selectivity with bimetallic release and current selectivity). This can be explained by the fact that experiment without load refer to “cold” start trip characteristic of a circuit breaker (Chen et al. 2013: 217–222), while the presence of a load shift the curve to the “warm” start trip characteristic. A load heats the conductor with extra current before the short circuit takes place, therefore it takes less current to reach an opening conditions for the automatic switches.
- Improved selectivity scheme with up-stream current limiting circuit breaker encounters larger tripping current than traditional time-current characteristic

scheme. It happens because up-stream current limiting circuit breaker has a capacity to let through larger current in order to maintain a proper selectivity by waiting until down-stream protection device trigger. Such application practice requires closer and more careful inspection, because from the worker's safety viewpoint, increasing of available current correlate with growing health hazard.

4 Simulation of the performed experiment

In order to evaluate effectiveness of two investigated methods of protection coordination, several simulations have been carried out by means of ABB DOC software (version 3.4.2.0000-28-Oct-16)

Since the experiment was conducted on the ABB equipment; therefore, ABB DOC software was chosen for performing the simulation. Achieved test results allow to simulate precisely the circuit breakers coordination and reveal weak spots of the traditional time-current protection scheme.

4.1 Description of ABB DOC software

DOC is the ABB program for drawing and calculating single-line diagrams of low and medium voltage electrical plants. In addition, it can be used for the selection of switching and protection devices and for their discrimination (ABB SACE 2011).

This software provides with possibility to draw the single-line diagram of a complete installation in order to dimension transformers and cables, select and coordinate switching and protection devices and configure the switchboards obtaining even complete bill of material. The blockset uses the ABB DOC program, allowing a model to be built using simple click and drag procedures. The libraries contain models of typical power equipment, such as circuit breakers, cables, busbars and others. These model’s validity is based on the experience of ABB equipment.

DOC is part of e-Design, the software suite, designed and produced by ABB for all professionals working in the electrical sector: designers, panel builders, installers and wholesalers. Its time domain solver provides sufficient graphical user interface and block module that allow the users to build system models with specific ABB devices and conduct massive simulation test at the same time. This paper describes design and implementation of simulation system for time-current and current protection schemes.

4.2 Configuration of simulated system

The dynamic simulation system for time-current and current selectivity is implemented in this paper according to its working principle and elementary configuration.

The single-line diagram of the study traditional selectivity coordination scheme without load is illustrated in Figure 4.1. This is a basic structure of the investigated short-circuit stand. The modifications, which will be described later, allow to simulate all four scenarios, in order to compare with the experimental data.

For the simplicity, which does not negatively affect the obtained results, four scenarios of the tests on the short circuit stand are simulated by means of four different models at ABB DOC software. The simulation as well as the experiment was performed at 0,4 kV.

Principally, the model consists of the following components

- power supply;
- WC1 – 1 meter of 3-phase 1,5mm^2 copper cable;
- QF1 – upstream 3-phase time-current or current selectivity 25A circuit breaker;
- B1 – 3-phase copper basbar;
- QF2 – downstream 1-phase time-current selectivity 16A circuit breaker;
- L1 – 1-phase static 2kW electric load.

During performing a simulation, these main parts are modified, however the overall structure remains the same.

