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**STOHAŠTIČKO DETERMINISTIČKA METODA
MONTE CARLO SIMULACIJE STRUJNIH HARMONIKA NA SN/NN
TRANSFORMATORSKIM STANICAMA
STOCHASTIC DETERMINISTIC METHOD OF
MONTE CARLO SIMULATION OF HARMONIC CURRENTS AT MV/LV
TRANSFORMER STATIONS**

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Sažetak: Na temelju mjerenja strujnih harmonika i opterećenja na gradskim transformatorskim stanicama 10(20)/0,4 kV koje napajaju kućanstva, u radu su istražene metode pronalaženja stohastičkog modela SN/NN transformatorske stanice kao skupnog izvora strujnih harmonika. Također je istražena mogućnost procjene statističke razdiobe tjednih vrijednosti strujnih harmonika na SN/NN transformatorskoj stanici Monte Carlo simulacijom, poznavajući podatke potrebne za planiranje mreže kao što su vršno opterećenje transformatorske stanice i tip potrošnje.

Ključne riječi: – harmonici
– mjerenje
– Monte Carlo simulacija
– Klaster analiza

Abstract: On the basis of the harmonic currents and load measurement at urban transformer stations 10(20)/0.4 kV which supply households, the method of finding the stochastic model of the MV/LV transformer station as a group source of harmonic currents is investigated. Also investigated is the possibility of assessment of the statistic distribution of weekly values of the harmonic currents at the MV/LV transformer station with Monte Carlo simulation, knowing the data needed for network planning such as the maximum load and the type of consumption.

Keywords: – harmonics
– measurement
– Monte Carlo simulation
– Cluster analysis

1. UVOD

U međunarodnim normama uveden je stohastički pristup definiranja razine elektromagnetske kompatibilnosti, [1, 2]. Suvremeni proračuni harmonika stoga u obzir trebaju uzeti stohastičku prirodu harmonika, [3, 4]. Stohastički proračun širenja harmonika u elektroenergetskom sustavu moguće je napraviti analitički ili numeričkom simulacijom. Ukoliko je promatrana mreža velika, proračun numeričkom simulacijom često je jedini mogući pristup, [5]. Za takav način stohastičkog proračuna harmonika potrebno je istražiti metodu pronalaženja stohastičkog modela SN/NN transformatorske stanice kao grupnog izvora strujnih harmonika. Model treba omogućiti procjenu statističke razdiobe tjednih vrijednosti strujnih harmonika na SN/NN transformatorskoj stanici Monte Carlo simulacijom, poznavajući uobičajene podatke potrebne za planiranje

1. INTRODUCTION

International standards have introduced the stochastic approach in defining the electromagnetic compatibility level, [1, 2]. Therefore, the new harmonic calculation should take into consideration the stochastic nature of harmonics, [3, 4]. Stochastic harmonic calculation in the electrical system could be made analytically or by numerical simulation. If the considered network is big, the numerical simulation often is the only possible approach, [5]. For such a type of stochastic harmonic calculation, it is necessary to investigate the method of determining the stochastic model of the MV/LV transformer station as a group source of harmonic current. The model should enable the stochastic distribution assessment of current harmonics at the MV/LV transformer station using Monte Carlo simulation, knowing the data usually necessary for network planning,

mreže kao što su vršno opterećenje transformatorske stanice i tip potrošnje.

2. MJERENJE HARMONIKA

U svrhu modeliranja SN/NN transformatorske stanice kao izvora harmonika, u Zagrebu su napravljena mjerenja harmonika na 18 gradskih transformatorskih stanica 10(20)/0,4 kV koje napajaju kućanstva, [6]. Mjerenja su na svakom mjernom mjestu trajala po tjedan dana. Izmjerene vrijednosti harmonika odnose se na pokazatelje u kratkom vremenu, $I_{h,sh}$. Znači da su mjerene deset minutne prosječne vrijednosti harmonika napona i struje u svim trima fazama.

