PRENAPONSKA ZAŠTITA OBJEKATA SPOJENIH NA NADZEMNU NISKONAPONSKU MREŽU

SURGE PROTECTION OF BUILDINGS CONNECTED TO AN OVERHEAD LOW-VOLTAGE NETWORK

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U prenaponskoj zaštiti na niskom naponu postoje tri klase uređaja prenaponske zaštite. Predstavljena metoda izbora uređaja prenaponske zaštite može se koristiti pri donošenju odluke koje klase treba biti uređaj prenaponske zaštite koji se postavlja u priključni mjerni ormarić objekta. Metoda je testirana na jednoj tipičnoj nadzemnoj niskonaponskoj mreži u Hrvatskoj. S obzirom na dobro iskustvo s uređajima prenaponske zaštite klase II u transformatorskim stanicama u toj mreži, može se zaključiti da je uređaj prenaponske zaštite klase II sasvim primjeren i za objekte spojene na niskonaponsku mrežu.

There are three classes of surge protective devices for low-voltage systems. The method for the selection of surge protective devices presented can be used to determine which class of surge protective device should be installed in the service entrance of a building. This method has been tested on a typical overhead low-voltage network in Croatia. Based upon good experience with Class II surge protective devices in the transformer stations of this network, it can be concluded that Class II surge protective devices are quite suitable for buildings connected to a low-voltage network.

Ključne riječi: nadzemna niskonaponska mreža, štićeni objekt, UPZ klasa I, UPZ klasa II, uređaj prenaponske zaštite (UPZ), vjerojatnost energetskog preopterećenja
Key words: class I SPD, class II SPD, overhead low-voltage network, probability of energy overloading, protected building, surge protective device (SPD)

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1 UVOD

Vrlo skoro distributeri električne energije u Hrvatskoj počet će ugrađivati ili nuditi mogućnost ugradnje prenaponske zaštite u kućni priključni-mjerni ormarić (KPMO). Postavlja se pitanje kakav uređaj prenaponske zaštite (UPZ) treba ugraditi u KPMO. Prema [1] razlikuju se UPZ klase I, UPZ klase II i UPZ klase III. UPZ klase I ispituje se strujnim valovima 8/20 μs, 10/350 μs te naponskim valom 1,2/50 μs. UPZ klase II ispituje se strujnim valom 8/20 μs i naponskim valom 1,2/50 μs. UPZ klase III ispituje se kombiniranim valom 1,2/50 / 8/20 μs (otvoreni krug/kratki spoj generatora). Oko uvođenja strujnog vala 10/350 μs za ispitivanje UPZ-a klase I postoji nesuglasje u prvom redu između IEC norme 61643-1 [1] i IEEE C62.45 [2], a šire bi se moglo reći između stajališta znanstvenika i stručnjaka iz Europe i SAD-a. U SAD-u se na priključak objekta ugrađuje uređaj prenaponske zaštite klase II.

2 PRENAPONSKA ZAŠTITA I UREĐAJI PRENAPONSKE ZAŠTITE

U prenaponskoj zaštiti na niskom naponu (NN) UPZ klase I često se naziva odvodnik struje munje (njem. Blitzstrom Ableiter), a UPZ klase II odvodnik prenapona (njem. Überspannung Ableiter). Njemačka norma [3] dijeli odvodnike prema klasi zahtjevnosti na:

- odvodnike klase A (prema [1] UPZ klase II) koji se instaliraju u nadzemnu NN mrežu na mjesta koja su za opću populaciju nedostupna. Odvodnici klase A ispituju se strujnim valovima 8/20 μs, a prekondicioniraju istim valovima,
- odvodnike klase B (prema [1] UPZ klase I) koji se instaliraju u svrhu izjednačavanja potencijala na mjestima gdje je potrebno odvoditi dijelove struje munje. Odvodnici klase B ispituju se strujnim valovima, I_{imp}, valnog oblika 10/350 μs, a prekondicioniraju valovima 8/20 μs,
- odvodnike klase C (prema [1] UPZ klase II) koji se instaliraju u svrhu prenaponske zaštite u fiksnim instalacijama, npr. u NN razvod. Odvodnici klase C ispituju se strujnim valovima 8/20 μs, a prekondicioniraju istim valovima,
- odvodnike klase D (prema [1] UPZ klase III) koji se instaliraju u svrhu prenaponske zaštite u fiksnim ili priključenim instalacijama, ili prije krajnjeg uređaja. Postoje specijalne izvedbe ovih odvodnika u formi instalacijske utičnice.

1 INTRODUCTION

In the very near future, distributors of electrical energy in Croatia will begin to install or offer the option of installing surge protective devices in service entrances. It is necessary to determine the type of surge protective device (SPD) to be installed in a service entrance. According to [1] there are three types of SPDs: Class I, Class II and Class III. Class I SPDs are tested using 8/20 μs and 10/350 μs current waves and a 1,2/50 μs voltage wave. Class II SPDs are tested with an 8/20 μs current wave and a 1,2/50 μs voltage wave. Class III SPDs are tested with a 1,2/50 / 8/20 μs combination wave (open circuit/short circuit of the generator). Regarding the introduction of the 10/350 μs current wave for the testing of Class I SPDs, there are discrepancies between IEC 61643-1 [1] and IEEE C62.45 [2], and more generally it could be said between the positions of professionals from Europe and the USA. In the USA, Class II surge protective devices are installed in the service entrances of buildings.

2 SURGE PROTECTION AND SURGE PROTECTIVE DEVICES

In surge protection at low voltages, Class I SPDs are frequently called lightning current arresters (German: Blitzstrom Ableiter), and Class II SPDs are called surge arresters (German: Überspannung Ableiter). The German standard [3] classifies arresters according to the performance requirements:

- class A surge arresters (according to [1] Class II SPDs) that are installed in an overhead low-voltage network in a place inaccessible to the general population. Class A surge arresters are tested with 8/20 μs current waves, and preconditioned with the same waves,
- class B surge arresters (according to [1] Class I SPDs) that are installed for the purpose of potential equalizing in places where protection against lightning strokes are necessary. Class B surge arresters are tested with 10/350 μs current waves, I_{imp}, and preconditioned with 8/20 μs waves,
- class C surge arresters (according to [1] Class II SPDs) are installed for surge protection in fixed installations, e.g. in low-voltage distribution. Class C surge arresters are tested with 8/20 μs current waves, and preconditioned with the same waves,
- class D surge arresters (according to [1] Class III SPDs) are installed for surge protection in fixed or mobile/fixed installations, or before the

Odvodnici klase D ispituju se kombiniranim generatorom (efektivnog unutarnjeg otpora 2) koji u praznom hodu proizvodi naponski val 1,2/50 µs, a u kratkom spoju strujni val 8/20 µs. Odvodnici klase D također se prekondicioniraju kombiniranim valom. Kao ispitni parametar za ovaj odvodnik navodi se napon praznog hoda U_{oc} kombiniranog generatora.

UPZ na bazi MO (metal-oksidnog) varistora nije pogodan za ispitivanje strujnim valom duljeg trajanja, za razliku od UPZ-a na bazi iskrišta. Za objašnjenje, neka se usvoji strujni val 10/350 µs kao predstavnik dugog vala, a strujni val 8/20 µs kao predstavnik kratkog vala. Da bi se jasno predočila razlika između strujnih valova 10/350 µs i 8/20 µs, oba su vala prikazana na slici 1.

Pri prolasku strujnog vala 10/350 µs kroz MO odvodnik napon na njemu relativno je visok u usporedbi s iskrištem. Kada se integrira produkt trenutačne vrijednosti struje, napona i vremena, dobije se velika energija koju bi trebala apsorbirati MO pločica. MO pločica može apsorbirati ograničenu količinu energije (zagrije se) da bi ostala termički stabilna jer je priključena na radni napon.

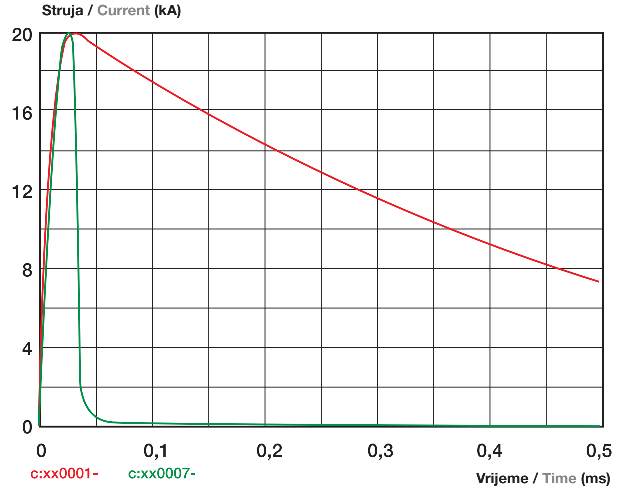
Pri prolasku strujnog vala 10/350 µs kroz iskrište napon na njemu je nizak (napon luka). Ako se sad integrira produkt trenutačne vrijednosti struje, napona i vremena, dobije se znatno manja energija koju treba apsorbirati iskrište. Zbog toga je iskrište pogodno za ispitivanje i duljim valovima.

final device. There are special versions in the form of a receptacle. Class D surge arresters are tested with a combination wave generator (2 effective internal resistance), which generates a 1,2/50 µs voltage wave in an open circuit, and an 8/20 µs current wave in a short circuit. Class D surge arresters are also preconditioned with a combination wave. The open circuit voltage U_{oc} of a combination wave generator is specified for this class of arresters.

