ANALIZA PODEŠENJA DISTANTNE ZAŠTITE PROVEDBOM PRIMARNIH POKUSA

ANALYSIS OF DISTANCE PROTECTION SETTING BY PERFORMING PRIMARY TRIALS

Kristijan Frlan, Opatija, Hrvatska – Ante Marušić – Juraj Havelka, Zagreb, Hrvatska

Na području zapadnog dijela elektroenergetskog sustava (EES-a) Hrvatske rekonstruirani su vodovi 110 kV prijenosne mreže radi poboljšanja sigurnosti i kvalitete pogona. Specifičnost razmatranog dijela EES-a je da u okruženju postoji samo jedan snažni izvor napajanja. To su dvije termoelektrane, Plomin 1 na naponskoj razini 110 kV i Plomin 2 na naponskoj razini 220 kV, smještene na istoj lokaciji. Kvar nastao u razmatranoj mreži napaja se gotovo isključivo iz jedne pojne točke. Navedeni nerazmjer u distribuciji struja kvara nerijetko rezultira pojavom takvih uvjeta koji ne jamče ispravno djelovanje zaštitnih releja na vodovima.
Relejna zaštita vodova postala je složeni sustav. Korištenjem telekomunikacijskih resursa zajedno s numeričkim zaštitnim relejima pojavila se potreba za ispitivanjem cjelokupnog sustava kao cjeline, a ne samo pojedinačnih dijelova. Provedbom primarnih pokusa u prijenosnoj mreži 110 kV ispitano je djelovanje sustava zaštite u okruženju kvara.
U radu su opisani pripremni radovi i sama provedba primarnih pokusa na T-spoju 110 kV-og voda TE Plomin – TS Šijana – TS Vinčent.

In the territory of the western part of the Croatian electrical power system (EPS) lines 110 kV of the transmission network have been reconstructed for the purpose of improvement of safety and drive quality. The particularity of the observed part of the EPS is that its environment includes only one powerful power supply source. Those are two thermal power plants on the same location, Plomin 1 with the voltage level of 110 kVand Plomin 2 with the voltage level of 220 kV. The fault which occurred in the observed network is charged almost entirely from one supply point. The said inconsistence in the fault currents distribution often results in the occurrence of such conditions that do not guarantee proper operation of the transmission lines' protection relays.
Relay protection of the transmission lines has become a complex system. The use of telecommunication resources together with numerical protection relays has given rise to the need for verification of the entire system as a whole and not only its individual parts. The performance of primary trials in the transmission network 110 kV was used to test the operation of the protection system in the fault ambience.
The work describes the preparatory work and the very performance of primary trials at the T-junction of the 110 kV transmission line of Plomin thermal power plant – Šijana substation – Vinčent substation.

Ključne riječi: distantna zaštita; ispitivanje s kraja na kraj; primarni pokusi; program CAPE; T-spoj
Key words: distance protection; end-to-end trial; primary trials; CAPE programme; T-junction

https://doi.org/10.37798/2009584307

1 UVOD

Cilj testiranja provedbom primarnih pokusa u hrvatskom elektroenergetskom sustavu bio je provjera rada distantne telezaštitne sheme. Na istarskom poluotoku postoje dvije termoelektrane, jedna ima snagu od 156 MVA i naponsku razinu od 110 kV, a druga ima snagu od 263 MVA i naponsku razinu od 220 kV. Obje su smještene na istoj lokaciji. Svaki kvar koji nastaje, neovisno o lokaciji, napajan je, bilo direktno ili indirektno, iz navedenih elektrana koje su jedini jaki izvor u regiji. Nejednolikost u tokovima snaga i doprinosu struji kratkog spoja može dovesti do krive prorade distantne zaštite. Kako bi se poboljšala sigurnost energetskog sustava izgrađen je 110 kV dalekovod baziran na principu T-spoja (krajnje točke T-spoja su: TE Plomin – TS Šijana – TS Vinčent) i štićen je distantnom telezaštitom. Podešenje zona štićenja je napravljeno pomoću CAPE programske podrške u kojoj su napravljene simulacije raznih kvarova pri različitim konfiguracijama mreže.

T-spoj nije uobičajen u hrvatskom elektroenergetskom sustavu pa je stoga to prva vrsta
T-voda koji je analiziran u zapadnom dijelu hrvatskog elektroenergetskog sustava. Upravo je to i razlog zbog kojeg su se provela primarna ispitivanja.

Zbog toga što ovakva ispitivanja zahtijevaju znatnu pripremu, cijeli posao je bio podijeljen u tri faze:

- simulacija pomoću CAPE programske podrške kako bi se dobili općeniti podaci o radu sustava i vrijednosti napona i struja tijekom ispitivanja s kraja na kraj,
- GPS sinkronizirano ispitivanje s kraja na kraj kako bi se provjerila podešenja zaštite i telekomunikacijskog sustava,
- primarno ispitivanje.

2 HRVATSKI ELEKTROENERGETSKI SUSTAV

Hrvatski prijenosni elektroenergetski sustav podijeljen je u četiri područja (slika 1). Zapadni dio sustava koji se razmatra u radu sastoji se od vodova 220 kV i 110 kV. Dvije termoelektrane smještene na istočnom dijelu poluotoka Istre jedina su dva snažna čvorišta u tom dijelu EES-a.

1 INTRODUCTION

The objective of testing by virtue of primary trials in the Croatian electrical power system was to verify the operation of the distance teleprotection scheme. There are two thermal power plants on the Istrian Peninsula, one operates with the power of 156 MVA and voltage level of 110 kV, and the other at 263 MVA of power and at the voltage level of 220 kV. Both are at the same location. Each occurring fault, independent of its location, is supplied, either directly or indirectly, from the said power plants which are the only powerful source in the region. The disparity of power flows and contributions to the short circuit current can bring about an improper trip of the distance protection. In order to improve the safety of the energy system, a transmission line has been constructed which is based on the principle of the T-junction (end points of the T-junction are: Plomin TPP – Šijana substation – Vinčent substation) and it is protected by distance teleprotection. The setting of protection zones was made by virtue of the CAPE programme support in which simulations of various faults were undertaken at different network configurations.

The T-junction is not usual for the Croatian electrical power system so this is the first type of the T-junction transmission lines which has been analysed in the western part of the Croatian energy power system. This is exactly the reason for the undertaking of primary trials.

As these kinds of trials require significant preparation, the entire work was divided in three phases:

- simulation by virtue of the CAPE programme support in order to obtain general data on the operation of the system and the value of voltages and currents during the end-to-end study,
- GPS end-to-end synchronous study in orde r to verify the protection and telecommunication system settings,
- primary study.

2 CROATIAN ELECTRICAL POWER SYSTEM

The Croatian transmission electrical power system is divided into four zones (Figure 1). The western part of the system analysed in the work consists of the transmission lines 220 kV and 110 kV. Two thermal power plants located in the eastern part of the Istrian peninsula are the only two powerful hubs in that part of the electrical power system.

Slika 1 — Hrvatski elektroenergetski sustav
Figure 1 — The electrical power system of the Republic of Croatia

Termoelektrana Plomin 1 (156 MVA) spojena je na naponsku razinu 110 kV, a Plomin 2 (263 MVA) na naponsku razinu 220 kV. Veza između 220 kV i 110 kV naponske razine realizirana je preko tri autotransformatora (150 MVA). Termoelektrane su spojene vodovima 220 kV s trafostanicama TS Melina 400/220/110 kV i TS Pehlin 220/110 kV i vodom 110 kV s trafostanicom TS Lovran. Na sjeveru Istre EES Hrvatske povezan je sa susjednim sustavom Slovenije vodom 110 kVTS Buje – TS Kopar (slika 2).

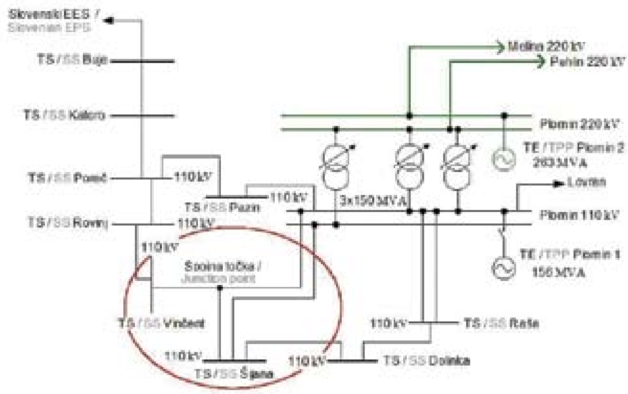
Hrvatski elektroenergetski sustav je spojen sa susjednim zemljama i zajedno s njima u Europsku UCTE sinkroniziranu mrežu. Hrvatski EES je po veličini jedan od najmanjih u Europi, ali je zbog zemljopisnog položaja bitan pri povezivanju istočnog i zapadnog UCTE sustava.

Glavna zaštita na svim vodovima je distantna. Releji su elektromehaničke, statičke i numeričke izvedbe. Prilikom pojave kvara isti se napaja gotovo isključivo iz čvorišta Plomin 220/110 kV kao jedinog snažnog izvora. Takva raspodjela toka struje kvara posljedica je konfiguracije EES-a na razmatranom području.

The Plomin 1 thermal power plant (156 MVA) is connected to the voltage level of 110 kV and the Plomin 2 (263 MVA) to the voltage level of 220 kV. The connection between the voltage levels of 220 kV and 110 kV was realized through three autotransformers (150 MVA). The thermal power plants are connected by transmission lines of with the Melina substation 400/220/110 kV and the Pehlin substation 220/110 kV and by the transmission line of 110 kV with the Lovran substation 110 kV. In the north of Istria, the Croatian EPS is connected to the neighbouring system of Slovenia by transmission lines of 110 kV SS Buje – SS Kopar (Figure 2).

The Croatian electrical power system is connected with the neighbouring countries and together with them to the European UCTE synchronised network. The Croatian EPS is one of the smallest in Europe according to its size, but because of its geographical position, it is crucial in connecting the eastern and the western UCTE systems.

The main protection in all the transmission lines is distance. Relays are of electromechanical, static and numerical design. When it occurs, a fault is charged almost exclusively from the Plomin hub 220/110 kV as the only powerful source. Such distribution of the fault current flow is a consequence of the EPS configuration in the observed area.