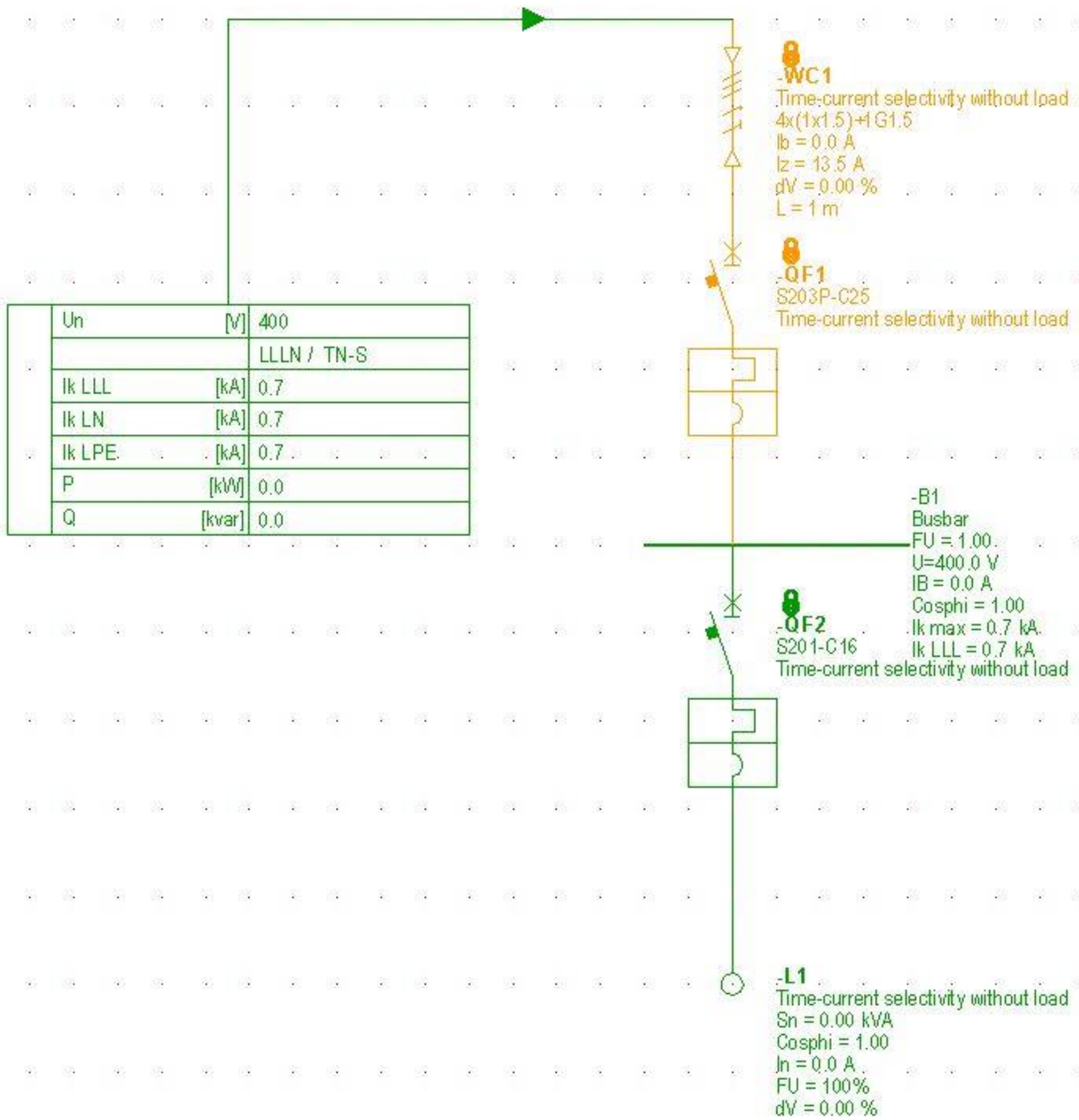

Figure 4.1 – Screenshot of the single-line diagram of time-current selectivity coordination scheme without load at ABB DOC program.

4.3 Simulation of the time-current selectivity coordination scheme without load

During the single-phase to neutral wire short-circuit, the current value approached 0.674 kA value. Therefore, this number is used at the power supply settings for accurate simulation at ABB DOC program. The 10% tolerance level is chosen during the simulation. In the "LV section default values" the electric source has the following characteristics: U=400V, configuration of source – LLLN, TN-S, network frequency – 50 Hz. In the "Network demand" section it is not possible to determine active power equal to zero, therefore a negligible value of 0.001 kW is applied.

As the value $I''k$ refers to 3-phase short circuit current, consequently there is a necessity to make a specific adjustment, which allows to define different types of faults. For that purpose, it is required to choose "option button" and correct the percentage of other types of faults in relation to three-phase short-circuit. As it is possible to set only "LLL" (3-phase short-circuit) value, the determination of the "Ik LN" to "Ik LLL" ration equal to 100%, allows to conduct a proper simulation based only on single-phase to ground short-circuit current level (Controls - Clearwater Tech).

After selection of circuit breakers, which were used in the experiment the following tripping curves were obtained. This is illustrated in Figure 4.4. The cross indicates the value of the applied single-phase to N-conductor short-circuit on the obtained diagram.

From this figure it can be seen that because of the duration of short circuit exceeds 10ms in our case, upstream and downstream automatic switches trip simultaneously.