An SPD based on a metal-oxide (MO) varistor is not suitable for testing with a current wave of long duration, unlike SPDs based on a spark gap. To demonstrate this, let us take a 10/350 µs current wave as a representative of a long wave, and an 8/20 µs current wave as a representative of a short wave. The difference between 10/350 µs and 8/20 µs current waves is evident in Figure 1.

When a 10/350 µs current wave passes through an MO arrester, the voltage is relatively high compared with a spark gap. When the products of the instantaneous current, voltage and time values are integrated, great energy is obtained which must be absorbed by an MO disc. An MO disc can absorb a limited amount of energy (it heats up) in order to remain thermally stable, since it is connected to a voltage source.

When a 10/350 µs current wave passes through a spark gap, the voltage is low (arc voltage). If the products of the instantaneous current, voltage and time values are now integrated, significantly less energy is obtained for the spark gap to absorb. Therefore, a spark gap is also suitable for testing with long waves.



Slika 1
Strujni valovi 10/350 µs i 8/20 µs, 20 kA
Figure 1
10/350 µs and 8/20 µs, 20 kA current waves

Energija koju apsorbira MO odvodnik razmjerna je površinama ispod krivulja na slici 1. Jasno je da ispitivanje strujnim valom 10/350 μs predstavlja mnogostruko veći energetski zahtjev za UPZ na bazi MO odvodnika. Zbog toga UPZ na bazi MO, uobičajene površine presjeka pločice, može termički izdržati strujne valove oblika 10/350 μs samo relativno male amplitude (do oko 5 kA).

U tablici 1 prikazano je mjesto postavljanja UPZ-a u odgovarajuće prenaponske kategorije te zadaća koju UPZ-i pojedinih klasa imaju. Prema tablici, svaki vod (električni, komunikacijski) koji ulazi u objekt, iz zone gdje su mogući udari munje, treba na ulazu u objekt štititi odgovarajuće postavljenim UPZ-om klase I. Za slučaj napajanja objekta električnom energijom preko nadzemne NN mreže dobije se slika 2. Ispred brojila je potrebno postaviti UPZ klase I (odvodnik struje munje). Tipično mjesto postavljanja UPZ-a klase II je razvodni ormar (ploča). UPZ klase II može sigurno odvesti strujne valove oblika 8/20 μs, amplituda u području kA i sniziti preostali napon UPZ-a klase I. UPZ klase III postavlja se između razvodnog ormara (ploče) i krajnjeg uređaja ili u utičnicu. Neki osjetljivi uređaji imaju, unutar kućišta, ugrađenu i vlastitu prenaponsku zaštitu.

Ovako koncipirana prenaponska zaštita, ako je korektno izvedena, daje gotovo apsolutnu zaštitu. Za prenaponsku zaštitu vrlo vrijednih instalacija i pogona, moglo bi se reći, oportuno je držati se gornjeg IEC koncepta. Za zaštitu jednostavnijih objekata (npr. obiteljske kuće) treba učiniti odgovarajuće pojednostavljenje. Zašto? Prvi je razlog taj što ovako koncipirana prenaponska zaštita za jednostavnije objekte nije zaživjela. Odnosno, bar što se tiče Hrvatske, jednostavniji objekti najčešće nemaju nikakvu prenaponsku zaštitu. Drugi razlog, koji je povezan s prvim, jest cijena ovako koncipirane zaštite.

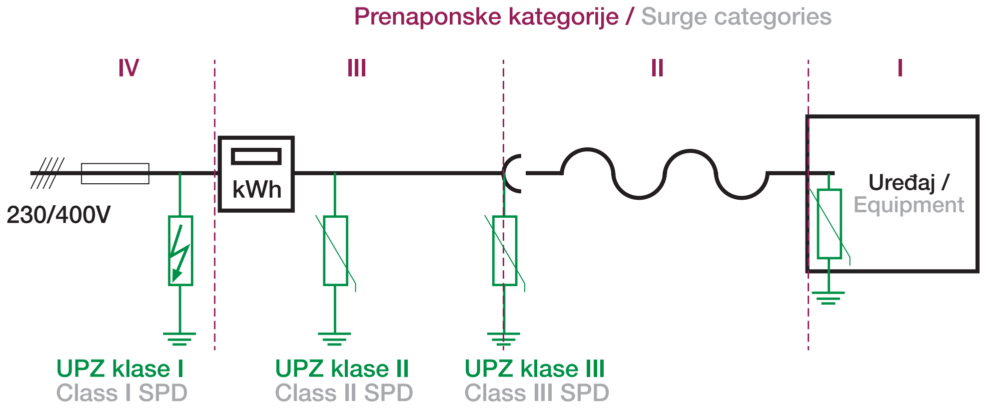
The energy absorbed by an MO arrester is proportional to the surfaces below the curves in Figure 1. It is clear that testing with a 10/350 μs current wave places a far greater energy requirement upon an MO-based SPD arrester. Therefore, an MO-based SPD, with the customary cross-sectional disc surface, can only thermally withstand 10/350 μs current waves of relatively low amplitudes (up to approximately 5 kA).

Table 1 presents the locations for SPD installation according to the corresponding surge categories and the tasks performed by the SPDs of the individual classes. According to the table, every line (power supply, communication) that enters a building from a zone where lightning strokes are possible should be protected at the entry to the building by a properly installed Class I SPD. Figure 2 presents the configuration when a building is supplied by an overhead low-voltage network. Upstream from the meter, it is necessary to install a Class I SPD (lightning current arrester). A typical site for the installation of a Class II SPD is the distribution panel. A Class II SPD can safely divert 8/20 μs current waves of amplitudes of the order of kA and decrease the residual voltage of a Class I SPD. A Class III SPD is placed between the distribution panel and the final device or a receptacle. Some sensitive devices have their own surge protection installed within the housing.

The configurations described above, if correctly performed, provide almost perfect protection. For the surge protection of very valuable installations and plants, it is opportune to adhere to the above IEC concept. However, for the protection of simpler buildings (e.g., family homes), simplification is necessary. Why? The first reason is that such a concept for the surge protection of simpler buildings has not become the norm. At least as far as Croatia is concerned, simpler buildings most often have no surge protection whatsoever. The second reason, in connection with the first, is the prohibitive cost of such surge protection.

Tablica 1 - Izbor i mjesto postavljanja UPZ-a [4]
Table 1-The selection and location of SPDs [4]

Mjesto postavljanja / Location Zadaća SPD-a / SPD task	Prenaponska kategorija / Surge categories		
	IV Priključak objekta / Service entrance	III Razvod / Distribution panel	II Utičnica / Receptacle
Izjednačavanje potencijala/ prenaponska zaštita uređaja / Potential equalizing/Equipment surge protection Odvođenje (dijela) struje munje / Diversion (partial) of lightning current	UPZ klase I - odvodnik struje munje / Class I SPD - lightning current arrester		
Prenaponska zaštita uređaja / Equipment surge protection Sniženje preostalog napona SPD-a klase I / Reduction of the residual voltage of Class I SPD Ograničenje induciranih prenapona / Limiting of induced voltage surges		UPZ klase II / Class II SPD	
Prenaponska zaštita uređaja / Equipment surge protection Ograničenje sklopnih prenapona / Limiting of switching surges Sniženje preostalog napona prethodnih UPZ / Reduction of the residual voltage of previous SPDs			UPZ klase III / Class III SPD



Slika 2
Prenaponska zaštita prema IEC-u
Figure 2
Surge protection according to the IEC

Jedno od mogućih pojednostavljenja prenaponske zaštite je tzv. kombinirani UPZ klase I koji u sebi ujedinjuje i UPZ klase II. Ovaj kombinirani UPZ klase I ima svojstvo klase I, kapacitet odvođenja relativno velikih struja valnog oblika 10/350 μs, a s druge strane svojstvo UPZ klase II, nizak preostali napon. Ovo se rješenje na prvi pogled čini optimalnim, ali glavni mu je nedostatak visoka cijena.

Drugo je rješenje jednostavno izostavljanje prvog stupnja (UPZ klase I), slika 3. Na njegovo bi se mjesto postavio UPZ klase II te bi se zaštita izvela u dva stupnja, što je i praksa distributera električne energije u SAD-u [5].

Očekivani nedostatak ovog rješenja je moguće energetsko preopterećenje UPZ-a klase II u KPMO-u objekta.

U sljedećem poglavlju prikazana je metoda kojom će se razmotriti energetsko opterećenje UPZ-a klase II u KPMO-u. Na taj će se način pokušati dati i odgovor na općenitu potrebu za UPZ-om klase I (odvodnikom struje munje). To nadalje znači i potrebu za ispitivanjem strujnim valom 10/350 μs. Naime, IEEE C62.45 [2] ne predviđa takav val za ispitivanje UPZ-a. Dakle, cilj je razmatranja koje slijedi provjera mogućnosti ugradnje UPZ-a klase II u KPMO-u, uzimajući prihvatljivim vrlo malu vjerojatnost (relativnu frekvenciju) energetskog preopterećenja tijekom životnog vijeka (jedanput u sto ili jedanput u dvjesto godina). Metoda polazi od pretpostavke da je prihvatljiv zanemarivo mali broj kvarova UPZ-a zbog energetskog preopterećenja, a uzima se u obzir vjerojatnost pojave struja munje određenih amplituda i vremena trajanja vala, za razliku od pristupa u IEC normama koje uzimaju maksimalno moguće vrijednosti.