Slika 2 — Zapadni dio Hrvatskog EES-a

Figure 2 — Western part of the Croatian EPS

2.1 T-spoj TE Plomin –TS Šijana –TS Vinčent

Vod realiziran na principu T-spoja između TE Plomin, TS Šijana i TS Vinčent konstruiran je za naponsku razinu 220 kV, ali je privremeno u pogonu pod naponom 110 kV. Dužine i impedancije pojedinih vodova prikazane su u tablici 1. Utjecaj različite dužine pojedinog odvojka i nejednak doprinos struji kvara uvjetovali su specifičan pristup prilikom određivanja podešenja za pojedine releje.

2.1 T-junction of TPP Plomin – Šijana substation –Vinčent substation

The transmission line realized on the principle of a T-junction between the TPP Plomin, Šijana substation and Vinčent substation was constructed for the voltage level of 220 kV, but it is currently operating at the voltage of 110 kV. Lengths and impedances of certain transmission lines are shown in Table 1. The impact of different lengths of certain extensions and unequal contribution to the fault current gave rise to a specific approach during the determination of the setting for certain relays.

Tablica 1 – Podaci za T-spoj
Table 1 – Data for the T-junction

Grana / Branch	Dužina / Length, km	Z_d, Ω	Z_0, Ω
Plomin – Spojna točka / Junction point	33,1	1,832+ j 13,83	6,62 + j 39,85
Vinčent – Spojna točka / Junction point	24,34	2,92 + j 10,17	12,04 + j 26,1
Šijana – Spojna točka / Junction point	10,11	1,214 + j 4,22	3,514 + j 10,8

3 KONFIGURACIJA RELEJNE ZAŠTITE

3.1 Podešenje distantne zaštite

Praksa je pokazala da je za zaštitu vodova najbolja opcija uporaba uzdužne diferencijalne zaštite. U ovom slučaju to nije bilo moguće realizirati, jer su u postojećim objektima numerički releji već bili ugrađeni u svojim zasebnim sustavima upravljanja i zaštite. Zbog toga je odabrana distantna zaštita s komunikacijskim vezama između releja. Pri tom

3 RELAY PROTECTION CONFIGURATION

3.1 Distance protection setting

Practice has shown that the best option for the protection of the transmission lines is the use of longitudinal differential protection. In this case, this cannot be realized because numerical relays, in their separate management and protection systems, were already installed in the existing facilities. Therefore, distance protection with telecommunitreba napomenuti da su korišteni releji različitih proizvođača i različitih generacija.

Algoritam distantne zaštite djeluje na način da određuje udaljenost do mjesta kvara mjerenjem impedancije, odnosno struje i napona. Nejednak doprinos struji kvara s pojedinih krajeva T-spoja uvjetovao je podešenja pojedinih releja. Impedancija koju mjeri relej ovisi o struji koja se mjeri na mjestu ugradnje strujnog mjernog transformatora, što u nekim slučajevima može rezultirati pogrešnim proradama releja [1].

Koncepcija distantne zaštite s komunikacijom među relejima zahtijeva pouzdane komunikacijske veze za prijenos signala za djelovanje distantne zaštite. Relej koji detektira kvar u prvoj zoni $1(Z_1)$ šalje signal za ubrzanje djelovanja na drugi kraj voda. Ukoliko je relej koji je primio signal detektirao kvar u zoni pobude, izdaje nalog za ubrzani isklop bez obzira na podešenu vremensku odgodu u višim zonama. Obično se zona $1(Z_1)$ podešava na 85 % do 90 % impedancije štićenog voda. Rezerva od 10 % do 15 % ostvaruje se zbog moguće netočnosti mjernih transformatora i samog algoritma releja, čije bi greške mogle dovesti do pogrešne prorade releja. Zona pobude koja omogućuje ubrzano djelovanje nakon primitka signala za djelovanje obično se podešava na 120 % do 130 % impedancije štićenog voda (Zona $2(Z_2)$) [2].

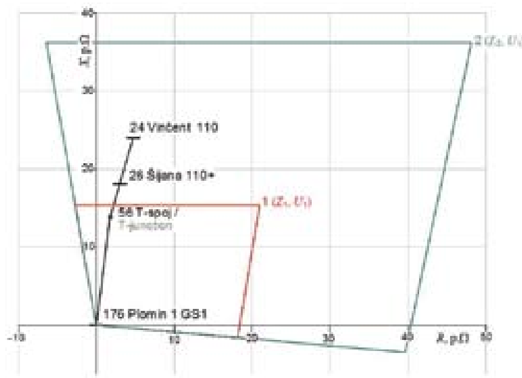
Programom CAPE modelirana je mreža prijenosnog područja (PrP) Rijeka, te su provedene simulacije različitih vrsta kvarova na različitim lokacijama na promatranom T-vodu. Analizom dobivenih rezultata došlo se do zaključka da relej u TE Plomin ne griješi u određivanju mjesta kvara bez obzira na tip i mjesto kvara, dok relej u TS Šijana, a posebice u TS Vinčent griješi. Pogreške u određivanju lokacije kvara posljedica su utjecaja dodatnih spojnih mjesta u zoni štićenja ili utjecaja otpora na mjestu kvara. Zbog navedenih razloga podešenja releja provedena su na način da zona $1(Z_1)$ svakog releja doseže preko spojne točke, dok je zona pobude koja omogućava ubrzano djelovanje povećana do zone $4(Z_4)$. Na slikama 3, 4 i 5 prikazana su podešenja pojedinih releja.

cation connections between relays was chosen. It should be added that the used relays are of different producers and different generations.

The distance protection algorithm works so that it determines the distance to the location of the fault by measuring impedance, that is, the current and the voltage. The settings of certain relays were dependant on unequal contribution to the fault current from certain ends of the T-junction. The impedance measured by the relay depends on the current measured at the point of installation of the current measuring transformer, which, in some cases, can result in improper relay trips [1].

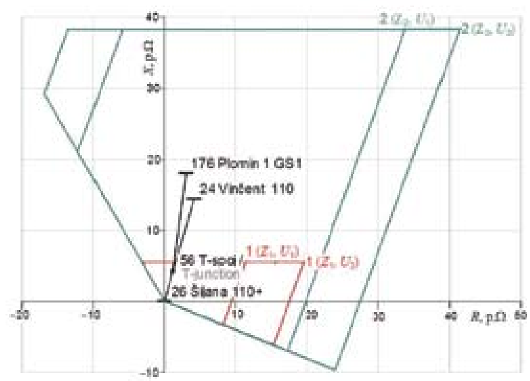
The distance protection concept with inter-relay communication requires reliable communication links for signal transmission for the effect of the distance protection. The relay which detects the fault in the first (Z_1) zone sends the signal for acceleration of the effect to the other end of the power line. If the relay which has received the signal detects the fault in the actuation zone, it issues an order for accelerated switch-off regardless of the set time delay in higher zones. The (Z_1) zone is usually set at 85 % to 90 % of the protected transmission line impedance. A backup of 10 % up to 15 % is realized because of the possible incorrectness of the measuring transformers and the very relay algorithm which errors could lead to an improper tripping of the relay. The actuation zone which enables accelerated operation after the receipt of the signal for effect is usually set at 120 % up to 130 % of the protected transmission line impedance $(2(Z_2)$ Zone) [2].

The CAPE programme was used to model the Rijeka transmission area network and the simulations of different types of faults have been implemented at different locations in the observed T-junction power line. The analysis of the obtained results gave rise to the conclusion that the relay in the Plomin thermal power plant does not mistake in determining the fault location regardless of the type and location of the fault, while the relay in the Šijana substation, just like the one in the Vinčent substation, does. The errors in determining the location of the fault are a consequence of the impact of additional junction points in the zone of protection or resistance impact at the location of the fault. Due to the stated reasons, the relay settings were done so that zone $1(Z_1)$ of each relay reaches beyond the junction point while the actuation zone, which enables accelerated effect, is extended to zone $4(Z_4)$. Figures 3, 4 and 5 show the settings of certain relays.



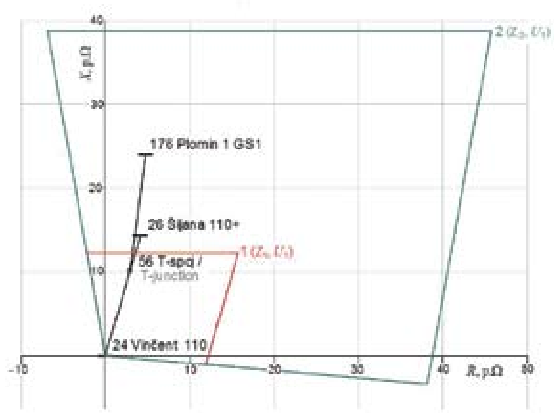
Slika 3 — Podešenje releja za TE Plomin

Figure 3 — Setting of the relay for the Plomin thermal power plant



Slika 4 — Podešenje releja za TS Šijana

Figure 4 — Setting of the relay for the Šijana substation



Slika 5 — Podešenje releja za TS Vinčent

Figure 5 — Setting of the relay for the Vinčent substation

Isklopna logika podešena je na sljedeći način:

— jednopolni isklop za jednopolne kvarove, i tropolni isklop za višefazne kvarove,
— automatski ponovni uklop za jednopolne kvarove uz beznaponsku pauzu od 1,2 s i au-

The switch-off logics are set as follows:

— one-pole switch-off for one-pole faults and three-pole switch-off for multi-phase faults,
— automatic re-switch-on for one-pole faults with voltage-free pause of 1,2 s and automatic

tomatski ponovni uklop za višepolne kvarove uz beznaponsku pauzu od 0,3 s,

— automatski ponovni uklop dozvoljen je ukoliko je kvar detektiran u zoni 1, ili nakon prijama signala za ubrzanje djelovanja uz detekciju kvara u zoni pobude.

3.2 Konfiguracija telekomunikacijskog sustava

Komunikacijski sustav između releja ostvaren je telekomunikacijskim uređajima koji prenose signale za djelovanje između pojedinih releja. Relej koji djeluje u zoni 1 izdaje nalog za isklop vlastitog prekidača i istodobno šalje signal prema ostala dva releja, slika 6. Prvi komunikacijski uređaj (telekom uređaj 1) prima signal iz pripadajućeg mu releja kao naponski impuls, pretvara ga u analogni frekvencijski signal (887 Hz) i šalje ga prema drugom komunikacijskom uređaju (telekom uređaj 2). Drugi uređaj pretvara analogni frekvencijski signal u digitalni signal koji se putem digitalne mreže šalje prema ostalim relejima, odnosno ostalim komunikacijskim uređajima (telekom uređaj 2).