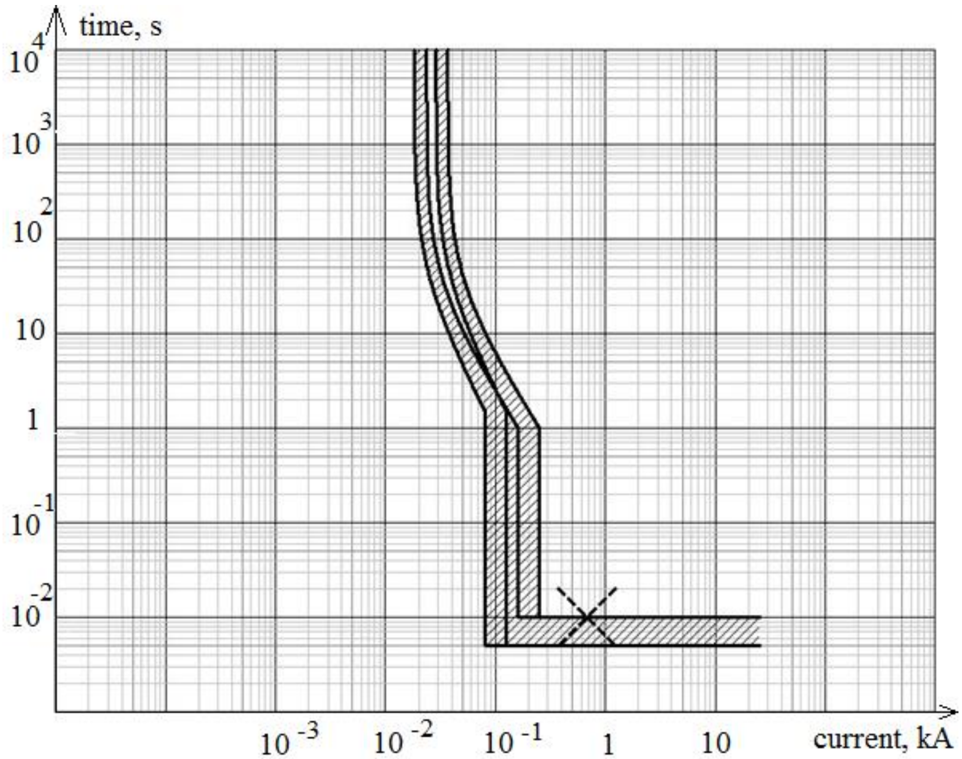

Figure 4.4 – Edited screenshot of the coordination curves for time-current selectivity scheme without load.

Based on the outcome of the investigation it is possible to conclude that, the proper discrimination scheme is not preserved.

4.4 Simulation of the time-current selectivity coordination scheme with load

During the single-phase to neutral wire short circuit, the current value approached 0.494 kA value. Therefore, this number is used at the power supply settings for accurate simulation at ABB DOC program (similar to the setting in Figure 4.2). However, some setting amendments must be done at load section.

All other settings, including the selection of the circuit breakers remains the same. After simulation of model the following tripping curves were obtained. This is shown in Figure 4.5. The cross indicates the value of the applied single-phase to N-conductor short-circuit on the obtained diagram.

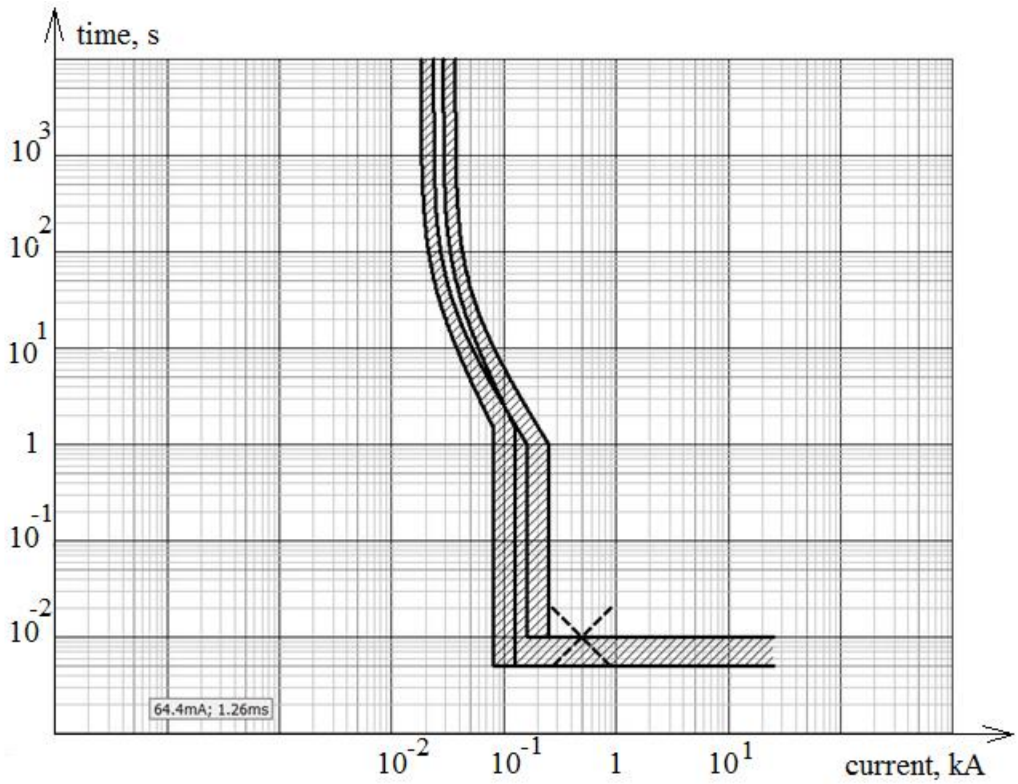

Figure 4.5 – Coordination curves for time-current selectivity scheme with single-phase static load.