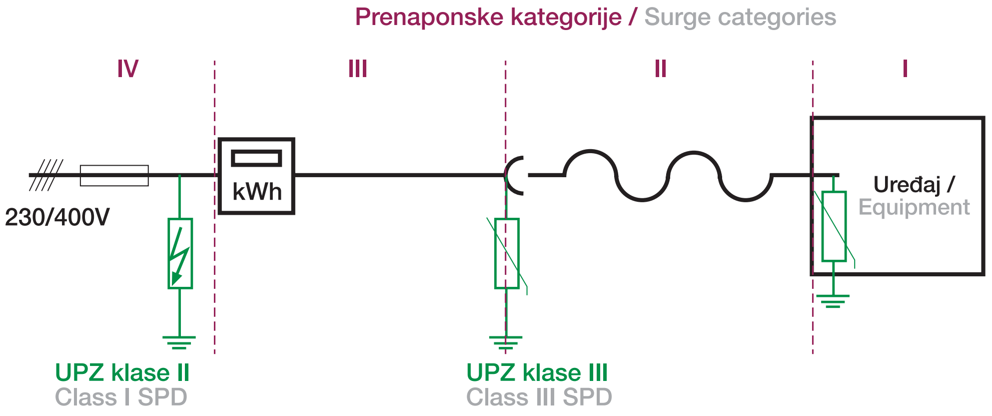
One of the possible simplifications of the surge protection configuration is a Class I SPD combined with a Class II SPD. This combined Class I SPD has the attributes of Class I, with the capacity to conduct relatively large 10/350 μs current waves, and the attribute of the low residual voltage of a Class II SPD. At first glance, this solution seems optimal but its major drawback is its high cost.

Another solution is simply to omit the first stage (Class I SPD), Figure 3. It is replaced by a Class II SPD and surge protection occurs at two levels, as is the practice of power distributors in the USA [5].

An anticipated drawback of this solution is the possibility of energy the overloading of the Class II SPD at the service entrance of a building.

In the next chapter, a method is presented for the energy load analysis of a Class II SPD at a service entrance. This is an attempt to provide an answer to the general need for Class I SPDs (lightning current arresters). It further signifies the need for testing with a 10/350 μs current wave. IEEE C62.45 [2] does not anticipate this waveform for SPD testing. The goal of the following analysis is to determine the possibility of installing Class II SPDs in a service entrance, taking into account the very low probability (relative frequency) of energy overloading during its lifetime (one time in a hundred years or one time in two hundred years). The method is based upon the premise that the very low number of SPD failures due to energy overloading is acceptable, and takes into account the probability of the occurrence of lightning currents of defined amplitude and wave duration, unlike the approach in the IEC standards that takes the maximum possible values.

Slika 3
Prenaponska zaštita u dva stupnja
Figure 3
Two-stagesurge protection



3 METODA IZBORA UREĐAJA PRENAPONSKE ZAŠTITE U NN SUSTAVIMA

Ideja metode izbora UPZ-a u NN sustavima, koja će biti izložena u nastavku, u najkraćem se sastoji u sljedećem:

- za svaku tipičnu primjenu UPZ-a napravi se odgovarajući EMTP-ATP (Electromagnetic Transient Program - verzija ATP) model,
- usvoji se prihvatljiv rizik kvara zbog energetskog preopterećenja UPZ-a klase II,
- prema usvojenom riziku odabire se odgovarajuća struja munje,
- provode se simulacije udara munje i računa energetskog opterećenja UPZ-a,
- simulacijama dobivena relativna frekvencija energetskog preopterećenja povezuje se s usvojenim rizikom te donosi zaključak je li UPZ klase II adekvatan za primjenu.

Blok-dijagram metode prikazan je na slici 4.

Zbog ograničenosti prostora svi elementi gornjeg blok dijagrama neće se opisivati detaljno. Npr. za prihvatljivi rizik kvara, zbog energetskog preopterećenja, UPZ-a klase II u KPMO-u obiteljske kuće, bez sustava zaštite od munje (SZM) predlaže se R_{TK} = 10-2 (jedanput u sto godina).

ATPDraw model NN mreže (s Al/Če vodičima ili samonosivim kabelskim snopom) je frekvencijski zavisan model s konstantnom realnom transformacijskom matricom (J. Marti). Ovaj model uključuje i skin-efekt. Isti je model usvojen i za priključak objekta na NN mrežu.

3 THE METHOD FOR THE SELECTION OF SURGE PROTECTIVE DEVICES IN LOW-VOLTAGE SYSTEMS

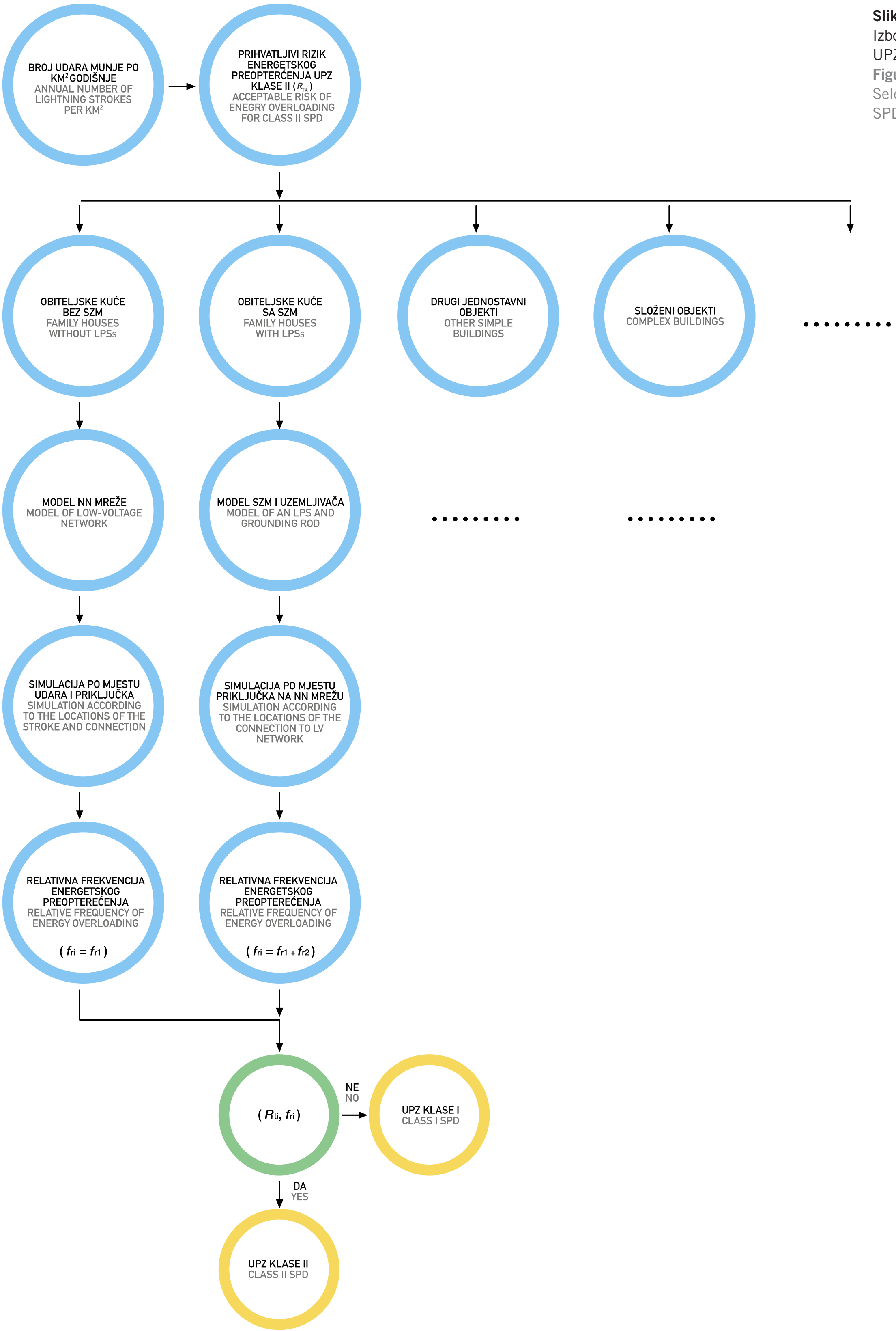
The concept of the method for the selection of SPDs in low-voltage systems, that will be presented, briefly consists of the following:

- for every typical SPD application, a corresponding EMTP-ATP (Electromagnetic Transient Program - version ATP) model is devised,
- an acceptable risk of failure due to the energy overloading of Class II SPDs is adopted,
- the corresponding lightning current is chosen according to the adopted risk,
- lightning stroke simulation is performed and the energy load of the SPD is calculated,
- through simulations, the relative frequency of energy overloading is obtained, which is then correlated with the adopted risk, on the basis of which it is concluded whether a Class II SPD would be adequate.

A block diagram of this method is presented in Figure 4.

Due to space limitations, all the elements of the above block diagram will not be described in detail. For example, as the acceptable risk of failure due to energy overloading with a Class II SPD at the service entrance in a family house without a lightning protection system (LPS), R_{TK} = 10-2 (once in a hundred years) is proposed.

The ATPDraw model of a low-voltage network (with aluminum/steel conductors or aerial bundle cable) is a frequency-dependent model with a constant, real transformation matrix (J. Marti). This model also includes the skin effect. The same model has been adopted for the connection of a building to a low-voltage network.