3. STATISTIČKA ANALIZA MJERENJA HARMONIKA

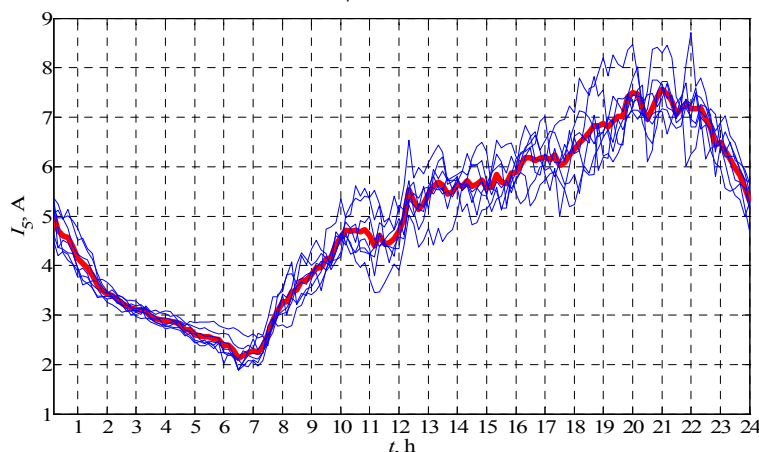
3.1 Tjedna krivulja harmonika struja

Rezultat mjerenja veličina $I_{L1,h}$, $I_{L2,h}$, $I_{L3,h}$ u svakoj fazi transformatorskog polja na SN/NN transformatorskoj stanici, tijekom tjedan dana, su vrijednosti $i_{L1,h}(d, t)$, $i_{L2,h}(d, t)$ i $i_{L3,h}(d, t)$. Prosječne vrijednosti struja harmonika tijekom tjedan dana na promatranoj transformatorskoj stanici računaju se iz:

$$i_{h,tj}(d, t) = \frac{i_{L1,h}(d, t) + i_{L2,h}(d, t) + i_{L3,h}(d, t)}{3}, \quad d \in [1, 7], \quad t \in [1, 144]. \quad (1)$$

Sedam dnevnih krivulja na promatranoj transformatorskoj stanici moguće je prikazati jednom prosječnom dnevnom krivuljom harmonika struja, slika 1. Vrijednosti $i_h(t)$ veličine I_h računaju se iz:

$$i_h(t) = \frac{\sum_{d=1}^7 i_{h,tj}(d, t)}{7}, \quad t \in [1, 144]. \quad (2)$$



Slika 1. Dnevne krivulje i prosječna dnevna krivulja 5. harmonika struja na TS 10(20)/0,4 kV – B. Magovca 48
Figure 1. Daily curves and average daily curve of the 5th harmonic current at TS 10(20)/0.4 kV – B. Magovca 48

such as the maximum load of the transformer station and the type of consumption.

2. HARMONIC MEASUREMENT

For the purpose of modeling the MV/LV transformer station as a harmonic source, measurements have been taken at 18 urban transformer stations 10(20)/0.4 kV that feed energy consumption of households in Zagreb, [6]. The measurement period at each measurement point was one week. The measured values are related to the short time indices, $I_{h,sh}$. This means that ten minute average values of harmonic voltage and current in all three phases were measured.