From this Figure it can be observed that because the duration of short circuit exceeds 10ms, upstream and downstream protective devices opens at the same time. The presence of single-phase static electric load does not affect the selectivity of both serially connected circuit breakers. In conclusion, it is evident that this simulation has presented the lack of proper discrimination scheme as it was shown during the experiment.

4.5 Simulation of the current selectivity coordination scheme without load

Single-phase to neutral wire short circuit current reached 1,044 kA during the performed experiment. This value of fault current was set similarly to previous cases. The cross indicates the value of the applied single-phase to N-conductor short-circuit on the obtained diagram. For visual representation of discriminative trips the reader is referred to Figure 4.8.

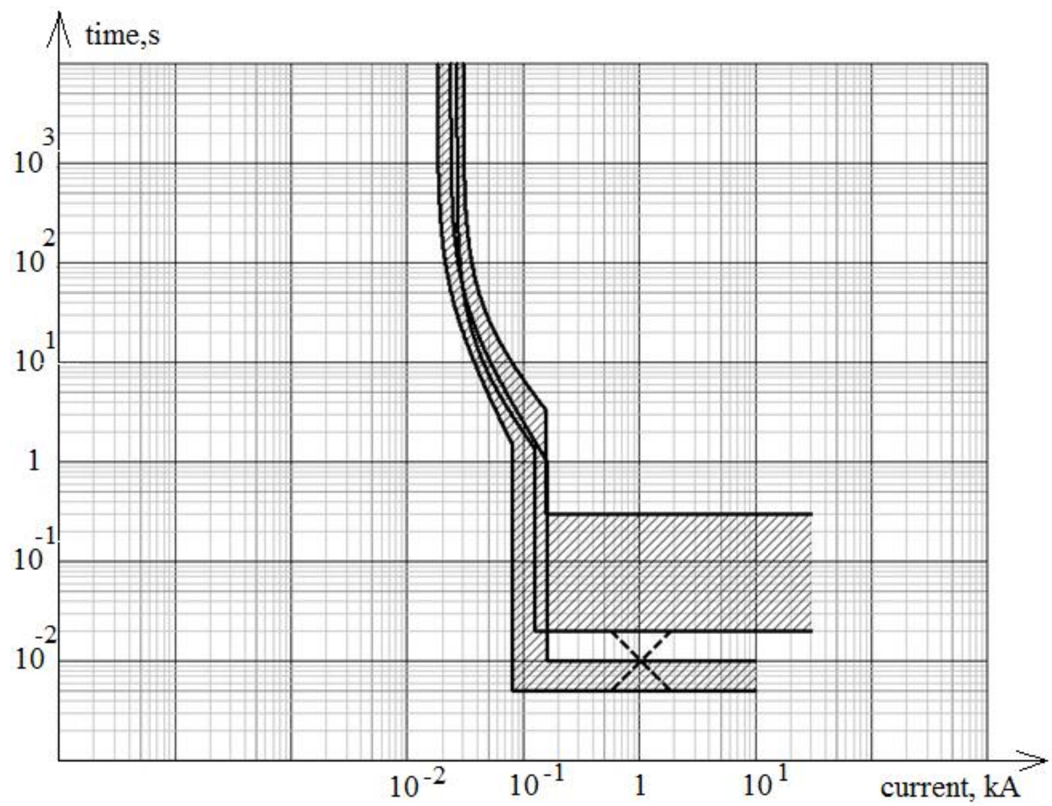

Figure 4.8 – Coordination curves for current selectivity scheme without any load.

The results obtained in the simulation are compatible with the experiment outcome. During the experiment, only downstream one-phase circuit breaker with time-current selectivity tripped, while the upstream three-phase automatic switch with current discrimination remained on duty. As it can be observed from the Figure 4.8, the time-current characteristics curves are separated between each other by 10ms, which leads to reliable and proper protection coordination.

4.6 Simulation of the current selectivity coordination scheme with load

Figure 4.9 presents protection coordination between upstream three-phase low-voltage circuit breaker with current selectivity and one-phase downstream circuit breaker with time-current discrimination.