Slika 4
Izbor odgovarajućeg UPZ-a za objekte
Figure 4
Selection of suitable SPDs for buildings

Pri udaru munje u najviši vodič NN mreže dolazi do preskoka i na ostale vodiče. Preskok se može modelirati na različite načine. Najčešće se koristi karakteristika napon/vrijeme koja daje ovisnost vršne vrijednosti napona specifičnog valnog oblika o vremenu do preskoka. Prema [6], za jednostavnije analize, detaljni model luka, koji nastaje pri preskoku izolatora, nije nužan. Električni luk dovoljno je modelirati kratkim spojem (idealni prekidač). Pritom se koristi izraz za određivanje napona, pri kojemu dolazi do preskoka zračnog razmaka:

When lightning strikes the highest conductor in a low-voltage network, a flashover to other conductors occurs. The flashover can be modeled in various ways. Most often, the voltage/time characteristic is used. It gives the dependence of the peak values of the voltage of a specific waveform on the time up to the flashover. According to [6] for a simpler analysis, a detailed model of the arc occurring at the flashover of the insulator is not essential. It is sufficient to model the electric arc with a short circuit (ideal switch). The following expression may be used to determine the voltage at which air gap flashover occurs:

$$U_{\mathrm{pr}} = K_1 + \frac{K_2}{t^{0,75}} \tag{1}$$

gdje su:

U_{pr} - preskočni napon u (MV),
$K_1 = 0,4\ l$,
$K_2 = 0,71\ l$,
l - dužina izolatora (ili zračni razmak) (m),
t - vrijeme trajanja čela (μs).

whereas:

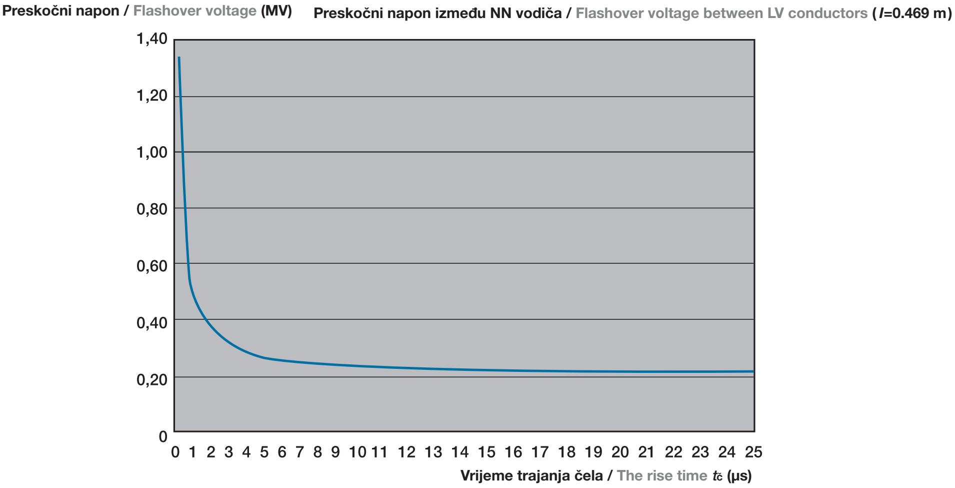
U_{pr} - the flashover voltage (MV),
$K_1 = 0,4\ l$,
$K_2 = 0,71\ l$,
l - the length of the insulator (or the air gap) (m),
t - the rise time (μs).

Izraz (1) za tipičnu nadzemnu NN mrežu izvedenu Al/Če vodičima prikazan je slikom 5.

Expression (1) for a typical overhead low-voltage network using aluminum/steel conductors is presented in Figure 5.

Slika 5 Vremenska ovisnost preskočnog napona zračnog razmaka između vodiča NN mreže

Figure 5 Time dependence of air gap flashover voltage between the conductors of a low-voltage network

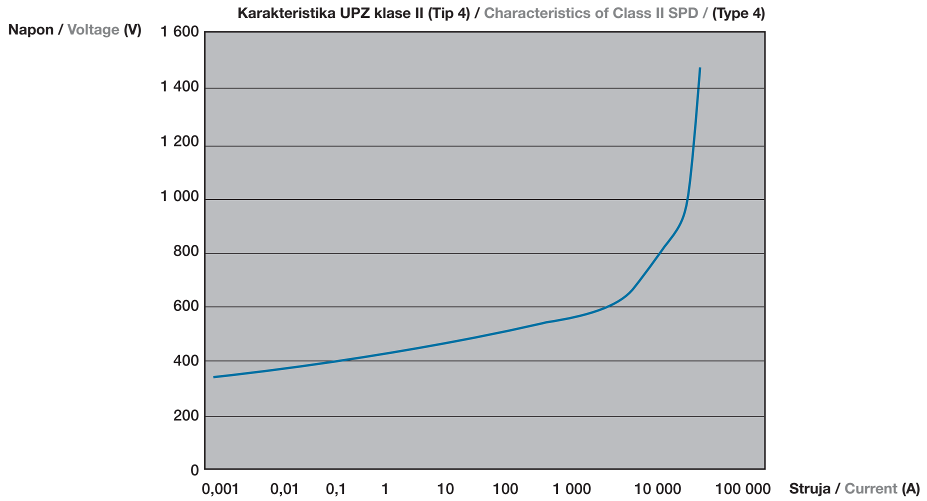


U nadzemnoj NN mreži UPZ-i klase II nalaze se u ormariću TS i na kraju mreže. U novije se vrijeme UPZ-i klase II postavljaju i na prvom stupu NN mreže ispred TS. Pretpostavka je također da je u KPMO-u objekta UPZ klase II. Za modeliranje UPZ-a u ATPDraw-u potrebna je *U-I* karakteristika. Kako *U-I* karakteristike NN UPZ-a obično nisu dostupne u katalozima proizvođača, mogu se snimiti u laboratoriju. Primjer djelomično laboratorijski snimljene karakteristike jednog UPZ-a klase II kakav se koristi u NN mreži dan je u tablici 2. Na slici 6 prikazana je strujno-naponska karakteristika istog UPZ-a. Ova se karakteristika koristi u modelu UPZ-a u ATPDraw-u.

In an overhead low-voltage network, Class II SPDs are installed in the transformer station cubicle and at the end of the network. In recent times, Class II SPDs are installed on the first pole of a low-voltage network upstream of the transformer station. Also, it is assumed that Class II SPDs are installed in the service entrance of a building. The voltage-current characteristic is necessary to make an SPD model in ATPDraw. Since voltage-current characteristics of low voltage SPDs are generally not available in manufacturer's catalogues, they can be obtained in the laboratory. An example of a voltage-current characteristic of a Class II SPD used in a low voltage network, partially taken in the laboratory, is presented in Table 2. The current-voltage characteristic of the same SPD is presented in Figure 6. This characteristic is used in the SPD model in ATPDraw.

Tablica 2 - Preostali napon pri strujnom valu 8/20 μs, UPZ klase II (Tip 4)
Table 2 - Residual voltage at 8/20 μs current wave, Class II SPD (Type 4)

MOSA 280 U_c = 280 V~, I_n = 10 kA, I_{max} = 20 kA, U_p = 1,1 kV							
1,03 kA	1,53 kA	2,03 kA	2,5 kA	4,5 kA	5,05 kA	5,75 kA	6,45 kA
750 V	800 V	840 V	880 V	980 V	1 020 V	1 030 V	1 050 V



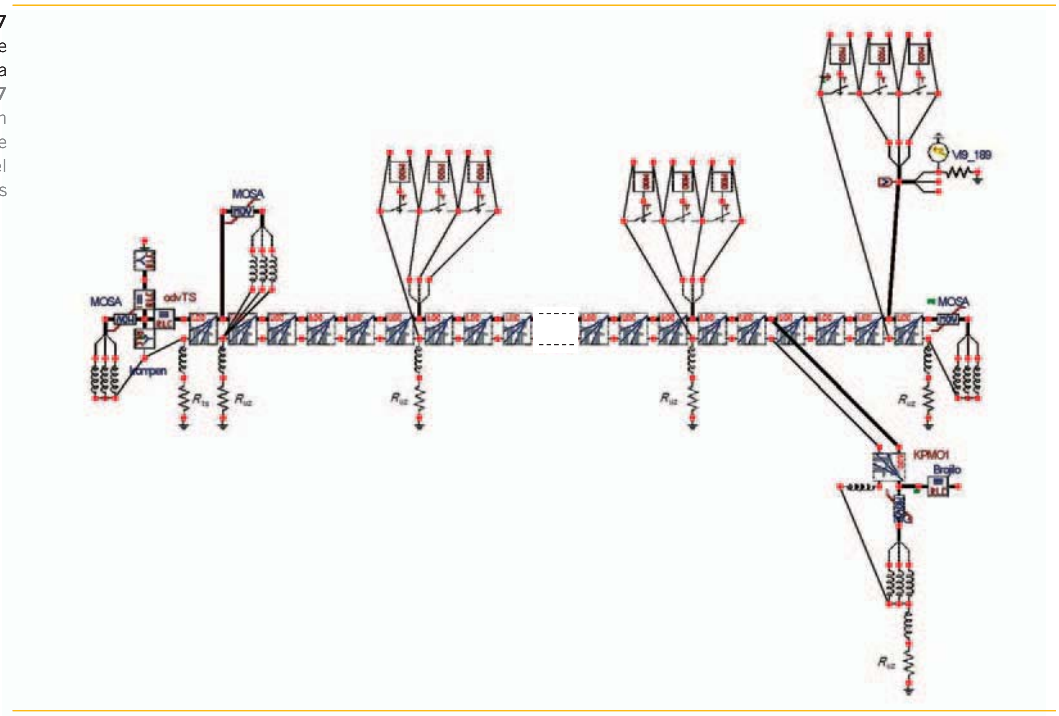
Slika 6
Strujno-naponska karakteristika UPZ-a u NN mreži
Figure 6
Current-voltage characteristics of an SPD in a low-voltage network

ATPDraw model NN mreže prikazan je na slici 7.