3. STATISTICAL ANALYSIS OF HARMONIC MEASUREMENT

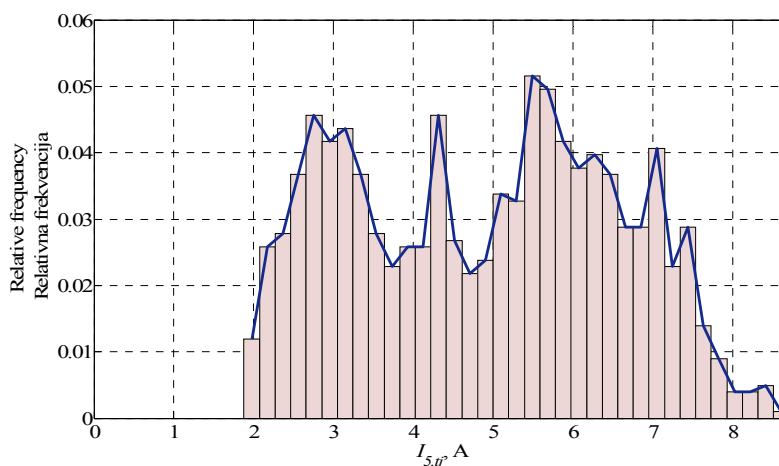
3.1. Weekly Harmonic Currents Curve

The result of measurement of the values $I_{L2,h}$, $I_{L2,h}$, $I_{L3,h}$ in each phase of the transformer bay at the MV/LV transformer station, during period of one week, are the quantities $i_{L1,h}(d, t)$, $i_{L2,h}(d, t)$ and $i_{L3,h}(d, t)$. The average values of harmonic currents during a period of one week on the monitored transformer station are calculated from:

It is possible to represent seven daily curves at the monitored transformer station with one average daily curve of harmonic current, Figure 1. The quantities $i_h(t)$ of the value I_h , are calculated from:

3.2 Histogrami i poligoni relativnih frekvencija

Zbog toga što je često teško unaprijed odrediti razdiobu koja najbolje opisuje slučajnu varijablu, koriste se histogrami i poligoni relativnih frekvencija. Ukoliko razdioba sadrži dva ili više vrhova, ne može se opisati samo jednom funkcijom. Takve se razdiobe nazivaju bimodalnima ili multimodalnima i pokazuju da izmjerena veličina $I_{h,tj}$ nije potpuno stohastička, već da u njoj postoji i određena deterministička komponenta, slika 2.



Slika 2. Histogram i poligon relativnih frekvencija vrijednosti prosječne tjedne krivulje 5. strujnog harmonika na TS 10/0,4 kV - B. Magovca 48

Figure 2. Histogram and polygon of relative frequencies of average weekly curve quantities of the 5th harmonic current at TS 10(20)/0.4 kV – B. Magovca 48

Budući da je teško unaprijed odrediti potreban broj i duljinu podintervala u kojem su vrijednosti slučajne varijable $I_{h,tj}$ stacionarne, moguće je primijeniti metodu dekompozicije vrijednosti nestacionarne slučajne varijable na deterministički i stohastički dio, [7]. Ukoliko su vrijednosti determinističke komponente određene prosječnom dnevnom krivuljom I_h , vrijednosti stohastičke komponente $S_{h,tj}$ dobivaju se iz:

$$s_{h,tj}(d,t) = i_{h,tj}(d,t) - i_h(t), \quad d \in [1,7], \quad t \in [1,144]. \quad (3)$$

4. GRUPIRANJE DNEVNIH KRIVULJA STRUJNIH HARMONIKA KLASTER ANALIZOM

4.1. Normiranje krivulja

Prosječne dnevne krivulje različitih transformatorskih stanica razlikuju se po obliku te najvećoj i najmanjoj postignutoj dnevnoj vrijednosti. Ukoliko se prosječne dnevne krivulje normiraju na interval [0, 1], nestaje razlika u najvećoj i najmanjoj postignutoj vrijednosti strujnih harmonika. Omjeri između najvećih i najmanjih vrijednosti normiranih krivulja ostaju nepromijenjeni korištenjem formule:

3.2 Histograms and polygon of relative frequencies

Since it is often difficult to define in advance the best distribution which describes the stochastic variable, histograms and polygons of relative frequencies are used. If the distribution has two or more peaks, it could not be described with only one function. Such distributions are called bimodal or multimodal and they show that the measured value $I_{h,tj}$ is not completely stochastic, but it comprises certain deterministic components, Figure 2.