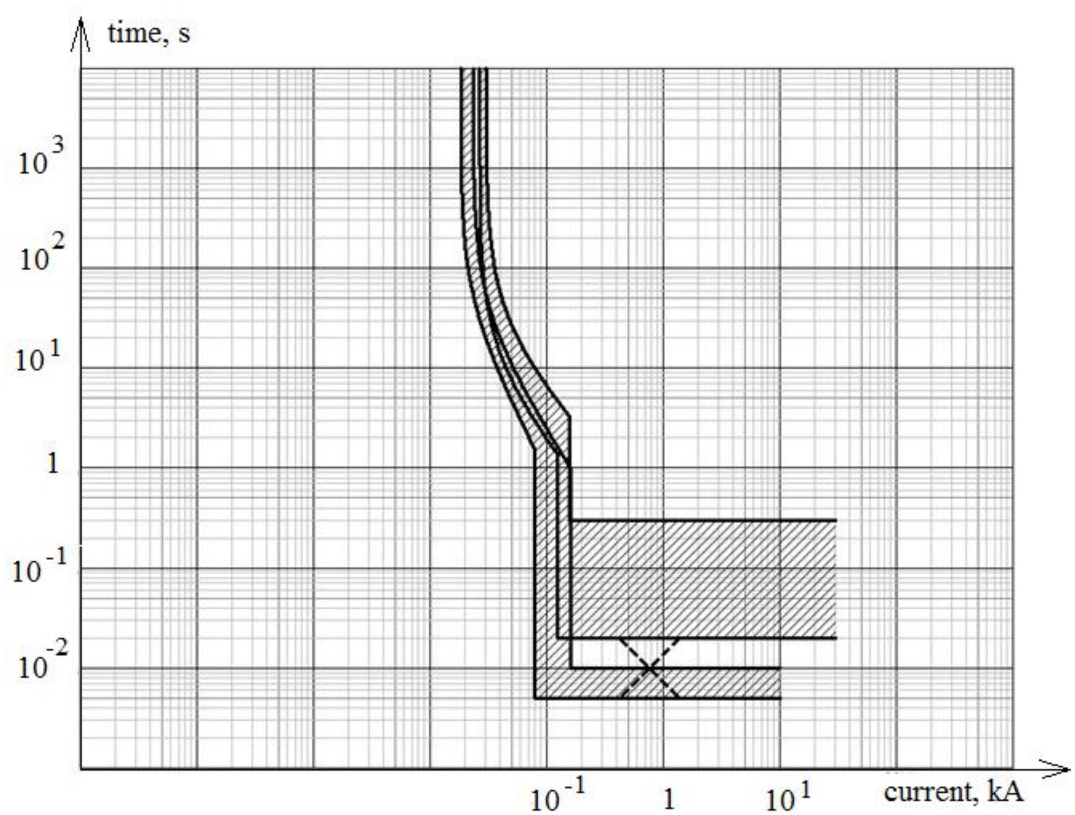

Figure 4.9 – Coordination curves for current selectivity scheme with single-phase static load.

The simulation was performed in order to prove reliability and viability of the proposed scheme. A single-phase to neutral wire short circuit value was set equal to 0,764 kA, as it was obtained during the experiment. The load characteristics were selected as a 2kW static load ($\cos\varphi = 1$).

As can be seen from Figure 4.9, there is a 10ms gap between two adjoining protective trips. That is ensure that the upstream automatic switch opens later than downstream one. The acquired data is in good correspond with the experiment results. The presence of load just slightly decreases to tripping current, because in that case, circuit breakers trip from “warm” starting point. In this respect, lower short circuit current is required for tripping the protective devices.

5 Complex approach to selection of protection coordination technique in low voltage grid

A lot of investigations are dedicated to the preserving the proper protection coordination between automatic switches placed in series over the last decades. However, despite obvious progress in developing new and improving existing tripping discrimination techniques, correlation of such techniques still require meticulous attention. The presented algorithm, Figure 5.1, embraces outcomes of previous investigation and available practical solution for facilitating the selection of the reliable and correct tripping selectivity between two circuit breakers.

In the provided algorithm, the term of “time-current selectivity” refers to the protection coordination implemented by modular-case circuit-breaker with bimetallic strip.

First of all, (1) grid analysis is required for identifying the topology of the system. It has significant impact on the preferable protection technique due to the differences in its realization. If it is a meshed electrical system (1.1) zone selective interlocking with directional relay need to be employed, because only this type possesses a special relay, which helps to find a section affected by short circuit and isolate this part. During this approach initially meshed (looped) grid transforms into radial one. However, when the studied grid has a radial configuration (1.2), further investigations are required.