An ATPDraw model of a low-voltage network is presented in Figure 7.

Slika 7
ATPDraw model nadzemne NN mreže s Al/Če vodičima

Figure 7
ATPDraw model of an overhead low-voltage network with aluminum/steel conductors



3.1 Vjerojatnost i distribucija struja munje koje pogađaju nn mrežu

Vjerojatnost pogotka struje munje u NN mrežu ovisi u gustoći udara munje u tlo, odnosno o kerauničkoj razini područja gdje se mreža nalazi.

Za određivanje broja udara munje u NN mrežu može se koristiti izraz iz [7], koji se koristi i za VN vodove:

3.1 Probability and distribution of lightning currents striking a low-voltage network

The probability of lightning currents striking a low-voltage network depends upon the density of the lightning striking the ground, i.e. the keraunic level of the area in which the network is located.

To determine the number of lightning strokes to a low-voltage network, it is possible to use the expression from [7], that is also used for high-voltage lines:

$$N_{\mathrm{L}} = 0{,}004 \cdot T^{1,35} \cdot (b + 4 \cdot h^{1,09}) \qquad (2)$$

gdje su:
N_{L} - broj udara munje u vod dužine 100 km u godini,
T - keraunički nivo (broj grmljavinskih dana u godini),
h - prosječna visina zaštitnog vodiča (m) (u slučaju NN mreže visina najvišeg vodiča),
b - vodoravna udaljenost između zaštitnih vodiča (u slučaju NN mreže nula).

whereas:
N_{L} - the number of lightning strokes to a 100 km power line per year,
T - the keraunic level (the number of days with thunder per year),
h - the average height of the grounding conductor (m) (in the case of a low-voltage network, the height of the highest conductor),
b - the horizontal distance between the grounding conductors (which is zero in the case of a low-voltage network).

Ako se usvoji keraunički nivo (npr. T = 35 dana), može se izračunati očekivani broj udara munje po jedinici dužine NN mreže. Uz prosječnu visinu najvišeg vodiča NN mreže iznad tla 7,1 m dobije se:

If a keraunic level (e.g., T = 35 days) is adopted, it is possible to calculate the anticipated number of lightning strokes per unit of length of a low-voltage network. With an average above-ground height of 7,1 m for the highest conductor of a low-voltage network, the following can be obtained:

$$N_{\mathrm{L}} = 16{,}46 \left[\frac{1}{\mathrm{km} \cdot 100 \cdot \mathrm{god}} \right] \tag{3}$$

Dakle za 1,0 km NN mreže može se očekivati 16,46 udara munje u 100 godina.

Poznata je činjenica da je više od 90 % silaznih munja negativnog polariteta [8], a da su pozitivni udari karakteristični za visoke građevine (npr. objekti na vrhovima planina, visoke zgrade...).

Najčešće korišteni izraz za raspodjelu vršnih vrijednosti negativnih silaznih struje munje je, prema [7]:

Hence, for a 1,0 km low-voltage network it is possible to anticipate 16,46 strokes of lightning per 100 years.

The fact is known that more than 90 % downward lightning strokes have a negative polarity [8], whereas strokes of positive polarity are characteristic for high buildings (e.g., buildings on tall mountains, high-rise buildings etc.).

The most frequently used expression for the peak value distribution of negative downward lightning currents, according to [7], is as follows:

$$P_I = \frac{1}{1 + \left(\frac{I}{31} \right)^{2,6}} \quad \text{(p.u.)} \tag{4}$$

gdje su:
P_I - vjerojatnost da je struja munje veća od I,
I - struja munje, kA.

whereas:
P_I - the probability that the lightning current is greater than I,
I - lightning current, kA.

Ako se u izraz (4) za P_I uvrsti 1/16,46 = 0,06075, dobije se:

If in expression (4) the value 1/16,46 = 0,06075 is substituted for P_I, the following is obtained:

$$I = 31 \cdot \left(\frac{1 - P_I}{P_I} \right)^{\frac{1}{2,6}} = 88{,}87 \text{ kA} \tag{5}$$

Prema (5), samo 6,075 % od svih struja munje bit će veće amplitude od 88,87 kA.

U skladu s (3), može se očekivati da će samo 1 udar munje, koja pogađa 1 km NN mreže u 100 godina, biti veći od 88,87 kA. Dakle, vjerojatnost udara munje amplitude struje veće od 88,87 kA u 1 km NN mreže je 0,01. Slično razmatranje može se provesti i za trajanje čela, odnosno hrpta struje munje.

Na kraju ovog dijela još se jedanput može sumirati prije izloženi primjer. U 1 km NN mreže, u vremenskom razdoblju od 100 godina, može se očekivati 16,46 udara munje. Od tih udara munje samo će 1 udar biti veće amplitude od 88,87 kA. Također će samo jedan udar munje imati vrijeme

According to (5), only 6,075 % of all lightning currents will be of amplitudes greater than 88,87 kA.

According to (3), it can be anticipated that only one lightning stroke that strikes a 1 km low-voltage network in 100 years will be greater than 88,87 kA. Hence, the probability of a lightning stroke of an amplitude greater than 88,87 kA in a 1 km low-voltage network is 0,01. A similar approach can be applied to determine the rise time and tail time of lightning current.

At the end of this section, it is possible once again to summarize the previously presented example. In a 1 km low-voltage network, during a period of 100 years, 16,46 lightning strokes are to be expected. Of these lightning strokes, only one stroke will be of trajanja čela dulje od 9 μs, odnosno vrijeme trajanja hrpta dulje od 189 μs. Zbog toga će se simulacija udara munje u NN mrežu provesti strujom amplitude 88,87 kA i valnog oblika 9/189 μs.

3.2 Rezultati simulacije energetskog opterećenja uređaja prenaponske zaštite u kućnom priključno-mjernom ormariću objekta

3.2.1 Rezultati za model NN mreže izvedene Al/Če vodičima

Poznato je iz teorije vjerojatnosti da relativna frekvencija nekog događaja teži vjerojatnosti tog događaja kada broj pokusa teži u beskonačnost. Kako je u praksi nemoguće provesti jako veliki broj simulacija za koji bi se moglo kazati da teži u beskonačnost, mora se koristiti relativna frekvencija događaja. S obzirom na to da postoji jako veliki broj promjenjivih veličina u modelu nadzemne mreže, mjestu udara munje, parametrima udara munje, mjestu priključka objekta s obzirom na mjesto udara itd., neke od njih moralo se držati konstantnima. Tako su sve simulacije provedene istom strujom munje 88,87 kA 9/189 μs. Parametri mreže i priključka također su držani konstantnima. Promjenjivo je bilo mjesto udara munje i mjesto priključka objekta u mrežu.

U slučaju promjene samo tih dvaju parametara dobije se jako veliki broj kombinacija. Npr. udar munje može pogoditi svaki stup u NN mreži (raspon dužine je 33 m, odnosno 35 m). Dakle, prema usvojenom modelu, u 1 km NN mreže moguće je 31 mjesto udara munje. Također, priključak objekta može biti bilo na kojem mjestu u mreži, od TS do zadnjeg stupa - dakle, na 31 mjestu prema usvojenom modelu. Ako se izračuna mogući broj kombinacija, dobije se 961. Samo za ovaj slučaj nadzemne mreže i kombinirajući samo dva parametra potrebno je napraviti 961 proračun.

Kako je jedan raspon NN mreže relativno kratak (33 m, odnosno 35 m) a dužina priključka još kraća (20 m), potrebno je imati i relativno mali korak proračuna u EMTP-ATP-u. Ako se pretpostavi brzina gibanja EM vala jednaka brzini svjetlosti 300 m/μs, jasno je da EM val prijeđe 20 m za 0,067 μs. Zbog toga je usvojen korak proračuna $\Delta t = 0{,}01$ μs.

Energija koju apsorbira UPZ, na bazi MO pločice, određena je izrazom:

an amplitude greater than 88,87 kA. Furthermore, only one lightning stroke will have a rise time longer than 9 μs, and a tail time longer than 189 μs. Therefore, the simulation of a lightning stroke in a low-voltage network will be performed with a current wave having an amplitude of 88,87 kA and a 9/189 μs waveform.

3.2 Results of energy load simulation for surge protective devices in the service entrance of a buildings

3.2.1 Results for a model of a low-voltage network with aluminum/steel conductors

It is known from probability theory that the relative frequency of an event approaches the probability of that event when the number of tests approaches infinity. Since in practice it is impossible to perform such a large number of simulations for which it would be possible to say that they approach infinity, it is necessary to use the relative frequency of an event. Since there are very many variables in a model of an overhead network, such as the location of the lightning stroke, the parameters of the lightning stroke, the location of the connection of a building relative to the location of the lightning stroke etc., some of these variables had to be considered as constants. Thus, all the simulations were performed with the same lightning current of 88,87 kA 9/189 μs. Network and connection parameters were also considered to be constants. The location of the lightning stroke and the location of the building connection to the network were variables.