Radi povećanja pouzdanosti komunikacijske mreže realiziran je drugi neovisni (rezervni) komunikacijski put. Relej koji prorađuje u zoni 1 šalje signal direktnim putem prema ostala dva releja. Rezervni put je ostvaren na način da komunikacijski uređaj dobiveni signal prosljeđuje prema onom kraju koji nije izvor signala za proradu.

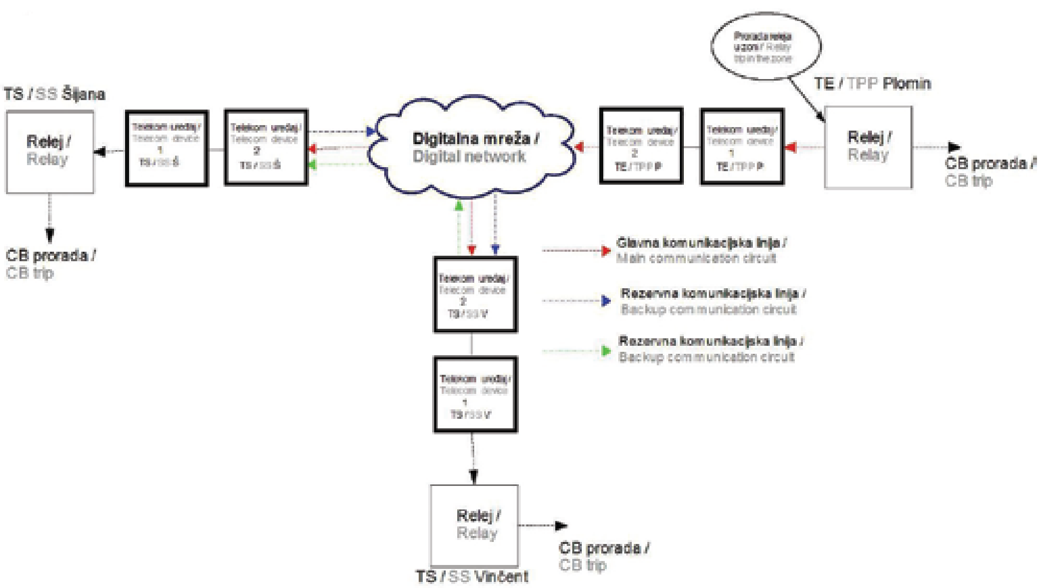
re-switch-on for multi-phase faults with a voltage-free pause of 0,3 s,

— automatic re-switch-on is allowed only if the fault is detected in zone 1, or after the receipt of the signal for accelerated effect with the detection of the fault in the actuation zone.

3.2 Telecommunication system configuration

The communication system between the relays is realized by telecommunication devices which transmit signals for effect between particular relays. The relay which operates in zone 1 issues the order for switch-off of its own breaker and simultaneously sends a signal towards the other two relays, Figure 6. The first communication device (telecom device 1) receives a signal from the pertaining relay as a voltage impulse, transforms it into an analogous frequency signal (887 Hz) and sends it towards the other communication device (telecom device 2). The other device transforms the analogous frequency signal into a digital signal which is sent through a digital network towards the other relays, that is, towards the other communication devices (telecom device 2).

For the purpose of increased reliability of the communication network, another independent (backup) communication path is realized. The relay which trips in zone 1 sends a signal directly towards the other two relays. The backup path is realized in such a manner that the communication device forwards the received signal to that end which is not the source of the trip signal.



Slika 6 — Telekomunikacijski sustav
Figure 6 — The telecommunication system

Veza između komunikacijskih uređaja neprestano se nadzire. Uređaji međusobno razmjenjuju analogne signale (2 720 Hz) koji se pretvaraju u digitalni oblik i šalju prema drugim uređajima. Ti signali služe za provjeru komunikacije među pojedinim uređajima. Ukoliko pojedini uređaj ne primi komunikacijski signal znači da je došlo do prekida veze između pojedinih uređaja i tada je cijeli sustav relejne zaštite neraspoloživ. Na slici 6 prikazan je blok dijagram komunikacijskih veza među relejima.

4 SIMULACIJA POMOĆU CAPE PROGRAMA

Da bi se dobile smjernice o ponašanju sustava prilikom kvarova u mreži, provedene su brojne simulacije programom CAPE. CAPE (engl. Computer-Aided Protection Engineering) komercijalni je program namijenjen inženjerima koji se bave relejnom zaštitom. Podaci koji se mogu dobiti kao rezultat simulacije struje su kvara i naponske prilike, te je program pogodan za definiranja podešenja za distantne releje. Program sadrži module koji omogućavaju analizu kvarova u mreži, analize koje pomažu pri budućem planiranju razvoja mreža i analize djelovanja releja.

Da bi se dobio uvid u ispravnost djelovanja sustava relejne zaštite i komunikacijskog sustava provedeni su primarni pokusi. Primarni pokusi izvedeni su na stupu broj 49 od TE Plomin prema točki čvorišta. Lokacija stupa je na 49,46 % dužine odvojka TE Plomin – Spojna točka (gledano iz smjera TE Plomin), odnosno 16,234 km od TE Plomin. Koristeći modul za kratki spoj [3] i grafički i koordinacijski modul [4] odabran je stup 49 i to iz razloga što se prema podacima dobivenim iz simulacija nalazi u zoni 1 releja u TE Plomin i u zoni 2 relejima u TS Šijana i TS Vinčent. Simulacije su također pokazale da releji u TS Šijana i TS Vinčent najviše griješe prilikom određivanja lokacije kvara.

Jednopolni i dvopolni kvarovi simulirani su radi kontrole isklopne logike.

Rezultati CAPE simulacije su prikazani u tablicama 2 i 3.

5 ISPITIVANJE S KRAJA NA KRAJ

Prije provedbe primarnih pokusa provedeno je ispitivanje s kraja na kraj sekundarnim injektiranjem analognih veličina u relej. Ovakav način ispitivanja koristi se prilikom puštanja u pogon

The link between communication devices is constantly supervised. The devices exchange analogous signals (2 720 Hz) which transform into digital form and are sent towards the other devices. Those signals serve for the verification of the communication between certain devices. In case a particular device does not receive a communication signal that means that a connection interruption has occurred between certain devices and then the entire relay protection system is unavailable. Figure 8 shows the block diagram of communication connections between the relays.

4 SIMULATION BY VIRTUE OF THE CAPE PROGRAMME

In order to obtain guidelines on the behaviour of the system when faults occur in the network, numerous simulations by virtue of the CAPE programme were performed. CAPE (Computer-Aided Protection Engineering) is a commercial programme intended for engineers who are involved in relay protection. Data which can be obtained as a result of the simulation are fault currents and voltage circumstances and the programme is fit for defining distance relays settings. The programme contains modules which enable the analysis of the network faults, analyses which facilitate the future planning of network development and analyses of relay effects.

In order to gain insight into proper relay protection system and communication system operation, primary trials have been preformed. Primary trials were performed on tower number 49 of the Plomin thermal power plant towards the hub point. The tower location is at 49,46 % of the length of the extension of Plomin TPP - junction point (viewed from the direction of Plomin TPP), that is, 16,234 km from the Plomin TPP. Using the short circuit modulus and the graphic and coordination modulus, tower 49 was chosen, namely, because, according to data obtained from the simulations, it is located in zone 1 of the Plomin TPP relay and in zone 2 of the Šijana substation and Vinčent substation relays. Simulations also showed that the relays in the Šijana and Vinčent substation are the most erroneous during the determination of the fault location.

One-pole and two-pole faults were simulated for the purpose of control of the switch-off logics.

The results of the CAPE simulation are shown in Tables 2 and 3.

5 END-TO-END STUDY

Before the implementation of primary tests, an end-to-end study was performed by secondary injection of

Tablica 2 – Doprinosi pojedinih struja za kvar na stupu 49 (za razne kvarove)
Table 2 – Contributions of certain currents to the fault on tower 49 (for different faults)

Lokacija / Location	Vrsta kvara / Type of fault	, A (Simulirane struje u releju / Simulated currents in the relay)			
		I_{L1}	I_{L2}	I_{L3}	$3I_0$
Plomin	L1-E	3 906∠82,441°	120∠90,549°	120∠90,419°	3 667,8∠-81,978°
	L1-L2	0,6∠61,791°	3 963∠-173,395°	3 963,0∠6,609°	/
Šijana	L1-E	1 311∠77,872°	130,2∠86,683°	130,2∠-86,875°	1 568,4∠-79,342°
	L1-L2	0,6∠89,807°	1 164,6∠-167,628°	1 164,6∠12,351°	/
Vinčent	L1-E	572,4∠77,529°	11,4∠123,354°	11,4∠123,1431°	551,4∠-78,370°
	L1-L2	0,000∠-136,181°	374,2∠-167,876°	574,2∠12,136°	/

Tablica 3 – Naponi na sabirnicama za kvar na stupu 49 (za razne kvarove)
Table 3 – Voltages on the busbars for the fault on tower 49 (for different faults)

Lokacija / Location	Vrsta kvara / Type of fault	V, kV(Fazni naponi na lokaciji releja / Phase voltages at the location of the relay)		
		V_{L1}	V_{L2}	V_{L3}
Plomin	L1-E	32,167 9∠0,0°	62,098 5∠-115,7°	61,846 8∠115,7°
	L1-L2	65,507 8∠-0,1°	44 630 0∠-138,6°	43,660 9∠137,2°
Šijana	L1-E	32,167 9∠0,0°	62,098 5∠-115,7°	61,846 8∠115,7°
	L1-L2	65,211 0∠-0,1°	36,737 8∠-150,2°	38,022 6∠151,2°
Vinčent	L1-E	31,817 5∠-0,1°	62,381 4∠-116,8°	62,555 0∠116,6°
	L1-L2	65,138 4∠-0,1°	37,236 7∠-149,2°	38,310∠150,0°

novih sustava relejne zaštite i pogodan je za testiranje cjelokupnog sustava zaštite, kao što su testiranja djelovanja zaštite na prekidače, testiranje komunikacijskog sustava te testiranje ispravnosti podešenja samih releja.