Further the possibility of bidirectional power flow should be considered (2). Very often presence of distributed power generators creates such conditions. In order to satisfy coordination requirements for bidirectional energy distribution, zone selective interlocking with directional relay should be used (2.1). Nevertheless, the vast majority of electrical installations employ grids with unidirectional topology, therefore (2.2) the configuration of the protected grid must be considered.

The studied electrical network might differ according to types of loads, which dominate at specific instances (3). Because the short circuit currents available at different points in the system are a concern, coordination study is usually performed in conjunction with a fault current study. The short circuit investigation evaluates the ability of the equipment to withstand and interrupt the prospective fault currents. The study-calculated fault currents are also used to plot protective device time-current characteristics for the coordination study and evaluate selectivity via manufacturers' published tables.

Significant part of power end-users in household and services sphere, have single-phase loads. For such systems the value of single-phase-to-ground fault current must be observed (3.1). It is evident that for industrial consumers with three-phase loads, the value of three-phase-to-ground short circuit current (3.2) must be calculated and considered for proper protection coordination.

With regards to single-phase power consumers, the short-circuit level equals to 630A is discussed (4). This value is taken due to the fact that maximum available rated current for miniature (modular-case) single-phase circuit-breakers is 63 A. As regards the trend of the curve, from a conceptual point of view, the considerations made for trip curve of C-type. For the visual representation of the time-current dependence with C-type trip curves, the reader is referred to Fig. 5.2. This characteristic identified by the short time delay which represents the trip time of the protection, in seconds, in correspondence with a multiple of rated current I_n. This multiple of rated current depends on the trip unit and is equal to $10 \times I_n$ for studied modular-case circuit-breakers (Martín et al. 2016: 1133–1153).