In the event of changes in only these two parameters, a very large number of combinations can be obtained. For example, lightning can strike every pole in a low-voltage network (with a pole spacing of 33 m or 35 m). According to the model adopted, in a 1 km low-voltage network, 31 sites of lightning strokes are possible. Furthermore, a building connection can be at any point within the network, from the transformer station to the last pole, i.e. at any of 31 places according to the adopted model. If the possible number of combinations is calculated, 961 is obtained. Only for this case of an overhead network and by combining two parameters, it is necessary to perform 961 calculations.

Since the pole spacing in a low-voltage network is relatively short (33 m or 35 m), and the length of the connection is even shorter (20 m), it is necessary to have a relatively small increment for calculation in the EMTP-ATP. If the velocity of the electromagnetic wave propagation is assumed to be equal to the speed of light (300 m/μs), it is clear that the electromagnetic wave requires 0,067 μs to travel 20 m. Therefore, the increment of $\Delta t = 0{,}01$ μs has been adopted.

The energy absorbed by a SPD based on an MO disc is determined by the following expression:

$$E = \int u(t) \cdot i(t) \cdot \mathrm{d}t \tag{6}$$

Poznata je činjenica da UPZ ograničava napon, pa u gornjem izrazu promjenjiva *u*(*t*) se mijenja ograničeno. Ako se pogleda promjenjiva *i*(*t*), ista se mijenja u granicama od manje od 1 mA do više desetaka kA, dakle više milijuna puta. Integraciju je stoga potrebno provoditi dokle god kroz UPZ teče znatnija struja, odnosno dok je napon na UPZ-u veći od njegova trajnog radnog napona.

Naravno, u vremenski promjenjivim prijelaznim procesima praktično je nemoguće za računanje energije koristiti navedeni analitički izraz. EMTP-ATP za računanje gornjeg izraza koristi numeričku integraciju zasnovanu na trapeznom pravilu (7).

$$E = \sum_{j=1}^{n} \frac{u_j + u_{j-1}}{2} \cdot \frac{i_j + i_{j-1}}{2} \cdot \Delta t \tag{7}$$

Ako se hoće numerički izračunati energija koju apsorbira UPZ, proračun je potrebno raditi toliko dugo dok kroz UPZ ne prestane teći znatnija struja. Mora se promatrati cijela prijelazna pojava do njezina potpunog prigušenja. To je vrijeme u slučaju udara munje u NN mreže dužine 1 km oko 1,8 ms, a u nekim slučajevima i dulje. Ako se sada potrebno vrijeme proračuna podijeli s korakom proračuna (Δt = 0,01 μs), dobije se *n* = 180 000 koraka proračuna. Jedan takav proračun na suvremenom računalu traje oko dvije minute.

Zbog toga su prvo učinjeni proračuni s korakom priključka i mjesta udara 100 m, tablica 3.

It is a well-known fact that an SPD limits voltage. Therefore, *u*(*t*) in the above expression changes within limits. The variable *i*(*t*) changes from less than 1 mA to many tens of kA, i.e. several million times. It is therefore necessary to perform integration as long as a significant current flows through an SPD, i.e. as long as the voltage on an SPD is greater than its continuous operating voltage.

In transient processes varying in time, it is practically impossible to use the above analytical expression for energy calculations. For the calculation of the above expression, EMTP-ATP uses numerical integration based upon the trapezoid rule (7).

In order to calculate the absorbed energy by an SPD numerically, it is necessary to perform the calculation for as long as significant current flows through it. It is necessary to observe the entire transient state until it is fully attenuated. This time in the case of a lightning stroke in a 1 km low-voltage network is approximately 1,8 ms, and in some cases longer. If the calculation time is now divided by the increment (Δt = 0,01 μs), it yields *n* = 180 000 calculation steps. On a modern computer, such a calculation requires approximately two minutes.

It is for this reason that calculations with both building connection distance and lightning stroke distance of 100 m are performed first, Table 3.

Tablica 3 - Energetsko preopterećenje UPZ-a klase II u KPMO-u i TS
Table 3 - Energy overloading of a Class II SPD at a service entrance and transformer station

		Mjesto udara u NN mrežu od TS (udar u fazu A) / Distance of lightning stroke in a low-voltage network from the transformer station (strike in Phase A)										
		0m	100m	200m	300m	400m	500m	600m	700m	800m	900m	1000m
Mjesto priključka objekta udaljeno od transformatorske stanice / Distance of building connection from transformer station	0m	A(1)	-(1)	-(1)	-(1)	-(1)	-(-)	-(-)	-(-)	-(-)	-(-)	-(1)
	100m	A(1)	A,BiC(1)	-(3)	-(3)	-(2)	-(2)	-(2)	-(2)	-(2)	-(2)	A(3)
	200m	A(1)	A(3)	A,BiC(1)	-(3)	-(3)	-(3)	-(2)	-(2)	-(2)	-(3)	A(3)
	300m	A(1)	-(3)	-(3)	A,BiC(2)	-(3)	-(3)	-(3)	-(3)	-(3)	-(3)	A(3)
	400m	A(1)	-(3)	-(3)	A(2)	A,BiC(1)	-(3)	-(3)	-(3)	-(3)	-(3)	A(3)
	500m	A(1)	-(3)	-(3)	-(2)	-(2)	A,BiC(2)	A(3)	-(3)	-(3)	-(3)	A(3)
	600m	A(1)	-(3)	-(3)	-(2)	-(2)	A(1)	A,BiC(1)	A(3)	A(3)	A(3)	A,BiC(3)
	700m	A(1)	-(3)	-(3)	-(3)	-(2)	-(2)	-(1)	A,BiC(2)	A(3)	A(3)	A,BiC(3)
	800m	A(1)	-(3)	-(3)	-(3)	-(2)	-(2)	-(2)	-(1)	A,BiC(1)	A,iB(2)	A,BiC(3)
	900m	A(1)	-(3)	-(3)	-(3)	-(2)	-(2)	-(2)	-(1)	-(2)	A,iC(2)	A,BiC(3)
	1000m	-(1)	-(3)	-(3)	-(3)	-(2)	-(2)	-(2)	-(1)	-(2)	-(1)	A,BiC(3)

Oznaka ”-” znači da nije energetski preopterećen niti jedan UPZ klase II / The sign ”-” means that no one SPD class II is energy overloaded

Kako se vidi iz tablice 3, mjesto udara munje mijenja se od transformatorske stanice pa do kraja mreže u koraku 100 m. Također, mjesto priključka objekta mijenja se od početka pa do kraja NN mreže. Udar munje je uvijek najviši vodič (faza A), što je u skladu s elektro-geometrijskim modelom udara. Neposredno nakon udara, u najvećem broju slučajeva, dolazi do preskoka na fazu B, zatim na C i na kraju na PEN (neutralni vodič sa zaštitnom funkcijom) vodič. Oznake A, B i C u tablici 3 označavaju energetski preopterećen UPZ klase II, u KPMO-u priključenog objekta, u dotičnoj fazi. Oznake (1), (2) i (3) u tablici 3 označavaju broj energetski preopterećenih UPZ-a klase II u TS, za dani slučaj mjesta udara munje i mjesta priključka objekta.

Kao kriterij energetskog preopterećenja svih UPZ-a usvojena je granica 1,5 kJ. Naime, postoje UPZ-i klase II nazivne struje 20 kA i maksimalne struje 65 kA (pa i 150 kA). Grubo se može usvojiti da UPZ klase II može 20 puta odvesti nazivnu struju, a najmanje 1 puta maksimalnu struju [9]. Ako se struja valnog oblika 8/20 µs amplitude 65 kA utisne u takav UPZ, dobije se disipirana energija veća od 2 kJ. Uzimajući u obzir mogućnost višestrukog udara munje, usvojena je energija 75 % izračunate, 1,5 kJ. Dakle, usvojen je kriterij, UPZ klase II (na bazi MO pločice) energetski je preopterećen ako je, pri udaru munje u NN mrežu, apsorbirao energiju veću od 1,5 kJ.

As seen from Table 3, the distance of the lightning stroke from the transformer station increases from the transformer station to the end of the network in increments of 100 m. Furthermore, the location of the building connection changes from the beginning to the end of the low-voltage network. Lightning always strikes the highest conductor (Phase A), which is in agreement with the electro-geometric stroke model. Immediately after the stroke, in the majority of cases there will be arcing to Phase B, then Phase C and finally to the PEN (Protection Earth Neutral) conductor. The designations A, B and C in Table 3 indicate an energy overloaded Class II SPD, located at the service entrance of a connected building, in the corresponding phases. The designations (1), (2) and (3) in Table 3 indicate the number of energy overloaded Class II SPDs at the transformer station for the given lightning stroke and building connection locations.

As the criterion for the energy overloading of all SPDs, the limit of 1,5 kJ has been adopted. There are Class II SPDs with a nominal current of 20 kA and maximum current of 65 kA (and even 150 kA). It can be roughly adopted that a Class II SPD can divert its nominal current 20 times, and its maximum current at least once [9]. When an 8/20 µs current wave of an amplitude of 65 kA is impressed into such a SPD, more than 2 kJ of dissipated energy is obtained. Taking into account the possibility of multiple lightning strokes, 75% of the calculated energy or 1,5 kJ is adopted. Thus, the adopted criterion for an overloaded Class II SPD (based on an MO disc) in a low-voltage network is when the absorbed energy from a lightning stroke is greater than 1,5 kJ.