Za provedbu ispitivanja s kraja na kraj potrebno je provesti sljedeće pripreme:

— provjeriti podešenja u pojedinim relejima,
— postaviti ispitivački tim na svakom kraju voda (2 inženjera na svakoj strani),
— sinkronizirati ispitne uređaje,
— pokrenuti programsku podršku i module za ispitivanje s kraja na kraj,
— definirati ispitivanje (mjesto i vrste kvara),
— definirati korake za sve strane (prije, poslije i za vrijeme kvara).

5.1 Program i modul za ispitivanje s kraja na kraj

Za provedbu testova korišten je Omicron sustav za sekundarna ispitivanja. Tri ispitna uređaja, svaki na jednom kraju 110 kV-nog T-spoja, sinkronizirani su putem GPS modula.

analogous dimensions into the relay. This manner of testing is used upon putting into operation new relay protection systems and it is suitable for testing the entire protection system, such as testing the effect of the protection on the breakers, testing the communication system and testing the proper setting of the very relays.

For the purpose of implementation of end-to-end studies, the following preparations need to be undertaken:

— check the settings in certain relays,
— set up a trial team at each end of the power line (2 engineers on each side),
— synchronize testing devices,
— start up the programme support and modulus for end-to-end studies,
— define the study (location and types of fault),
— define the steps for all aspects (before, after and during the fault).

5.1 End-to-end study programme and modulus

For the implementation of the tests, the Omicron system for secondary trials was used. Three test devices, each at one end of the 110 kV T-junction were synchronized by virtue of the GPS modulus.

5.2 Definiranje ispitivanja (lokacija i kvarovi)

Program CAPE korišten je za simulaciju kvarova na lokaciji stupa 49 od TE Plomin prema spojnoj točki na 49,46 % dužine voda (16,234 kV) kao što je opisano u poglavlju 4. Simulirani kvarovi su bili jednopolni (L1-E) i dvopolni (L1-L2). Na taj način je zaštita testirana za jednopolne kratke spjeve između faze i zemlje i za dvopolne kratke spojeve.

5.3 Definicija sekvenci

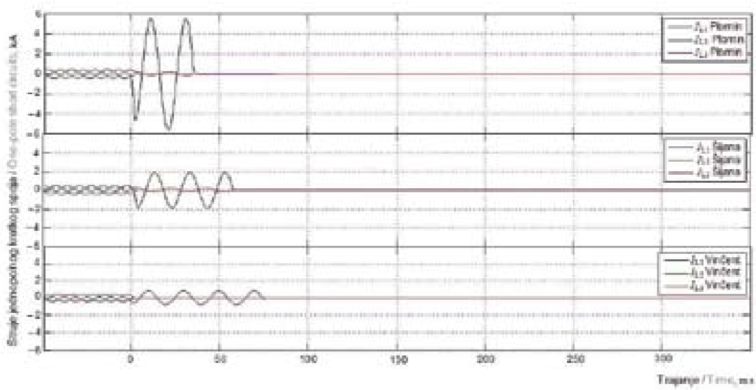
Ispitivanje s kraja na kraj je provedeno pomoću programskog modula (engl. state sequencer). Strujne i naponske vrijednosti dobivene su simulacijom u CAPE programskoj podršci i korištene su za ispitivanje pojedinih releja, ovisno o lokaciji na kojoj su postavljeni. Svaka ispitna sekvenca sastojala se od vrijednosti prije, za vrijeme i poslije kvara. Podešenja za uvjete prije kvara su bila ista za sve releje. Struja prije kvara na lokaciji stupa 49 iznosila je 300 A, što je uobičajeno opterećenje dalekovoda. Stanje za vrijeme kvara dobiveno je iz CAPE programske podrške. Slika 7 pokazuje valne oblike definiranih sekvenci, na mjestu mjerenja, za vrijeme jednopolnog kratkog spoja.

5.2 Definition of the study (location and faults)

The CAPE programme was used for simulation of faults at the location of tower 49 from the Plomin TPP towards the junction point at 49,46 % of length of the transmission line (16,234 kV) as described in Chapter 4. Simulated faults were one-pole (L1-E) and two-pole (L1-L2). In such a way the protection was tested for one-pole short circuits between phase and ground and for two-pole short-circuits.

5.3 Definition of sequences

End-to-end study was performed by virtue of the state sequencer programme modulus. Current and voltage values were obtained by virtue of simulation in the CAPE programme support and used for the study of certain relays, depending on their location. Each trial sequence consisted of the value before, during and after the fault. Settings for the pre-fault conditions were equal for both relays. The pre-fault current at the location of tower 49 amounted to 300 A which is usual for the power-transmission line loading. The state during the fault was obtained from the CAPE programme support. Figure 7 shows the wave forms of the defined sequences at the location of the measurement and at the moment of the one-pole short-circuit.



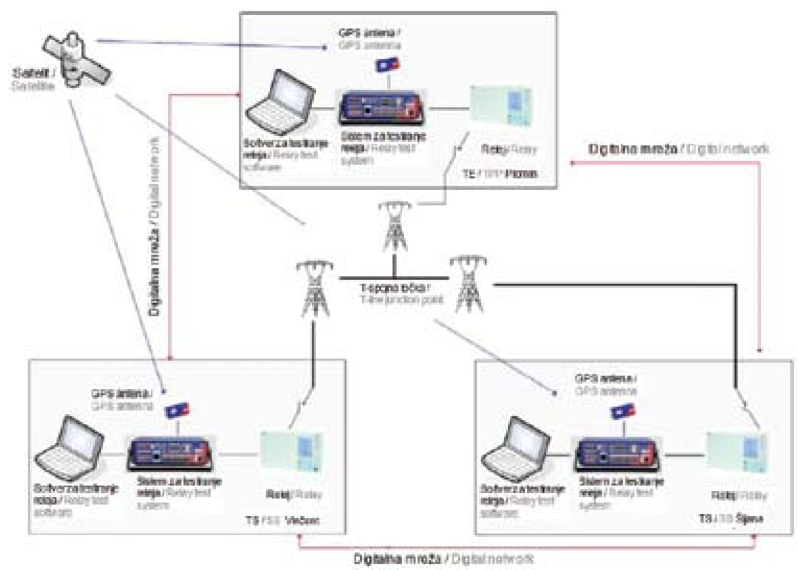
Slika 7 — Vrijednosti struja za ispitivanje s kraja na kraj po sekvencama za jednopolni kratki spoj (L1-E) na stupu 49
Figure 7 — Values of the currents for the end-to-end trial according to the sequences for a one-pole short circuit (L1-E) on tower 49

5.4 Priprema i početak ispitivanja

Tri ispitna uređaja za sekundarna ispitivanja vremenski su međusobno sinkronizirana putem GPS sustava (slika 8). Pripremljeni testovi injektiraju se u releje kada GPS modul ispitnog uređaja primi satelitski signal. Na taj način sva tri uređaja započinju testiranje u isto vrijeme.

5.4 Preparation and beginning of the study

Three testing devices for secondary trials were temporally inter-synchronized by virtue of the GPS system (Figure 8). The prepared tests were injected into the relays when the testing device GPS modulus received the satellite signal. In such a way, all three devices initiated the test at the same time.



Slika 8 — Konfiguracija sustava za ispitivanje s kraja na kraj
Figure 8 — Configuration of the end-to-end trial system

Procedura ispitivanja bila je definirana na sljedeći način:

— instrumenti za testiranje se podešavaju s GPS sinkroniziranim vremenom,
— na računalu se pokreće simulacijski program i spaja se na opremu,
— inženjeri na oba kraja voda komuniciraju i odabiru odgovarajuće ispitivanje, unose parametre potrebne za ispitivanje i započinju s ispitivanjem:

- fazorske vrijednosti napona i struja te vrijeme ispitivanja prenose se RS232 protokolom iz programske podrške na računalu u ispitnu opremu,
- vrijeme iz GPS prijamnika i vrijeme ispitivanja iz programa stalno se uspoređuju,
- kada je vrijeme u prijamniku identično vremenu ispitivanja, tada se istodobno pokreće testiranje na svakom kraju voda.

Releji su bili testirani simulacijskim signalom prilikom čega vod nije bio u pogonu. Provedeni su testovi za jednopolni (L1-E) i dvopolni (L1-L2) kvar bez djelovanja na prekidač i za jednopolni kvar (L1-E) s djelovanjem na prekidač.

5.5 Rezultati ispitivanja

Analiza djelovanja releja provedena je na temelju zapisa numeričkih releja. Rezolucija snimanja je 0,5 ms za relej u TE Plomin i TS Vinčent, te 1 ms za relej u TS Šijana. Relej u TE Plomin detektirao je kvar u zoni $1(Z_1)$, a releji u TS Vinčent i TS Šija-

The trial procedure is defined as follows:

— testing instruments are set with GPS-synchronized time,
— the simulation programme is launched on the computer and connected to the equipment,
— engineers at both ends of the transmission lines communicate and choose the adequate trial, introduce parameters necessary for the trial and begin with the trial:

- phasor voltage and current values and the trial time are transmitted by the RS232 protocol from the programme support in the computer into the testing equipment,
- the time from the GPS receiver and the trial time from the programme are constantly compared,
- when the time in the receiver is equal to the trial time, then the testing is simultaneously launched at each end of the power line.

The relays were tested by simulation signal whereat the transmission line was out of operation. Tests were performed for the one-pole (L1-E) and two-pole (L1-L2) fault without effect on the breaker and for the one-pole fault with effect on the breaker.