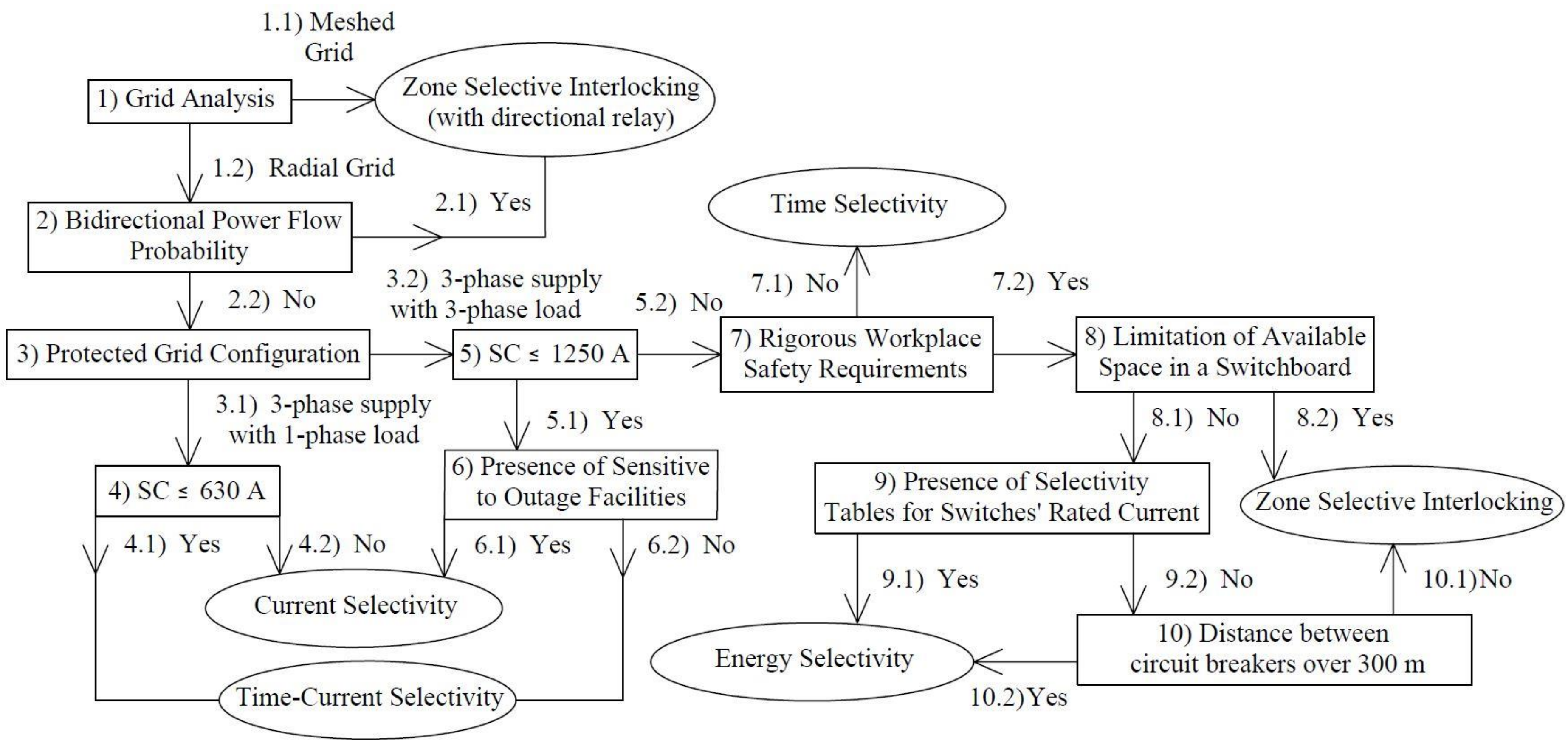

Figure 5.1 – Algorithm for choosing the optimal protection coordination technique for low-voltage grids.

The similar logic applies for the analysis of three-phase fault current (5), however for such cases, corresponding miniature circuit-breakers at rated 125A current is available.

If fault current is below 630A, then time-current selectivity based on thermal-magnetic release can be used as the most economical solution (4.1). However, in case of excessing this value, upstream protective device will trip simultaneously with load-side breaker and the protection coordination will be no longer preserved (4.2). Therefore, more expensive current selectivity technique must be used.

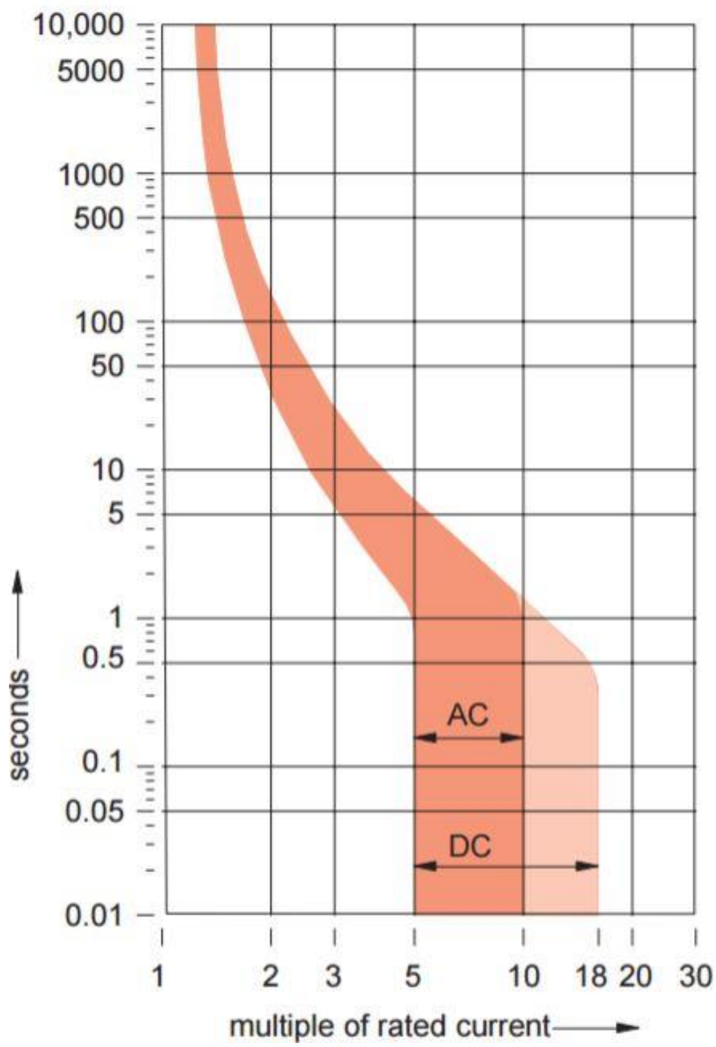

Figure 5.2 – C-type trip curve of modular-case circuit-breaker (Controls - Clearwater Tech).

Regarding to three-phase loads' network, the fault current below 1250 A (5.1) allows to apply more budget tripping coordination techniques such as time-current and current selectivity. In this case, presence of sensitive to outage facilities must be taken into account (6). IT servers and other time-sensitive equipment are vulnerable to interruption by power loss and could result in reduced revenue and the loss of customers. Therefore, for such instances, current selectivity is recommended (6.1), otherwise, low-cost time-current tripping coordination method is advisable (6.2).