Analizom rezultata iz tablice 3 zaključuje se da je preopterećenje UPZ-a klase II u KPMO-u češće za udar munje u NN mrežu kod TS i pri kraju mreže. Za udaljenost 100 m od TS, UPZ-i u fazama A, B i C u KPMO-u energetski su preopterećeni samo ako je udar munje i priključak objekta na istom mjestu, ili eventualno udaljen 100 m, u nekim slučajevima. Za objekt priključen na NN mrežu više od 100 m od mjesta udara munje, niti jedan UPZ u KPMO-u nije preopterećen. Sličan zaključak vrijedi približno prvih 700 m od TS. Ako se pogledaju udaljenosti, 800 m, 900 m, vidi se da su UPZ-i u KPMO-u sada preopterećeni i za slučaj priključka nešto dalje od mjesta udara munje. Odgovor zašto je to tako krije se u sljedećoj činjenici. Utisnuti strujni val prijeđe cijelu udaljenost od 1 km za cca 3,3 μs a kako je riječ o relativno dugom valu (amplitude 88,8 kA valnog oblika 9/189 μs), jasno je da dolazi do višestrukih refleksija prije negoli je cijeli val i utisnut u NN mrežu.

Na mjestu utiskivanja struje, u pravilu, dolazi do preskoka između svih faznih vodiča, a također je modelirana i mogućnost preskoka na svakom stupu na kojemu je PEN vodič povezan sa zemljom. Na pojedinim od tih stupova također dolazi do preskoka između pojedinih ili svih vodiča. To je jedan od načina na koji se energija struje munje odvodi u zemlju. Kako je PEN vodič povezan sa zemljom svakih 200 m, to nije razlog za “nesimetriju” rezultata u tablici 3. Razlog se krije u činjenici da na strani TS postoje dva sloga od tri UPZ-a klase II, jedan u ormaru TS, a drugi na prvom stupu ispred TS. Suprotno tomu, na kraju NN mreže samo je jedan slog UPZ-a na zadnjem stupu. Poznato je izvanredno svojstvo MO odvodnika (UPZ klase II), koje nemaju odvodnici na bazi iskrišta (UPZ klase I), da dijele energiju koju odvode. Ovo je očigledan primjer tog izvanrednog svojstva. Udari munje u NN mrežu kod TS (udaljenost 0 m) i sam kraj mreže (udaljenost 1000 m) uzrokuju veće energetsko opterećenje UPZ-a u KPMO-u, zbog toga jer UPZ-i u TS i na kraju mreže smanjuju prenapon te sprečavaju preskok između faznih vodiča međusobno, a i prema PEN vodiču. Na taj se način cijela energija udara munje odvodi UPZ-ima, što rezultira većim energetskim opterećenjem svih UPZ-a.

Ako se napravi suma svih slučajeva, dobije se sljedeći omjer. Od 363 moguća dobiveno je u 66 slučajeva energetsko preopterećenje UPZ-a klase II u KPMO-u objekta, što je relativna frekvencija preopterećenja od približno 18,2 %. S obzirom na usvojenu vjerojatnost pojave amplitude struje munje i usvojenu najnepovoljniju situaciju samo jednog priključka, to je ohrabrujući rezultat i

Through analysis of the results from Table 3, it is concluded that the overloading of Class II SPDs in the service entrance due to lightning strokes in a low-voltage network is more frequent at the transformer station and at the end of the network. At a distance of 100 m from the transformer station, the SPDs in Phases A, B and C at the service entrance are overloaded only if the lightning stroke and building connection are in the same location, or eventually at a distance of 100 m in some cases. For a building connected to a low-voltage network over 100 m from the site of the lightning stroke, not a single SPD at a service entrance was overloaded. A similar conclusion applies for approximately the first 700 m from the transformer station. If distances of 800 m and 900 m are considered, it is seen that the SPDs at service entrances are also overloaded in the case of a connection somewhat further from the site of the lightning stroke. The answer to why this is so lies in the following fact. An impressed current wave travels at a distance of 1 km for approximately 3,3 μs. Since this is a relatively long wave (amplitude 88,8 kA, 9/189 μs waveform), it is clear that there are multiple reflections before the entire wave is impressed in the low-voltage network.

At the site of current impression, as a rule there is flashover between all the phase conductors, and the possibility of flashover is also modeled for every pole on which a PEN conductor is connected to the ground. On some of these poles, there are also flashovers among individual or all the conductors. This is one of the ways in which the electrical energy of the lightning current is conducted to the ground. Since a PEN conductor is connected to the ground every 200 m, this is not the reason for the “asymmetry” of the results in Table 3. The reason is concealed in the fact that on the side of the transformer station there are two stacks of three Class II SPDs, one in the transformer station cubicle and the other on the first pole in front of the transformer station. At the end of the low-voltage network, there is only one SPD stack on the last pole. Distribution of surge current among MO arrestors (Class II SPDs) is an exceptional property, which lightning current arresters based on spark gap (Class I SPDs) lack. This is an obvious example of such an exceptional property. Lightning strokes to a low-voltage network at a transformer station (at a distance of 0 m) and at the very end of the network (at a distance of 1000 m) cause greater energy overloading of the SPDs at service entrances, because the SPDs at the transformer station and at the end of the network reduce the surge and prevent flashover among phase conductors and also to the PEN conductor. In this manner, the entire energy of a lightning stroke is diverted by the SPDs, resulting in a greater energy load on all the SPDs.

If all the cases are added up, the following ratio is obtained. Out of 363 possible cases, overloading of navodi na zaključak da je UPZ klase II adekvatan za postavljanje u KPMO.

Treba se još jednom vratiti na nesimetričnost rezultata u tablici 3. Dakle, kada bude više priključaka s UPZ-ima klase II u KPMO-u, situacija će biti znatno povoljnija zbog spomenutog izvanrednog svojstva MO odvodnika da dijele energiju koju odvode. Što je veći broj priključaka s UPZ-ima klase II u KPMO-u, to je vjerojatnost njihova energetskog preopterećenja manja.

U simulacijama je računato, osim energetskog opterećenja UPZ-a klase II u KPMO-u, i energetsko opterećenja UPZ-a klase II u stupnoj TS. Naime, za UPZ u stupnoj TS i u Europi a i u Hrvatskoj prihvaćeno je da bude klase II (MO). Usvojeni kriterij energetskog preopterećenja je isti kao i za UPZ u KPMO-u. Dakle, ako je energija koju apsorbira UPZ pri udaru munje u NN mrežu veća od 1,5 kJ, tada je taj UPZ energetski preopterećen. Rezultati u tablici 3. su iznenađujući. Gotovo svaki udar u NN mrežu rezultira energetskim preopterećenjem jednog, dva ili tri UPZ-a klase II u TS. Ako se izračuna relativna frekvencija energetskog preopterećenja UPZ-a klase II u TS, dobije se 71,3 % (259/363). Također, niti kondenzator za kompenzaciju jalove snage ne smanjuje energetsko opterećenja UPZ-a u TS, što bi se očekivalo. Kondenzator u prvom trenutku prima energiju, ali kako je riječ o dugom valu, napon na kondenzatoru poraste te UPZ počinje voditi struju. Zatim se akumulirana energija u kondenzatoru prazni, prema zemlji, kroz UPZ u TS. Dakle, kondenzator za kompenzaciju u TS ne smanjuje energetsko opterećenje UPZ-a.

Kako je ovaj rezultat ipak iznenađujući, provedena je usporedba sa stvarnim stanjem. U jednom distribucijskom području u kontinentalnoj Hrvatskoj, čija mreža odgovara simuliranom primjeru, pregledano je desetak stupnih TS s ugrađenim UPZ-ima klase II na NN strani. Naravno, prava statistička usporedba nije se mogla napraviti zbog sljedećih razloga:

- nepostojanja nikakve sustavnosti u odabiru UPZ-a na NN u TS (svi su klase II, ali različitih proizvođača i različitih nazivnih struja I_n = 5 i 10 kA),
- neprovođenja periodičnog niti bilo kakvog drugog pregleda UPZ-a na NN u TS,
- samo pojedine TS, odnosno NN izvodi imaju montiran i UPZ klase II na prvom stupu NN mreže ispred TS,
- nepostojanja praktično niti jednog objekta u NN mreži koji u KPMO-u ima ugrađenu bilo kakvu prenaponsku zaštitu.

the Class II SPDs at the service entrances was noted in 66, a relative overload frequency of approximately 18,2%. Taking into account the adopted value for the occurrence of lightning current amplitude and the adopted worst-case scenario for only one connection, this is an encouraging result and leads to the conclusion that Class II SPDs are adequate for installation at service entrances.

It is necessary to return once again to the asymmetry of the results in Table 3. When there are several connections with Class II SPDs at a service entrance, the situation will be significantly more favorable due to the previously noted exceptional property of an MO varistor to distribute the surge current. The more connections to Class II SPDs at a service entrance, the lower the probability of their becoming overloaded.

In the simulations, in addition to the energy load of the Class II SPDs at the service entrance, the energy load of the Class II SPD at the pole-mounted transformer station is calculated. For SPDs on pole-mounted transformer stations in Europe and in Croatia, it has been accepted that they should be Class II (MO). The adopted criterion for energy overloading is the same for an SPD at a service entrance. Hence, if the energy absorbed by an SPD from a lightning strike in a low-voltage network is greater than 1,5 kJ, the SPD is overloaded. The results in Table 3 are surprising. Nearly every stroke to a low-voltage network results in the energy overloading of one, two or three Class II SPDs at the transformer station. If the relative frequency of the overloading of Class II SPDs at transformer stations is calculated, 71,3 % (259/363) is obtained. Furthermore, the condenser for reactive power compensation does not reduce the energy load of the SPD at the transformer station, as would be expected. At the first moment, the condenser receives energy but since this is a long wave, the voltage at the condenser increases and the SPD begins to conduct current. Then the accumulated energy in the condenser discharges to the ground, through the SPD at the transformer station. Therefore, the condenser for reactive power compensation in a transformer station does not reduce the energy load of the SPD.