5.5 Results of the trial

The analysis of the relay effect was undertaken based on the numerical relays records. The recording resolution is 0,5 ms for the relay at the Plomin TPP and Vinčent substation, and 1 ms for the Šijana substation relay. The relay at the Plomin TPP na u zoni $2(Z_2)$. Relej u TE Plomin djelovao je bez vremenskog zatezanja, a preostala dva releja djelovala su nakon primitka signala za ubrzanje djelovanja (bez ubrzanog djelovanja imali bi vremensko zatezanje od 500 ms). Nakon analize zapisa numeričkih releja može se zaključiti sljedeće:

— relej u TE Plomin izdaje nalog za isklop 24 ms nakon nastanka kvara,
— na osnovi injektiranih sekundarnih veličina relej je izračunao da je kvar nastao 15,7 km odnosno na 47,5 % dužine štićenog voda za kvar L1-E, a za kvar L1-L2 na 16,4 km odnosno 49,6 %,
— relej u TE Plomin izdaje nalog za slanje signala za ubrzanje djelovanja 24 ms nakon nastanka kvara,
— relej u TS Šijana prima signal 48 ms nakon nastanka kvara i izdaje nalog za isklop prekidača. Vrijeme prijenosa signala je 24 ms,
— relej u TS Vinčent prima signal 5 ms nakon nastanka kvara i izdaje nalog za isklop prekidača. Vrijeme prijenosa signala je 31 ms.

Prema analizi sustav zaštite i telekomunikacija za prijenos signala djelovali su zadovoljavajuće, te se zaključilo da se može pristupiti primarnim pokusima.

6 STVARNI DVOPOLNI KRATKI SPOJ NA T SPOJU

Nekoliko dana nakon sekundarnih ispitivanja s kraja na kraj grmljavinsko nevrijeme uzrokovalo je dvopolni kvar (L1-L2). Sustav zaštite i telekomunikacija nije djelovao ispravno. Lokacija kvara bila je takva da je relej u TE Plomin detektirao kvar u zoni 1 te je nakon 24 ms izdao nalog za isklop vlastitog prekidača i nalog za slanje signala za ubrzanje djelovanja prema preostala dva releja. Ostali releji detektirali su kvar u zoni pobude te su primili signal za ubrzano djelovanje.

Na osnovi zapisa iz numeričkog releja provedena je analiza. Relej u TS Šijana primio je signal 318 ms nakon nastanka kvara, a relej u TS Vinčent 428 ms. Prijenos signala u ovom slučaju trajao je 294 ms do TS Šijana, odnosno 404 ms do TS Vinčent. Kašnjenje u prijenosu signala uzrokovalo je definitivni isklop voda u TS Šijana i TS Vinčent. Na slici 9 prikazani su analogni i digitalni signali iz releja u TE Plomin i TS Vinčent.

detected a fault in zone $1(Z_1)$ and the relays of the Vinčent and Šijana substations in zone $2(Z_2)$. The relay at the Plomin TPP acted without a delay in time, and the other two relays acted after the receipt of the signal for accelerating the effect (without accelerated functioning, there would have occurred a delay in time of 500 ms). After the analysis of the records of the numerical relays, the following conclusion can be made:

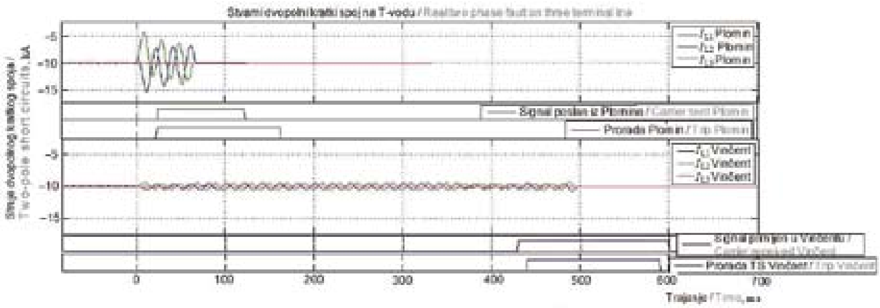
— the Plomin TPP relay issues the order for switch-off 24 ms after the occurrence of the fault,
— based on the injected secondary dimensions, the relay calculated that the fault occurred at 15,7 km that is, 47,5 % of the length of the protected transmission line for the L1-E fault, and for the L1-L2 fault at 16,4 km, that is 49,6 %,
— the Plomin TPP relay issues the order for sending the signal for accelerated effect 24 ms after the occurrence of the fault,
— the Šijana substation receives the signal 48 ms after the occurrence of the fault, Signal transmission time is 24 ms,
— the Vinčent substation receives the signal 5 ms after the occurrence of the fault and issues the order for switch-off of the breaker. Signal transmission time is 31 ms.

According to the analysis, the protection and telecommunication system for signal transmission acted satisfactorily and the conclusion was that primary trials can be started.

6 REAL TWO-POLE SHORT CIRCUIT AT THE T-JUNCTION

A few days after the secondary end-to-end trials, stormy weather conditions caused a two-pole fault (L1-L2). The protection and telecommunications system did not work properly. The location of the fault was such that the relay at the Plomin TPP detected a fault in zone 1 and after 24 ms issued an order for switch-off of its own breaker and an order for sending the signal for accelerated effect towards the other two relays. The other relays detected a fault in the actuation zone and received a signal for accelerated effect.

Based on the records from the numerical relay, an analysis was performed. The Šijana substation relay received a signal 318 ms and the Vinčent substation 428 ms after the occurrence of the fault. The signal transmission in this case took 294 ms to the Šijana substation, that is, 404 ms to the Vinčent substation. The delay in signal transmission caused a definite switch-off of the transmission line at the Šijana and Vinčent substations. Figure 9 shows analogous and digital signals from the relay at the Plomin TPP and the Vinčent substation.



Slika 9 — Podaci iz releja za dvopolni kratki spoj na stupu 49 T voda
Figure 9 — Data from the relay for the two-pole short circuit on pole 49 of the T-line

Nakon analize djelovanja sustava zaštite zaključeno je sljedeće:

— snaga analognog signala kojeg komunikacijski uređaji razmjenjuju radi nadzora veze podešena je na 12 dB. Podešena vrijednost može varirati ±1 dB,
— drugi komunikacijski uređaj pretvara taj signal u digitalni i šalje ga prema drugom kraju voda,
— snaga analognog signala koji se šalje kao kriterij za ubrzanje djelovanja podešena je na 5 dB,
— dozvoljena snaga signala koji se pretvara iz analognog u digitalni je 4 dB. Signal koji prijeđe podešenu vrijednost postaje izobličen,
— na osnovi zapisa iz numeričkih releja vidljivo je da je prijenos signala obavljen s velikim kašnjenjem,
— analiza je pokazala da je signal za ubrzanje (podešene snage 5 dB) prešao podešeni limit od 4 dB, te je na taj način postao izobličen. Pojačanje signala moglo je nastati zbog povećanja potencijala, različitih rezonancija, itd.,
— takav izobličeni signal pretvoren je u digitalni i putem digitalne mreže poslan prema ostalim relejima,
— temeljem iskustva može se zaključiti da takav signal nije imao zadovoljavajući format,
— pretvaranje takvog digitalnog signala u analogni uzrokovalo je kašnjenje u prijenosu signala.

Sukladno zaključcima analize podešeni su parametri komunikacijskog sustava kako slijedi:

— snaga signala za provjeru veze između konvertera je bila podešena na 6 dB,
— snaga signala za ubrzanje djelovanja ostala je 5 dB,
— dozvoljena snaga signala koji se pretvara iz analognog u digitalni podešena je na 0 dB.

After the analysis of the protection system effect, the following conclusion was made:

— the power of the analogous signal exchanged by the communication devices for the purpose of supervision of the connection is set at 12 dB. The set value can vary by ±1 dB,
— the other communication device turns that signal into a digital signal and sends it to the other end of the line,
— the power of the analogous signal sent as a criterion for accelerated effect, is set at 5 dB,
— the allowed power of the signal which changes from analogous to digital is 4 dB. The signal which exceeds the set value becomes deformed,
— based on the records from the numerical relays, it is evident that the transmission of the signal happened with a significant delay,
— analysis has shown that the signal for acceleration (power set at 5 dB) exceeded the set limit of 4 dB and thus became deformed. Strengthening the signal could have occurred due to increased potential, different resonances, etc.
— such a deformed signal was transformed into a digital signal and sent through the digital network to the other relays,
— experience points to the conclusion that such a signal was of unsatisfactory format,
— transformation of such a digital signal into an analogous signal caused the delay in the transmission of the signal.

According to the conclusions of the analyses, the parameters of the communication system were set as follows:

— the power of the signal for checking the connection between the converter was set at 6 dB,
— the power of the signal for accelerated effect remained at 5 dB,
— the allowed power of the signal which transforms from analogous to digital is set at 0 dB.

Neuspjeli otklon kvara za vrijeme dok je vod bio u pogonu pokazao je potrebu primarnog ispitivanja.

Unsuccessful fault removal while the transmission lines were operative, pointed to the need for primary trial.

7 PRIMARNO ISPITIVANJE

Nakon promjene parametara u komunikacijskom sustavu pristupilo se provedbi primarnih pokusa. Primarni pokusi provedeni su na stupu 49 na odvojku od TE Plomin do točke čvorišta (49,46 %, 16,234 km). Zbog rasporeda vodiča na stupu, slika 10, provedeni su pokusi L1-E i L1-L2.

7 PRIMARY TRIAL

After the change of the parameters in the communication system, the performance of primary trials was initiated. Primary trials were performed on tower number 49 on the extension from the Plomin thermal power plant to the hub point (49,46 %, 16,234 km). Because of the arrangement of the conductors on the tower, Figure 10, tests L1-E and L1-L2 were performed.

Slika 10 — Raspored vodiča na 49-om stupu
Figure 10 — Arrangement of the conductors on the 49th tower

Prije provedbe pokusa vod je bio izvan pogona, bakrena žica presjeka 1 m^2 pričvršćena je za fazu L2 i odmaknuta od voda izolatorskom trakom. Nakon toga vod se uključuje, izolatorska traka se presijeca i žica pada na konzolu stupa, što uzrokuje jednopolni kratki spoj između L1-E.

Na isti način provedena je priprema za dvopolni kvar, samo što je žica pričvršćena za fazu L1 te presijecanje izolatorske trake pada na fazu L2, što uzrokuje kvar (L1-L2).