Keeping in mind that it is difficult to define in advance the necessary number and the length of the subinterval in which the values of the stochastic variable $I_{h,tj}$ are stationary, it is possible to apply the method of decomposition of the values of the non-stationary stochastic variable to the deterministic and stochastic part. If the values of deterministic component are defined with an average daily curve I_h , the values of stochastic component $S_{h,tj}$, are calculated from:

4. GROUPING OF DAILY CURRENT HARMONIC CURVES USING CLUSTER ANALYSIS

4.1. Normalizing of the Curves

The average daily curves from the various transformer stations are distinguished by shape and by achieved maximum and minimum daily values. If average daily curves are normalized to the interval [0, 1], the difference in achieved maximum and minimum daily values disappears. The ratio between maximum and minimum values remains unchanged using the formula:

$$i_{h,n}(t) = \frac{i_h(t)}{\max(i_h(t))}, \quad t \in [1, 144]. \quad (4)$$

Normirane krivulje moguće je grupirati po sličnosti oblika u klastere. Svaki klaster dalje se nadomješta prototipnom krivuljom koja ga karakterizira.

The normalized curves could be grouped in clusters by similarity of shape. Each cluster is further represented by a prototype curve which characterizes it.

4.2. Hijerarhijska klaster analiza

Za promatrani skup normiranih prosječnih dnevnih krivulja 5. harmonika struja primjenom:

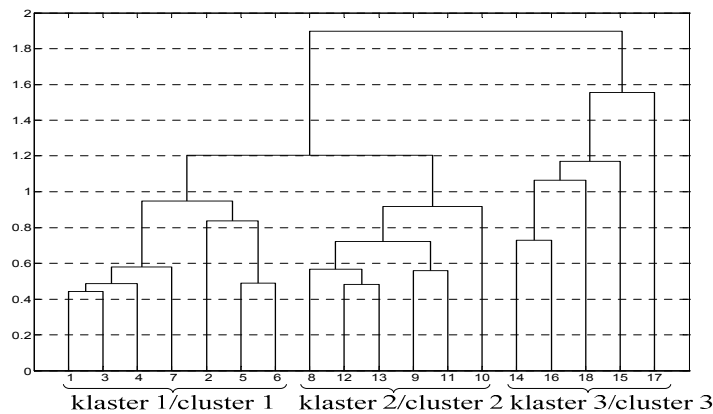
4.2. Hierarchical Cluster Analysis

For the considered set of normalized average daily curves of the 5th current harmonics using the formula:

$$d^2(\mathbf{x}_r, \mathbf{x}_s) = (\mathbf{x}_r - \mathbf{x}_s)(\mathbf{x}_r - \mathbf{x}_s)^T = \sum_{j=1}^n (x_{rj} - x_{sj})^2, \quad (5)$$

izračunate su vrijednosti međusobnih euklidskih udaljenosti krivulja. Rezultat hijerarhijske klaster analize često se grafički prikazuje kao stablo koje se zove dendrogram, [8], na kojemu su vidljivi odnosi između klastera i podklastera te poredak spajanja klastera, slika 3.

the values of Euclidean distances between curves are calculated. The result of Hierarchical Cluster Analysis often is represented by a tree which is called dendrogram, [8], in which the relations between clusters and sub clusters and order of linkage between clusters can be seen, Figure 3.



Slika 3. Dendrogram klastera normiranih prosječnih dnevnih krivulja 5. harmonika struja
Figure 3. Cluster dendrogram of normalized average daily curves of the 5th current harmonic

Za klastere normiranih prosječnih dnevnih krivulja 5. harmonika izmjenjenih na SN/SN stanicama, slika 4, računaju se pripadajući centriodi pomoću formule:

For clusters of normalized average daily 5th harmonic curves measured at the MV/LV transformer station, Figure 4, the related centroids are calculated using formula:

$$c_h(t) = \frac{\sum_{i=1}^{n_k} i_{n,h}(t)}{n_k}, \quad t \in [1, 144]. \quad (6)$$