Since this result was unexpected, a comparison was performed with an actual situation. In a distribution network in continental Croatia, which corresponds to the simulated example, ten pole-mounted transformer stations with installed Class II SPDs on the low-voltage side were inspected. Naturally, it was not possible to perform a proper statistical comparison for the following reasons:

- the SPDs in the transformer stations of the low-voltage network had not been selected systematically. (They were all Class II SPDs but

Ipak, pregledom spomenutih desetak TS uočeno je da postoji određeni broj pokvarenih UPZ-a klase II (pokvaren ovdje znači da je proradio toplinski rastavni uređaj i odvojio UPZ od NN mreže). Veliki dio tih kvarova može se pripisati energetskom preopterećenju. Svi pokvareni UPZ-i klase II bili su nazivne struje 5 kA. Također, rezultat pregleda ovog malog skupa je da je u pojedinim TS pokvaren jedan NN UPZ klase II, u pojedinim dva, a nije pronađena niti jedna TS (od desetak pregledanih) sa sva tri pokvarena UPZ-a. Slično je zapaženo i u simulacijama: rezultat simulacije je u nekim slučajevima jedan preopterećen UPZ u TS, a u drugima dva, odnosno tri.

Dakle, simulacija pokazuje da će mnogo češće biti energetski preopterećen UPZ klase II u TS (a također i na prvom stupu) nego u KPMO-u priključenog objekta.

Kako (u Hrvatskoj) ipak postoji stanovito iskustvo s NN UPZ-ima klase II u stupnim TS i u NN mreži, kao kriterij za izbor UPZ-a za KPMO može poslužiti i usporedba relativne frekvencije energetskog preopterećenja istih s onim u TS.

3.2.2 Utjecaj ulaznih parametara na rezultate simulacija

Razmatran je utjecaj vrijednosti otpora uzemljenja objekta na energetsko opterećenje UPZ-a klase II u KPMO-u, [10]. Najkraće se može kazati, povećanje otpora uzemljenja objekta, bez sustava zaštite od munje, smanjuje energetsko opterećenje UPZ-a u KPMO-u objekta. U tom smislu, za objekt koji se projektira bez sustava zaštite od munje, a s prenaponskom zaštitom, nije potrebno dodatno ulagati u uzemljivač (iznad zahtjeva primijenjene zaštitne mjere) s idejom da bi se poboljšala prenaponska zaštita. Uputnije je uložiti sredstva na sustavno izjednačavanje potencijala u objektu nego na uzemljivač niskog otpora uzemljenja.

Razmatran je također i utjecaj vrijednosti otpora uzemljenja nultog vodiča duž NN mreže na energetsko opterećenje UPZ-a klase II u KPMO-u, [10]. Najkraće se može kazati, povećanje vrijednosti otpora uzemljenja nultog vodiča duž NN mreže ili nepostojanje tih uzemljenja nema velik utjecaj na energetsko opterećenja UPZ-a u KPMO-u. S druge strane, ako se pogleda utjecaj povećanja otpora uzemljenja nultog vodiča duž NN mreže na energetsko opterećenje UPZ-a u TS, jasan je nepovoljan utjecaj. Stoga se zaključno može kazati, smanjenje otpora uzemljenja nultog vodiča duž NN mreže je povoljno za prenaponsku zaštitu cjelokupne NN mreže.

from different manufacturers and had different rated currents, $I_n = 5$ and 10 kA),
- there had been no periodical or any other inspections of the SPDs in the transformer stations of the low-voltage network,
- only some of the transformer stations or low-voltage connection points had Class II SPDs installed on the first poles of the low-voltage network or in front of the transformer stations,
- there were practically no buildings in the low-voltage network with any surge protection installed at the service entrances.

Nonetheless, during the inspection of these ten transformer stations, it was noted that there was a certain number of Class II SPDs that were out of order, i.e. thermally sensitive fuses had disconnected the SPDs from the low-voltage network. A high percentage of these failures can be attributed to energy overloading. All the Class II SPDs that were out of order had a nominal current of 5 kA. Furthermore, the results of the inspection of this small group showed that in some of the transformer stations one low-voltage Class II SPD was out of order, in some two, but not a single transformer station was found (of the ten inspected) in which all three of the SPDs were out of order. A similar observation was made in the simulations, so that in some cases there was one overloaded SPD at a transformer station, and in others two or three.

Hence, simulation demonstrates that Class II SPDs at a transformer station (and also on the first pole) are much more frequently overloaded than at the service entrances of connected buildings.

Since there has been some experience in Croatia with low-voltage Class II SPDs installed at pole-mounted transformer stations and in low-voltage networks, criteria for the selection of the SPDs for service entrances can be based upon comparison of the relative frequencies of the energy overloading of the SPDs at such locations with those at transformer stations.

3.2.2 The impact of input parameters on the simulation results

The impact of the ground resistance value of buildings on the energy loads of Class II SPDs at service entrances has been studied [10]. It can briefly be stated that the increase of a building's ground resistance value, without a lightning protection system, reduces the energy loading on the SPDs at the service entrance of the building. In this sense, for a building that is designed without a lightning protection system but with surge protection, it is not necessary to make further investment in the grounding system (above the requirements of the protective measure applied) with the idea of improving surge protection. It is more advisable to invest in systematic potential equalizing in the building than in low resistance grounding.

Razmatran je i utjecaj broja priključenih objekata koji imaju UPZ klase II u KPMO-u na energetsko opterećenje UPZ-a, [10]. Povećanje broja priključenih objekata s UPZ-ima u KPMO-u smanjuje vjerojatnost njihova energetskog preopterećenja pri udarima munje u NN mrežu. To se moglo i očekivati jer je poznata činjenica, a koja je i prije spomenuta, da UPZ-i klase II (kao i bili koji drugi odvodnici prenapona na MO bazi) imaju svojstvo da dijele struju, odnosno energiju koju odvode u zemlju, na način da svaki UPZ odvodi dio ukupne energije.

4 ZAKLJUČNO RAZMATRANJE

Razvijena metode izbora UPZ-a u NN sustavima sastoji se od sljedećeg: za svaku tipičnu primjenu UPZ-a napravi se odgovarajući EMTP-ATP model. Usvoji se prihvatljivi rizik kvara zbog energetskog preopterećenja UPZ-a klase II. Prema usvojenom riziku odabire se odgovarajuća struja munje. Provode se simulacije udara munje i računa energetsko opterećenje UPZ-a. Simulacijama dobivena relativna frekvencija energetskog preopterećenja povezuje se s usvojenim rizikom te donosi zaključak je li UPZ klase II adekvatan za primjenu.

Metoda je testirana i na preciznijem rasteru (kombiniranjem mjesta priključka i mjesta udara po 33 m, odnosno 35 m, što je jedan raspon NN mreže) [10]. Precizniji raster daje još povoljnije rezultate, odnosno potvrđuje mogućnost primjene UPZ-a klase II za razmatranu NN mrežu. To nadalje znači da se grubi raster može koristiti u praktičnim primjenama, a da će dobiveni rezultati biti na strani sigurnosti.

Primjenom ovakve metode, za različite tipične primjene UPZ-a, može se zaključiti kakav UPZ je adekvatan.

The impact of the neutral ground resistance value of the conductor along a low-voltage network upon the energy loading of a Class II SPD at a service entrance [10] was also studied. It can be briefly stated that an increase in the neutral ground resistance values along a low-voltage network or the lack of such grounding does not have a great impact upon the energy loading of an SPD at a service entrance. On the other hand, when the impact of an increased neutral ground resistance value along a low-voltage network on the energy loading of a SPD at a transformer station is studied, the undesirable impact is clear. Therefore, in conclusion it may be stated that reducing the neutral ground resistance value of the conductor along a low-voltage network has a favorable impact on the surge protection of the entire low-voltage network.

The impact was also studied of the number of connected buildings that have Class II SPDs in their service entrances on the energy loading of an SPD [10]. In a low-voltage network, an increased number of connected buildings with SPDs installed at the service entrances reduces the probability of their energy overloading during lightning strokes. This could be anticipated because it is known, as previously mentioned, that Class II SPDs (like any other MO-based surge arresters) have the property to distribute current, that is, the energy they divert to the ground, so that each SPD diverts a part of the total energy.

4 CONCLUSION

A method for choosing SPDs in low-voltage systems has been developed, as follows: A suitable EMTP-ATP model should be prepared for each typical application. The acceptable risk of failure due to the energy overloading of a Class II SPD is adopted. The corresponding lightning current is chosen according to the adopted risk. Lightning stroke simulation is performed and the energy loading of the SPD is calculated. Through simulations, the relative frequency of energy overloading is obtained, which is then correlated with the adopted risk, on the basis of which it is concluded whether a Class II SPD would be adequate.

This method has also been tested on a more precise scale by combining the locations of the connections with the locations the lightning strokes in increments of 33 m, or respectively 35 m, which represents one segment of a low-voltage network) [10]. A more precise scale yields more accurate results, i.e. confirms the possibility for the application of Class II SPDs in the low-voltage network being considered. Furthermore, this means that a rough scale can be used in practical applications and the results obtained will be on the side of safety.

Through the application of such a method, it is possible to determine which SPDs are suitable for various typical applications.

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