7.1 Analiza jednopolnog kratkog spoja (L1-E)

Na temelju zapisa iz numeričkih releja, na slici 11 prikazane su analogne veličine i digitalni signali zabilježeni tijekom kvara L1-E. Referentne točke za vremensku analizu su početak i prestanak kvara:

— relej u TE Plomin izdaje nalog za isklop prekidača 28 ms nakon nastanka kvara, struja kvara nestaje nakon 63 ms,
— relej je izmjerio lokaciju do mjesta kvara 51,1 %, odnosno 16,9 km,
— pogreška u određivanju lokacije je +2,04 %,

Before the performance of the tests the power line was out of operation, the copper wire with the intersection of 1 m^2 was attached to L2 phase and detached from the power line by isolation tape. After that the transmission line is switched on, the isolation tape is cut and the wire falls on the tower console and this causes a short circuit between L1-E.

The preparation for the two-pole fault was performed in the same manner, but the wire was attached to L1 phase and the cutting of the isolation tape fell onto L2 phase which caused the fault (L1-L2).

7.1 Analysis of the one-pole short-circuit (L1-E)

Based on the records from the numerical relays, Figure 11 shows analogous dimensions and digital signals recorded during the L1-E fault. The reference points for temporal analysis are the beginning and the end of the fault:

— the Plomin TPP relay issues the order for breaker switch-off 28 ms after the occurrence of the fault, and the fault current occurs after 63 ms,
— the relay measured the distance to the fault location of 51,1 %, that is, 16,9 km,

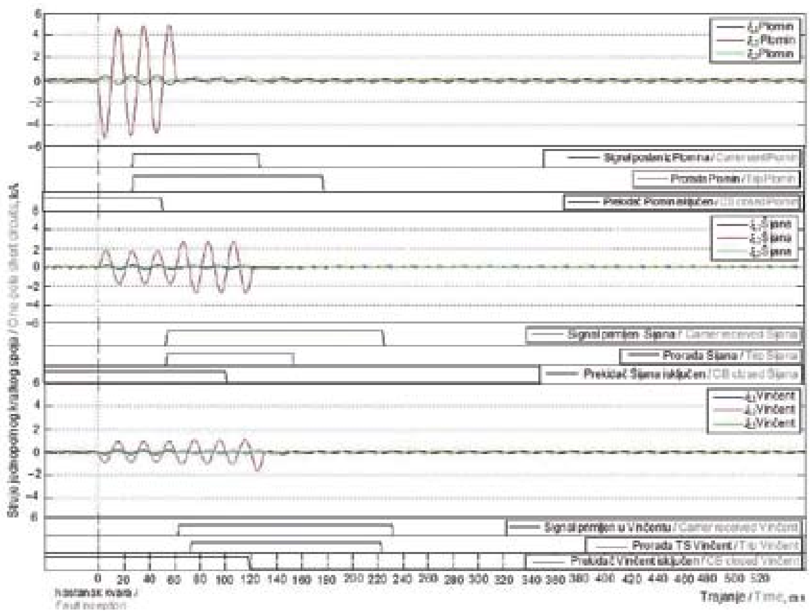
odnosno 0,67 km,

— relej u TS Šijana detektirao je kvar u zoni $2(Z_2)$, primio signal za ubrzanje djelovanja 54 ms nakon nastanka kvara te nakon toga izdao nalog za isključenje. Prijenos signala trajao je 26 ms. Struja kvara nestaje nakon 122 ms,
— relej u TS Vinčent detektirao je kvar u zoni $2(Z_2)$, primio je signal za ubrzanje 65 ms nakon nastanka kvara te nakon toga izdao nalog za isključenja. Prijenos signala trajalo je 37 ms. Struja kvara prestaje nakon 133 ms,
— 65 ms nakon nastanka kvara struja se povećava u TS Šijana i TS Vinčent. Razlog povećanja je isključenje prekidača u TE Plomin pa se kvar napaja iz preostala dva kraja voda,
— 122 ms nakon nastanka kvara struja se povećava u TS Vinčent kao posljedica isključenja prekidača u TS Šijana. Kvar se napaja samo iz TS Vinčent,
— struja kvara potpuno nestaje 133 ms nakon isključenja prekidača u TS Vinčent,što je 70 ms nakon nestanka struje kvara u TE Plomin. Svi releji odradili su uspješno automatski ponovni uklop.

Trenutak uklopa prekidača nakon beznaponske pauze nije prikazan (beznaponska pauza podešena na 1,2 s), jer bi slika bila nepregledna.

— the error in location determination is +2,04 %, that is, 0,67 km,
— the Šijana substation relay detected a fault in zone $2(Z_2)$, received the signal for accelerated effect 54 ms after the occurrence of the fault, and after that issued the switch-off order. Duration of signal transmission was 26 ms. Fault current disappeared after 122 ms,
— the Vinčent substation relay detected a fault in zone $2(Z_2)$, received the signal for accelerated effect 65 ms after the occurrence of the fault, and after that issued the switch-off order. Duration of signal transmission was 37 ms. Fault current ends after 133 ms,
— 65 ms after the occurrence of the fault, the current increases at the Šijana and Vinčent substations. The reason for the increase is the switch-off of the Plomin TPP breaker so that the fault is charged from the other two line ends,
— 122 ms after the occurrence of the fault, the current increases at the Vinčent substation as a consequence of the switch-off of the breaker at the Šijana substation. The fault is charged only from the Vinčent substation.
— the fault current completely disappears 133 ms after the switch-off of the breaker at the Vinčent substation, and that is 70 ms after the disappearance of the fault current at the Plomin TPP. All the relays successfully performed automatic re-switch-on.

The moment of breaker switch-on after the voltage-free pause is not shown (voltage-free pause set at 1,2 s) because then the image could not be easily surveyed.



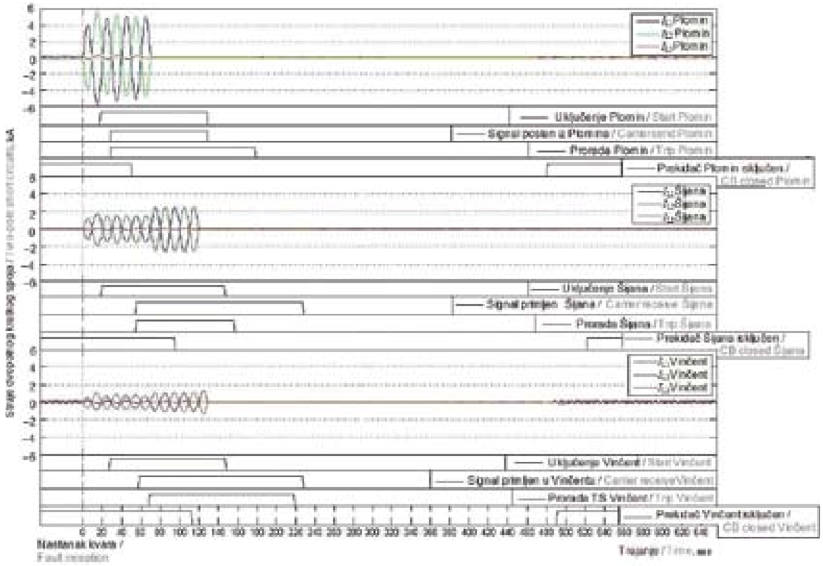
Slika 11 — Analogne i digitalne vrijednosti za vrijeme ispitivanja pomoću jednopolnog kratkog spoja (L1-E)
Figure 11 — Analogous and digital values during the trial by virtue of the one-pole short circuit (L1-E)

7.2 Analiza dvopolnog kratkog spoja L1-L2

Na temelju zapisa iz numeričkih releja na slici 12 prikazane su analogne veličine i digitalni signali zabilježeni tijekom kvara L1-L2. Slika 13 prikazuje paljenje luka za vrijeme kvara.

7.2 Analysis of the two-pole short-circuit L1-L2

Based on the records from the numerical relays, Figure 12 shows analogous values and digital signals recorded during the L1-L2. Figure 13 shows the ignition of the arch during the fault.



Slika 12 — Analogne i digitalne vrijednosti za vrijeme ispitivanja kod dvopolnog kratkog spoja (L1-L2)
Figure 12 — Analogous and digital values for the duration of the trial at a two-pole short circuit (L1-L2)

Slika 12 — Luk za vrijeme dvopolnog kratkog spoja (L1-L2) za vrijeme ispitivanja
Figure 12 — The arch during the two-pole short circuit (L1-L2) during the trial

Referentne točke za vremensku analizu su početak i prestanak kvara:

- relej u TE Plomin izdaje nalog za iskop prekidača 28 ms nakon nastanka kvara, struja kvara nestaje nakon 71 ms,
- relej je izmjerio lokaciju do mjesta kvara 47 %, odnosno 15,5 km,
- pogreška u određivanju lokacije je – 2,46 %, odnosno – 0,734 %,
- relej u TS Šijana detektirao je kvar u zoni 2(Z_2), primio je signal za ubrzanje djelovanja 54 ms nakon nastanka kvara, te nakon toga

The reference points for temporal analysis are the beginning and the end of the fault.

- the Plomin TPP relay issues the order for breaker switch-off 28 ms after the occurrence of the fault, and the fault current disappears after 71 ms,
- the relay measured the distance to the fault location at 47 %, that is, 15,5 km,
- the error in location determination is – 2,46 %-, that is, – 0,734 %,
- the Šijana substation relay detected a fault in zone 2(Z_2), received the signal for accelerated

izdao nalog za isključenje. Prijenos signala trajao je 26 ms. Struja kvara nestaje nakon 120 ms,

— relej u TS Vinčent detektirao je kvar u zoni $2(Z_2)$, primio je signal za ubrzanje 59 ms nakon nastanka kvara, te nakon toga izdao nalog za isključenja. Prijenos signala trajalo je 31 ms. Struja kvara prestaje nakon 130 ms,
— struja kvara potpuno nestaje 130 ms nakon isključenja prekidača u TS Vinčent, što je 59 ms nakon nestanka struje kvara u TE Plomin,
— relej u TE Plomin izdaje nalog za uklop prekidača 321 ms nakon nastanka kvara. Na temelju zapisa numeričkih releja prekidač je ponovno uključen 382 ms nakon nastanka kvara,
— relej u TS Šijana izdaje nalog za uklop prekidača 392 ms nakon nastanka kvara. Na temelju zapisa numeričkog releja prekidač je ponovno uključen 522 ms nakon nastanka kvara,
— relej u TS Vinčent izdaje nalog za ponovni uklop prekidača 378 ms nakon nastanka kvara. Na temelju zapisa numeričkog releja prekidač je ponovno uključen 490 ms nakon nastanka kvara,
— svi releji su ispravno odradili ciklus tropolnog automatskog ponovnog uklopa.