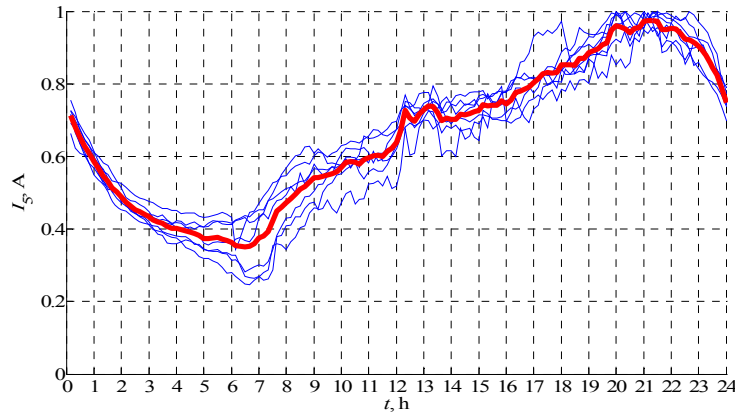
Ukoliko se centroid nadomjesti polinomom, dobiva se analitička formula za određivanje procijenjene vrijednosti prosječne dnevne krivulje strujnih harmonika:

If the centroid is substituted with the polynomial curve, the result is an analytical formula for calculating the estimated values of the average daily harmonic current curve:

$$\hat{i}_h(t) = (a_{k,6} t^6 + a_{k,5} t^5 + a_{k,4} t^4 + a_{k,3} t^3 + a_{k,2} t^2 + a_{k,1} t + a_{k,0}) \hat{y}_h, \quad t \in [1, 144], \quad (7)$$

gdje su $a_{k,p}$ koeficijenti polinoma kojima se nadomještaju prototipne krivulje klastera, tablica 1.

where $a_{k,p}$ are the coefficients of the polynomial curves for the substitution of the prototype curve of the clusters, Table 1.



Slika 4. Normirane prosječne dnevne krivulje 5. harmonika struja i pripadajući centroid klastera 1
 Figure 4. Normalized average daily curves of the 5th harmonic current and the corresponding centroid of cluster 1

Tablica 1. Koeficijenti polinoma kojima se nadomještaju prototipne krivulje 5. strujnog harmonika klastera 1, 2 i 3
 Table 1. Polynomial coefficients for fitting prototype curve of the 5th harmonic current for clusters 1, 2 and 3

Klaster Cluster	$a_{k,6}$	$a_{k,5}$	$a_{k,4}$	$a_{k,3}$	$a_{k,2}$	$a_{k,1}$	$a_{k,0}$
$k=1$	$-7,5989 \cdot 10^{-12}$	$-2,9732 \cdot 10^{-9}$	$-4,1785 \cdot 10^{-7}$	$2,3364 \cdot 10^{-5}$	$-1,8595 \cdot 10^{-4}$	$-1,7678 \cdot 10^{-2}$	0,07051
$k=2$	$-3,3505 \cdot 10^{-12}$	$1,1126 \cdot 10^{-9}$	$-1,1933 \cdot 10^{-7}$	$2,2206 \cdot 10^{-6}$	$4,5349 \cdot 10^{-4}$	$-2,6000 \cdot 10^{-2}$	0,72050
$k=3$	$-6,2592 \cdot 10^{-12}$	$2,5913 \cdot 10^{-9}$	$-3,9498 \cdot 10^{-7}$	$2,5545 \cdot 10^{-5}$	$-5,0234 \cdot 10^{-4}$	$-4,4534 \cdot 10^{-3}$	0,65010

Odstupanja polinoma od normiranih krivulja unutar klastera moguće je izračunati iz:

Residual values of polynomial curve from normalized curves within cluster could be calculated from:

$$\Delta i_{h,k}(i, t) = i_{h,n}(i, t) - i_{h,k}(t), \quad i \in [1, n_k], \quad t \in [1, 144], \quad (8)$$

Srednja vrijednost i standardna devijacija odstupanja polinoma od normiranih krivulja unutar klastera izračunava se pomoću:

The mean value and standard deviation of residuals of polynomial curve from the normalized curves within cluster are calculated from:

$$\mu_{\Delta i_{h,k}} = \frac{\sum_{i=1}^{n_k} \sum_{t=1}^{144} \Delta i_{h,k}}{n_k \cdot 144}, \quad (9)$$

$$\sigma_{\Delta i_{h,k}} = \sqrt{\frac{\sum_{i=1}^{n_k} \sum_{t=1}^{144} (\Delta i_{h,k}(i, t) - \mu_{\Delta i_{h,k}})^2}{n_k \cdot 144 - 1}}. \quad (10)$$

Tablica 2. Srednja vrijednost i standardna devijacija odstupanja polinomne krivulje od normiranih krivulja 5. harmonika struja unutar klastera

Table 2. Mean value and standard deviation of residuals of polynomial curve from the normalised 5th harmonic current curves within cluster

Klaster	n_k	$\mu_{\Delta i_{h,k}}$	$\sigma_{\Delta i_{h,k}}^2$
$k=1$	7	$2,56 \cdot 10^{-15}$	0,049
$k=2$	6	$2,97 \cdot 10^{-15}$	0,048
$k=3$	5	$-1,55 \cdot 10^{-15}$	0,071

Tablica 2 prikazuje srednju vrijednost i standardnu devijaciju odstupanja polinoma od normiranih krivulja 5. harmonika struja unutar klastera.

Table 2 shows the mean value and standard deviation of residuals of the polynomial curve from the normalised 5th harmonic current curves within the cluster.

5. PROGNOZA DNEVNE KRIVULJE STRUJNIH HARMONIKA

5. PROGNOSIS OF DAILY HARMONIC CURRENT CURVE

5.1. Regresijska analiza

5.1. Regression analysis

Pretpostavka o koreliranosti vršnih opterećenja transformatorskih stanica i vršnih vrijednosti prosječnih dnevnih krivulja strujnih harmonika dovodi do zaključka da je nezavisna varijabla vršno opterećenje transformatorske stanice, dok je zavisna varijabla vršna vrijednost prosječne dnevne krivulje strujnih harmonika. Vršno opterećenje transformatorske stanice veličina je koja se najčešće koristi u planiranju srednjonaponskih elektroenergetskih mreža. Skup vrijednosti nezavisne varijable dobiva se iz:

The assumption that the peak load of transformer stations and the peak value of the average daily harmonic current curves are correlated leads to the conclusion that the independent variable is the transformer station peak load and the dependent variable is the peak value of the average daily harmonic current curve. The peak load of the transformer station is the most frequently used data in medium voltage network planning. The set of independent variable values are calculated from:

$$x_i = S_{m,i} = \max(S_i(t)), \quad t \in [1, m]. \quad (11)$$

Skup vrijednosti zavisne varijable dobiva se iz:

The set of dependent variable values are calculated from:

$$y_i = I_{hm,i} = \max(I_{h,sr}(t)), \quad t \in [1, m]. \quad (12)$$

Model linearne regresije s procijenjenim parametrima je:

The linear regression model with estimated parameters is:

$$y_i = \hat{y}_i + \hat{e}_i, \quad \hat{y}_i = \hat{\alpha} + \hat{\beta} x_i, \quad i = [1, n]. \quad (13)$$

Procijenjeni parametri računaju se iz, [9]:

The estimated parameters are calculated from, [9]:

$$\hat{\beta} = \frac{\sum_{i=1}^n x_i y_i - n \bar{x} \bar{y}}{\sum_{i=1}^n x_i^2 - n \bar{x}^2}, \quad (14)$$

$$\hat{\alpha} = \bar{y} - \hat{\beta} \bar{x}. \quad (15)$$

Na temelju (14) i (15) izračunati su procijenjeni parametri modela linearne regresije, tablica 3. Koeficijent determinacije r^2 i koeficijent korelacije r izračunati su iz:

On the basis of (14) and (15), the estimated parameters of linear regression model are calculated, Table 3. The determination coefficient r^2 and correlation coefficient r are calculated from:

$$r^2 = \frac{\sum_{i=1}^n (\hat{y}_i - \bar{y})^2}{\sum_{i=1}^n (y_i - \bar{y})^2}, \quad 0 \leq r^2 \leq 1. \quad (16)$$

Razmotri li se povezanost između zavisne i nezavisne varijable, uzevši u obzir koeficijente korelacije i determinacije, vidljivo je da je kod struja 3. i 5. harmonika korelacija čvrsta, kod 7. i 13. harmonika korelacija je srednja, dok je kod 9., 11. harmonika korelacija slaba, tablica 3.