A further focus is laid on relatively high three-phase short circuit current (5.2). Although the time selectivity is easy to realize as well as cheaper than zone selective interlocking and energy protection coordination techniques workplace safety aspect must be addressed. While time selectivity provides required discrimination of up-stream and down-stream protection devices, it cannot be characterized as the best instantaneous coordination solution since immediate response does not exist on both breakers. In this case, a risk for workers' health during an arcing event on the main bus increases, because the main breaker must wait until its short time delay is attained before it starts tripping. From a worker safety standpoint, applying a main breaker without instantaneous protection is disputable practice given the need to mitigate arc flash incident energy and the alternatives for doing so while achieving coordination. As a result, time selectivity should be utilizing only for facilities not complying with strict workplace safety regulations (7.1), otherwise further investigations should be carried out (7.2).

Basically, in order to obtain energy selectivity between two circuit-breakers, the upstream protection automatic switch should be used in the bigger frame size than the load-side device. However, it is common situation, when the available space within switching board limits frame size of equipment inside it (8). For such instances, zone selective interlocking would be a reliable resolution (8.2). If the switching panel has enough internal space, additional aspects should be taken into account for finding an optimal balance between system reliability and cost effectiveness (8.1).

Well-known respectful manufactures of protective devices test their products under different conditions in order to develop valid discrimination or selectivity tables. At specific cases, where rated together with fault currents are calculated utilization of such tables could be a sound practice (9.1), which implies application of energy coordination. If not (9.2), the distance between automatic switches should be addressed.

As mentioned previously in Chapter 2, zone selective interlocking (ZSI) allows two or more circuit-breakers to communicate with each other so that a short circuit or ground fault will be cleared by the breaker closest to the fault in the minimum time. ZSI systems use control wires (called restraint wires) to provide the communication link between the electronic trip devices. ZSI wiring should be run separately from power distribution conductors or bus in order to prevent interference with the ZSI restraint signal. If the length of the restraint wire exceeds 300 m, a restraint interface module (RIM) must be used to boost the restraint signal (Schneider Electric 2012). In such cases, the topology of protection discrimination becomes progressively sophisticated (10). As a result, if the available internal space of switchboard allows to increase a frame size of the grid-side breaker, it would be more reasonable approach for maintaining the proper selectivity performance (10.2). Otherwise, zone selective interlocking should be employed (10.1).

6 Conclusions and recommendations

6.1 Conclusions

The main contribution of this work are:

- A comprehensive review of available protection discrimination schemes such as time-current selectivity with bimetallic release, current, time, energy and zone selectivity is conducted.
- The drawbacks of widely used time-current selectivity with bimetallic release for low voltage automatic switches are revealed by means of literature analysis and then are proven with the help of the conducted experiment and performed simulation on specially designed software. Although the automatic switches were selected according to existing practice, the experiment and modelling indicate that more detailed approach must be used for guaranteeing the proper protection discrimination.
- Summing up the obtained short circuit current values, it can be concluded that in case of presence a load on the studied circuit, the protection devices opened faster, due to shifting of tripping curve to the “warm” start characteristic.
- Existing tripping coordination techniques are analyzed and correlated with each other. The complex approach to selection of reliable and effective protection discrimination technique between low voltage circuit breakers is developed in form of algorithm. The flowchart is explicitly described in order to assist its correct application.

6.2 Recommendations and future works

Although many aspects of the tripping discrimination in low-voltage systems have been covered by this investigation, several other issues are should be developed during future investigation. Some of the objectives that are deemed interesting are listed as follows:

- During the experiment and simulation, the effect of bolted short circuit current on the protection coordination was investigated, while the majority of real faults are phase-to-ground arc-flashed accidents. Taking into consideration dynamic impedance can dramatically increase accuracy of prediction of circuit breakers' behavior under an abnormal current conditions. Study related abovementioned aspects can be done in the future works.
- Protection of generators can significantly influence on tripping discrimination leading to outage of sound parts of the grids. Sometimes selective coordination can be impaired by the self-protection function provided by the gen-set manufacturer. In this situation, it is suggested that the downstream circuit breaker must be selected and set to coordinate with the generator protection characteristic rather than to the prospective fault current. Impact of generators' self-protection on selectivity needs to be addressed in the future investigations.
- The overall research presented in this thesis only deals with low voltage distribution network, while the objectives are relevant for middle voltage grids as well. Such conditions can be observed in the future studies.
- Whole simulations were performed in ABB DOC software package due the available equipment in the short circuit stand. However, creating and testing an electronic models of studied system in Matlab Simulink provide more thorough analysis of protection discrimination.

- Performed investigation does not address residual current protection selectivity. If an electrical system has user devices with earth leakage currents which exceed the normal values, it is advisable to install various devices on the main branches with an upstream main residual current functionality. Such case can be investigated in the future research for developing valid tripping coordination.

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