8 ANALIZA REZULTATA

Rezultati primarnih pokusa također su iskorišteni i za provjeru točnosti modela mreže pomoću CAPE sustava za zapadni dio EES-a Hrvatske. Simulirani kvarovi u mreži su iskorišteni za definiranje sekvenci end to end testiranja. Releji su se ponašali kako je i bilo predviđeno u simulaciji. Nakon primarnih ispitivanja zapisi iz releja su bili od velike koristi za određivanje točnosti modela budući da je topologija mreže i lokacija kvara poznata. Analiza rezultata je pokazala da su razlike između vrijednosti dobivenih simulacijom i onih koje su dobivene iz releja u zadovoljavajućim granicama. Valja napomenuti da je struja prije kvara podešena na vrijednost nula s obzirom da CAPE program ne podržava proračun tokova snaga. Osim toga, algoritam korišten za COMTRADE [5] ne podržava upravljanje prekidačem pa stoga simulirane struje kvara nisu mogle biti zaustavljene.

8.1 Usporedba rezultata za jednopolni kratki spoj (L1-E)

Usporedba rezultata dobivenih simulacijom za jednopolni kvar (L1-E) sa stvarnim rezultatima dobivenim iz zapisa releja prikazana je u tablici 4, a grafički na slici 14. Grafički prikaz simulacije je dobiven algoritmom iz CAPE programske podrš-

effect 54 ms after the occurrence of the fault, and after that issued the switch-off order. Duration of signal transmission was 26 ms. Fault current disappeared after 120 ms,

— the Vinčent substation relay detected a fault in zone $2(Z_2)$, received the signal for acceleration 59 ms after the occurrence of the fault, and after that issued the switch-off order. Duration of signal transmission was 31 ms. Fault current ended after 130 ms,
— the fault current completely disappears 130 ms after the switch-off of the breaker at the Vinčent substation, and that is 59 ms after the disappearance of the fault current at the Plomin TPP.
— the Plomin TPP relay issues the order for switch-on 321 ms after the occurrence of the fault, Based on the records of numerical relays, the breaker was switched on again 382 ms after the occurrence of the fault,
— the Šijana substation relay issues the order for breaker switch-on 392 ms after the occurrence of the fault, Based on the records of numerical relays, the breaker was switched on again 522 ms after the occurrence of the fault,
— the Vinčent substation relay issues the order for breaker re-switch-on 378 ms after the occurrence of the fault, Based on the records of numerical relays, the breaker was switched on again 490 ms after the occurrence of the fault,
— All the relays properly performed the three-pole automatic re-switch-on cycle.

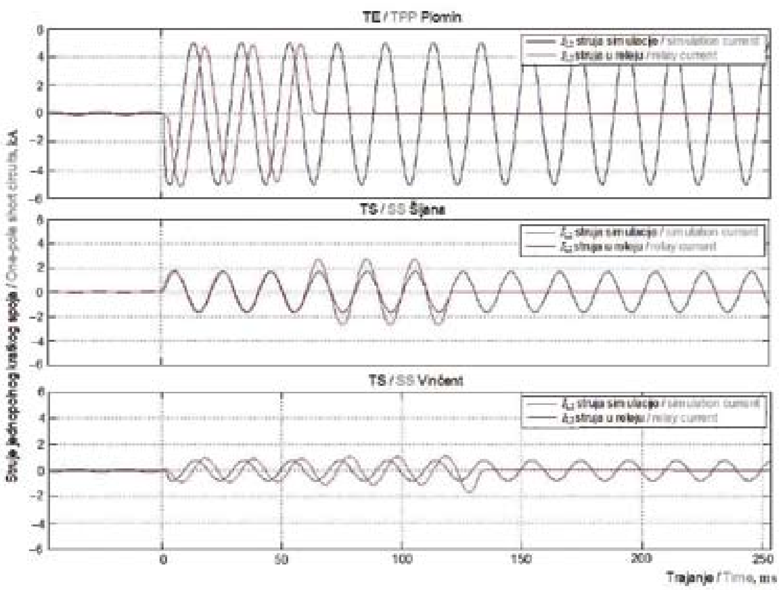
8 RESULT ANALYSIS

The results of primary trials were also used for the verification of the accuracy of the network model by virtue of the CAPE system for the western part of the Croatian electrical power system. Simulated faults in the network were used for defining the sequences of the end-to-end trial. The relays acted as was predicted in the simulation. After the primary trials, the relay records were highly helpful for the determination of the accuracy of the model as the topology of the network and the location of the fault were known. The analysis of the results showed that the differences between the values obtained by simulation and those obtained from the relays are within satisfactory limits. It needs to be pointed out that the current before the fault was set at zero considering the fact that the CAPE programme does not support the estimation of power flows. Besides that, the algorithm used for COMTRADE [5] did not support the operation of the breaker so the simulated current faults could not be stopped.

8.1 Comparison of results for the one-pole short circuit (L1-E)

The comparison of results obtained by virtue of simulation for the one-pole fault (L1-E) with real results obtained from the relay records is shown in Table 4 ke stvaranjem COMTRADE datoteka s kvarovima. Rezultati su zatim obrađeni u MATLAB-u i uspoređeni sa zapisima iz releja.

and graphically in Figure 14. The graphic presentation of the simulation was obtained by virtue of the algorithm from the CAPE programme support by creating the COMTRADE fault files. Results were then analysed in MATLAB and compared with the relay records.



Slika 14 — Usporedba struja izmjerenih u releju i simulaciji za vrijeme jednopolnog kratkog spoja (L1-N)
Figure 14 — Comparison of currents measured in the relay and in the simulation during the one-pole short circuit (L1-N)

Razlike između vrijednosti dobivenih simulacijom i stvarnih vrijednosti su zadovoljavajuće za TE Plomin i TS Šijanu, dok je najveće odstupanje za TS Vinčent, 21 %.

The differences between the values obtained by simulation and the real values are satisfactory for the Plomin TPP and the Šijana substation while the greatest deviation occurred for the Vinčent substation, 21 %.

Tablica 4 – Usporedba rezultata za jednopolni kratki spoj (L1-E) za fazu u kvaru
Table 4 – Comparison of results for the one-pole short circuit (L1-E) for the phase at fault

		Zapis iz releja / Relay records		CAPE simulacija / CAPE simulation		Razlika / Difference , %
		Iznos / Value	Kut / Angle, °	Iznos / Value	Kut / Angle, °	
Plomin	I_{L1}	3,45 kA	102,8	3,59 kA	158,4	4,0
	V_{L1}	63,5 kV	67,2	59,7 kV	–60.0	5,9
Šijana	I_{L1}	1,24 kA	–44,4	1,35 kA	162,0	8,8
	V_{L1}	32,9 kV	24,8	32,3 kV	–120,0	1,8
Vinčent	I_{L1}	0,71 kA	–14,67	0,56 kA	163,0	21,0
	V_{L1}	36,9 kV	–74,8	32,2 kV	119,2	12,7

Na slici 14 valja obratiti pozornost na povećanje struje releja. To se javlja iz razloga upravljanja prekidačem u TE Plomin i promjene toka struje u mreži [6]. Slično kao i u slučaju usporedbe TS Šijana, za relej u TS Vinčent struja ima jednu vrijednost u trenutku nastanka kvara i ta vrijednost raste kada relej u Plominu proradi. Konačni porast struje nastaje zbog prorade releja u TS Šijana.

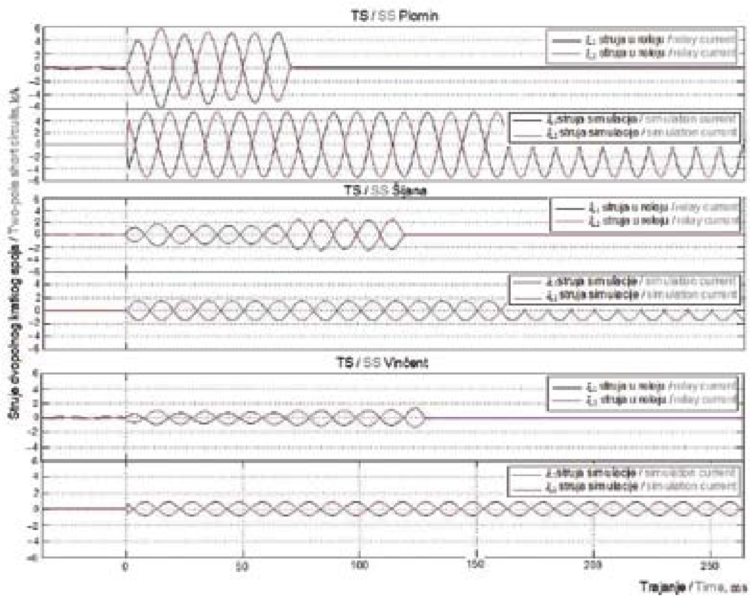
As regards Figure 14, attention should be paid to the increased relay current. That happens because of the operation of the breaker at the Plomin TPP and because of the change of the current flow in the network [6]. Similarly to the case of comparison for the Šijana substation, the current for the Vinčent substation relay is at a certain value at the moment of fault occurrence and that value increases when the relay in Plomin trips. The final current increase occurs due to the Šijana relay trip.

8.2 Usporedba rezultata za dvopolni kratki spoj (L1-L2)

Usporedba rezultata dobivenih simulacijom za dvopolni kvar (L1-L2) sa stvarnim rezultatima dobivenim iz zapisa releja prikazana je u tablici 5 i grafički na slici 15. Grafički prikaz simulacije je dobiven algoritmom iz CAPE programske podrške stvaranjem COMTRADE datoteka sa kvarovima. Rezultati su zatim obrađeni u MATLAB-u i uspoređeni sa zapisima iz releja.

8.2 Comparison of results for the two-pole short circuit (L1-L2)

The comparison of results obtained by virtue of simulation for the two-pole fault (L1-L2) with real results obtained from the relay records is shown in Table 5 and graphically in Figure 15. The graphic presentation of the simulation was obtained by virtue of the algorithm from the CAPE programme support by creating the COMTRADE fault files. Results were then analysed in MATLAB and compared with the relay records.