Considering the relationship between dependent and independent variables, taking into account correlation and determination coefficients, it is obvious that for the 3rd and the 5th harmonic current the correlation is strong, for the 7th and the 13th harmonic current the correlation is medium and for the 9th and the 11th harmonic current the correlation is weak, Table 3.

Tablica 3. Modeli linearne regresije s procijenjenim parametrima i faktori korelacije
 Table 3. Linear regression model with estimated parameters and correlation factors

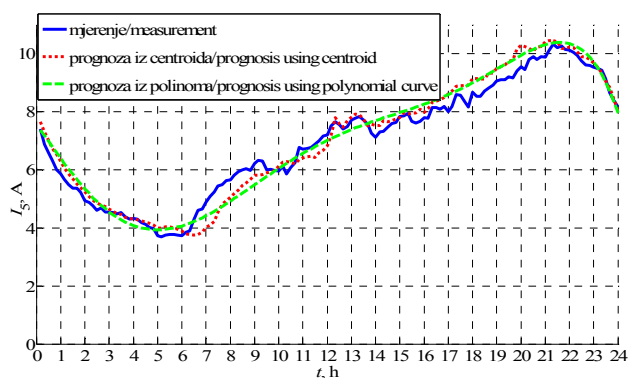
Zavisna varijabla Dependent variable	Model linearne regresije Linear regression model	r^2	r	Jakost korelacije Correlation strength
I_{3m}	$\hat{y} = 5,8171 + 0,0797 x$	0,72	0,85	Čvrsta (strong)
I_{5m}	$\hat{y} = 2,6287 + 0,0455 x$	0,87	0,93	Čvrsta (strong)
I_{7m}	$\hat{y} = 1,0174 + 0,0196 x$	0,53	0,73	Srednja (medium)
I_{9m}	$\hat{y} = 1,9914 + 0,0037 x$	0,30	0,55	Slaba (weak)
I_{11m}	$\hat{y} = 1,4823 + 0,0052 x$	0,23	0,48	Slaba (weak)
I_{13m}	$\hat{y} = 1,0455 + 0,0046 x$	0,26	0,51	Slaba (weak)

5.2. Primjeri prognoze

Uvrštavanjem izmjerenih vrijednosti vršnih opterećenja u odgovarajuće modele jednostavne linearne regresije, tablica 3, dobivaju se procijenjene vrijednosti zavisne varijable, ili procijenjene vršne vrijednosti prosječne dnevne krivulje harmonika struja. Množenjem vrijednosti prototipne krivulje s procijenjenom vršnom vrijednošću prosječne dnevne krivulje strujnih harmonika na promatranoj transformatorskoj stanici, dobivaju se procijenjene vrijednosti prosječne dnevne krivulje strujnih harmonika:

$$\hat{i}_h(t) = c_k(t) \cdot \hat{y}_h, \quad t = [1, n]. \quad (17)$$

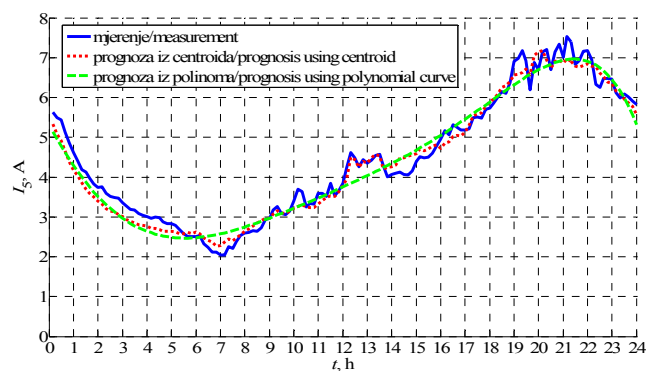
Korištenjem (17) i (7) te vršne vrijednosti prosječne dnevne krivulje strujnih harmonika na promatranoj transformatorskoj stanici, procijenjene iz odgovarajućih modela jednostavne linearne regresije, tablica 3, određuju se prognoze prosječne dnevne krivulje 5. strujnog harmonika, slike 5 i 6.