Slika 15 — Usporedba struja izmjerenih u releju i simulaciji za vrijeme dvopolnog kratkog spoja (L1-L2)
Figure 15 — Comparison of currents measured in the relay and in the simulation during the two-pole short circuit (L1-L2)

Razlike za dvopolni kratki spoj nešto su veće, ali još uvijek zadovoljavaju kriterije točnosti modela. Najveća razlika se javlja kod releja u TS Šijana, i iznosi 19,2 %. Najveća naponska razlika je kod releja u TS Vinčent i iznosi 12 %.

Na temelju rezultata dobivenih analizom nakon provedenih primarnih pokusa može se zaključiti da releji proračuju u skladu sa zahtjevima pogona elektroenergetskog sustava [7] i [8]. Točnost modela je zadovoljavajuća pa se podaci dobiveni simulacijama kvarova mogu koristiti prilikom određivanja podešenja za pojedine releje.

The differences for the two-pole short circuit are somewhat greater but still satisfy the criteria of model accuracy. The greatest difference occurs at the relays in the Šijana substation and it amounts to 19,2 %. The greatest voltage difference occurs at the relays at the Vinčent substation and it amounts to 12 %.

Based on the results obtained by the analysis after the performance of primary trials, the conclusion can be drawn that the relays trip in accordance with the requests of the electrical power system drives [7] and [8]. The accuracy of the model is satisfactory because the data obtained by simulation of faults can be used when determining the settings for certain relays.

9 ZAKLJUČAK

Pokazano je da sekundarno testiranje releja ponekad nije dovoljno da se dobije uvid u funkcionalnost sustava zaštite. Provedenim ispitivanjem s kraja na kraj zaključeno je da sustav zaštite djeluje ispravno.

9 CONCLUSION

The presented secondary testing of the relays is sometimes not sufficient for gaining an insight into the functionality of the protection system. The performed end-to-end trial gives rise to the conclusion that the protection system works properly.

Tablica 5 – Usporedba rezultata za dvopolni kratki spoj (L1-L2) za fazu u kvaru
Table 5 – Comparison of results for the two-pole short circuit (L1-L2) for the phase at fault

		Zapis iz releja / Relay records		CAPE simulacija / CAPE simulation		Razlika / Difference, %
		Iznos / Value	Kut / Angle, °	Iznos / Value	Kut / Angle, °	
Plomin	I_{L1}	3,88 kA	–30,4	3,47 kA	–51,9	10,5
	I_{L2}	3,75 kA	150,4	3,47 kA	128,1	7,3
	V_{L1}	42,0 kV	–10,7	39,6 kV	–22,8	5,6
	V_{L2}	41,6 kV	–83,3	40,0 kV	–96,8	3,8
Šijana	I_{L1}	1,04 kA	166,5	1,24 kA	–47,0	19,2
	I_{L2}	1,08 kA	–15,7	1,24 kA	132,0	14,8
	V_{L1}	37,2 kV	172,0	36,7 kV	–164,0	1,3
	V_{L2}	35,8 kV	119,4	38,1 kV	–89,1	6,4
Vinčent	I_{L1}	0,52 kA	158,3	0,55 kA	–47,0	7,1
	I_{L2}	0,61 kA	–25,2	0,55 kA	133,0	5,3
	V_{L1}	37,5 kV	166,8	33,0 kV	–29,2	12,0
	V_{L2}	36,5 kV	109,7	39,3 kV	–89,6	7,8

Nakon predpodešenja parametara komunikacijskog sustava provedbom primarnih pokusa ispitano je djelovanje releja u okruženju u kojem oni moraju raditi prilikom pojave kvara na štićenom objektu.

Naknadnom analizom zaključeno je da su releji i sustav komunikacije ispravno djelovali. Unatoč korištenju dva komunikacijska pretvornika i digitalne mreže kao medija za prijenos signala za djelovanje zaštite, kašnjenje u prijenosu signala je bilo manje od 40 ms.
Nesinkronizirani isklopi i uklopi prekidača nisu uzrokovali nestabilnosti unutar elektroenergetskog sustava, što navodi na zaključak da ovakav sustav zaštite udovoljava kriterijima sigurnog pogona.

Usporedbom analognih vrijednosti struja i napona dobivenih simulacijom pomoću CAPE programske podrške i vrijednosti koje je zabilježio relej tijekom primarnog testiranja na 49-om stupu pokazuju da je matematički model elektroenergetske mreže na kojoj je izvedena simulacija dobro dizajniran. Razlike u vrijednostima su u prihvatljivim granicama od 3,8 % do 10,5 % za TE Plomin, 1,3 % do 19 % za TS Šijana i 5,3 % do 21 % za TS Vinčent. Zaključak je da su ulazni podaci za sekundarno ispitivanje bili dobri.

Sekundarno ispitivanje na vodu Plomin – Šijana – Vinčent je pokazalo da takvi testovi ponekada nisu dovoljni kako bi se dobili relevantni podaci pomoću kojih se može jamčiti puna zaštita štićenog objekta. Ispitivanje provedeno sekundarnim injektiranjem analognih vrijednosti (ispitivanje s kraja na kraj) pokazalo je da sustav radi ispravno, ali tijekom pravog kvara pokazalo se da ipak nije

After the pre-setting of the parameters of the communication system by performing primary trials, the functioning of the relays in an environment in which these must operate at the instance of occurrence of a fault in the protected facility was tested.

Subsequent analysis resulted in the conclusion that the relays and the communication system worked properly. Although two communication converters and the digital network as the medium for the transmission of the signal for the protection functioning were used, the delay in signal transmission was less than 40 ms.
Unsynchronised breaker switch-offs and switch-ons did not cause instabilities within the electrical power system which gives rise to the conclusion that such a protection system meets safe operation criteria.

The comparison of analogous values of currents and voltages obtained by simulation by virtue of the CAPE programme support and the values recorded by the relay during the primary trial at the 49th tower, show that the mathematical model of the electrical power network, which was subjected to the simulation, was well designed. The differences in the values are within acceptable limits of 3,8 % up to 10,5 % for the Plomin TPP, 1,3 % up to 19 % for the Šijana substation, and 5,3 % do 21 % for the Vinčent substation. The conclusion is that input data for the secondary trial were right.

The secondary trial at the Plomin – Šijana – Vinčent transmission line showed that such tests are sometimes not sufficient to get relevant data which can guarantee full safety of the protected facility. The trials performed by secondary injection of analogous values (end-to-end trial) showed that the system works properly but during the real fault it was revealed that it is nevertheless not completely satispotpuno zadovoljavajuće, jer ulazne vrijednosti potrebne za ispitivanje (naponi i struje) nisu bile jednake vrijednostima koje su se javile tijekom pravog kvara.

Nakon predpodešenja parametara komunikacijskog sustava provedbom primarnih pokusa ispitano je djelovanje releja u okruženju u kojem oni moraju raditi prilikom pojave kvara na štićenom objektu.

Na promatranom vodu se nakon ispitivanja javilo nekoliko kvarova i zaštita je ispravno proradila u svakom slučaju.

Ovakav sustav zaštite najviše ovisi o dostupnosti i pouzdanosti telekomunikacijskog sustava pa valja napomenuti da se sustav zaštite u ovom slučaju ne može razmatrati neovisno od sustava komunikacije, već sve treba sagledavati kao jedinstvenu cjelinu.

factory because input values necessary for the trial (voltages and currents) were not equal to the values which occurred during the real fault.

After the pre-setting of the parameters of the communication system by implementing primary trials, the functioning of the relays in an environment in which these must operate at the instance of occurrence of a fault in the protected facility was tested.

After the trial, several faults occurred on the observed transmission line and the protection tripped properly at every instance.

This kind of protection system depends mostly on the availability and the reliability of the telecommunication system so it needs to be stressed that the protection system in this case cannot be observed separately from the communication system but that the entire issue needs to be observed as a unique whole.

LITERATURA / REFERENCES

[1] ALEXANDER, G.E., ANDRICHAK, J.G., Application of Phase and Ground Distance Relays to Three Terminal Lines, GE Protection and Control, Malvern, PA, GE – 3964
[2] CIGRE SC34 WG34/35.11, Protection Using Telecommunications, 2000
[3] CAPE Short Circuit Tutorial, Electrocon International, Inc., May 2000
[4] CAPE Coordination Graphics Tutorial, Electrocon International, Inc., April 2000
[5] IEEE Standard Common Format for Transient Data Exchange (COMTRADE), for Power Systems, IEEE C37.111-1999
[6] FRLAN,K., Analysis of Influence of Intermediate In-feeds and Fault Resistance Upon Distance Protection Functionality, Master Thesis, Faculty of Electrical Engineering and Computing, University of Zagreb, Zagreb, 2006
[7] FRLAN, K., RUBEŠA, R., MARUŠIĆ, A., Influence of New Over-head Power Lines on the Operation of the Relay Protection System, IEEE, Africon 2007, Windhoek, Namibia, 2007
[8] RUBEŠA, R., FRLAN, K., MARUŠIĆ, A., Influence of Fault Resistance on the Operation of Relay Protection Before and After the Construction of New Lines, European Power and Energy Systems, Europes 2007, August 2007, Palma de Mallorca, Spain

Adresa autora:

Mr. sc. **Kristijan Frlan**
kristijan.frlan@hep.hr
HEP Operater prijenosnog Sustava d.o.o.
M. Tita 166, 51410 Opatija, Hrvatska
Prof. dr. sc. **Ante Marušić**
ante.marusic@fer.hr
Dr. sc. **Juraj Havelka**
juraj.havelka@fer.hr
Sveučilište u Zagrebu
Fakultet elektrotehnike i računarstva
Unska 3, 10000 Zagreb, Hrvatska

Author's Adresses:

Kristijan Frlan, MSc
kristijan.frlan@hep.hr
HEP Operator prijenosnog sustava d.o.o.
M. Tita 166, 51410 Opatija, Croatia
Prof. **Ante Marušić**, PhD
ante.marusic@fer.hr
Juraj Havelka, PhD
juraj.havelka@fer.hr
University of Zagreb
Faculty of Electrical Engineering and Computing
Unska 3, 10000 Zagreb,Croatia

Uredništvo primilo rukopis:
2009-05-09

Prihvaćeno:
2009-06-02

Manuscript received on:
2009-05-09

Accepted on:
2009-06-02