5.2 Examples of prognosis

By inserting the measured values in the corresponding simple linear regression models, Table 3, the estimated values of dependent variables are calculated, i.e. the estimated peak values of the average daily harmonic curve are thus determined. Multiplying the values of the prototype curve with the estimated peak value of the average daily harmonic curve at the considered transformer station, the estimated values of the average daily harmonic curve are obtained:

By using (17) and (7) with the peak values of the average daily harmonic curve at the considered transformer station, estimated from corresponding simple linear regression model, Table 3, the prognosis of the average daily 5th harmonic current curves is determined, Figures 5 and 6.



Slika 5. Prognoza prosječne dnevne krivulje 5. strujnog harmonika na TS 10/0,4 kV B. Magovca 38 i B. Magovca 44
 Figure 5. Prognosis of daily average 5th current harmonic curve at TS 10/0.4 kV B. Magovca 38 and B. Magovca 44

6. STOHAŠTIČKO DETERMINISTIČKA METODA MONTE CARLO SIMULACIJE

6.1. Algoritam Monte Carlo simulacije tjedne krivulje strujnog harmonika

Poznavajući dva redovito dostupna podatka, vršno opterećenje S_m i tip potrošnje, moguće je Monte Carlo simulacijom procijeniti statističku razdiobu tjednih vrijednosti strujnih harmonika na SN/NN transformatorskoj stanici. Razdioba vrijednosti tjedne krivulje strujnog harmonika može se procijeniti tako da se u iteraciji Monte Carlo simulacije zbroje vrijednosti determinističke i stohastičke komponente strujnih harmonika. Deterministička komponenta je prosječna dnevna krivulja strujnog harmonika koja se određuje analitički iz (7). Stohastička komponenta dobiva se simuliranjem vrijednosti Normalne razdiobe (18).

Algoritam Monte Carlo simulacije tjedne krivulje strujnog harmonika prikazan je na slici 7. Algoritam se sastoji iz sljedećih koraka:

- Za promatranu SN/NN transformatorsku stanicu potrebno je odrediti vrijednost vršnog opterećenja S_m . Navedena veličina koristi se u planiranju sredjonaponskih mreža kao ulazna veličina u proračunu tokova snaga gdje se, ukoliko ne postoje mjerenja, najčešće procjenjuje iz broja i tipa kupaca priključenih na mrežu niskog napona.
- Transformatorska stanica se svrstava u jedan od klastera.
- Temeljem modela jednostavne linearne regresije, tablica 3, iz vršne vrijednosti opterećenja transformatorske stanice procjenjuje se vršna vrijednost prosječne dnevne krivulje strujnog harmonika \hat{y}_h .
- Početak Monte Carlo simulacije.
- Početak izračuna normirane prosječne dnevne krivulje strujnog harmonika.
- Temeljem koeficijentata polinoma, tablica 1, za međuvrijeme t računa se vrijednost normirane prosječne dnevne krivulje strujnog harmonika, (13).
- Metodom inverzne transformacije simuliraju se vrijednosti stohastičke komponente normirane tjedne krivulje strujnog harmonika. Zbroj normiranih vrijednosti determinističke i stohastičke komponente tjedne krivulje pomnožen s procijenjenom vršnom vrijednošću prosječne dnevne krivulje daje skup simuliranih vrijednosti tjedne krivulje strujnog harmonika:

$$\hat{i}_{h,tj}(m,t) = \left(i_{h,k}(t) + N\left(\mu_{\Delta i_{h,k}}, \sigma_{\Delta i_{h,k}}\right) \right) \hat{y}_h. \quad (18)$$

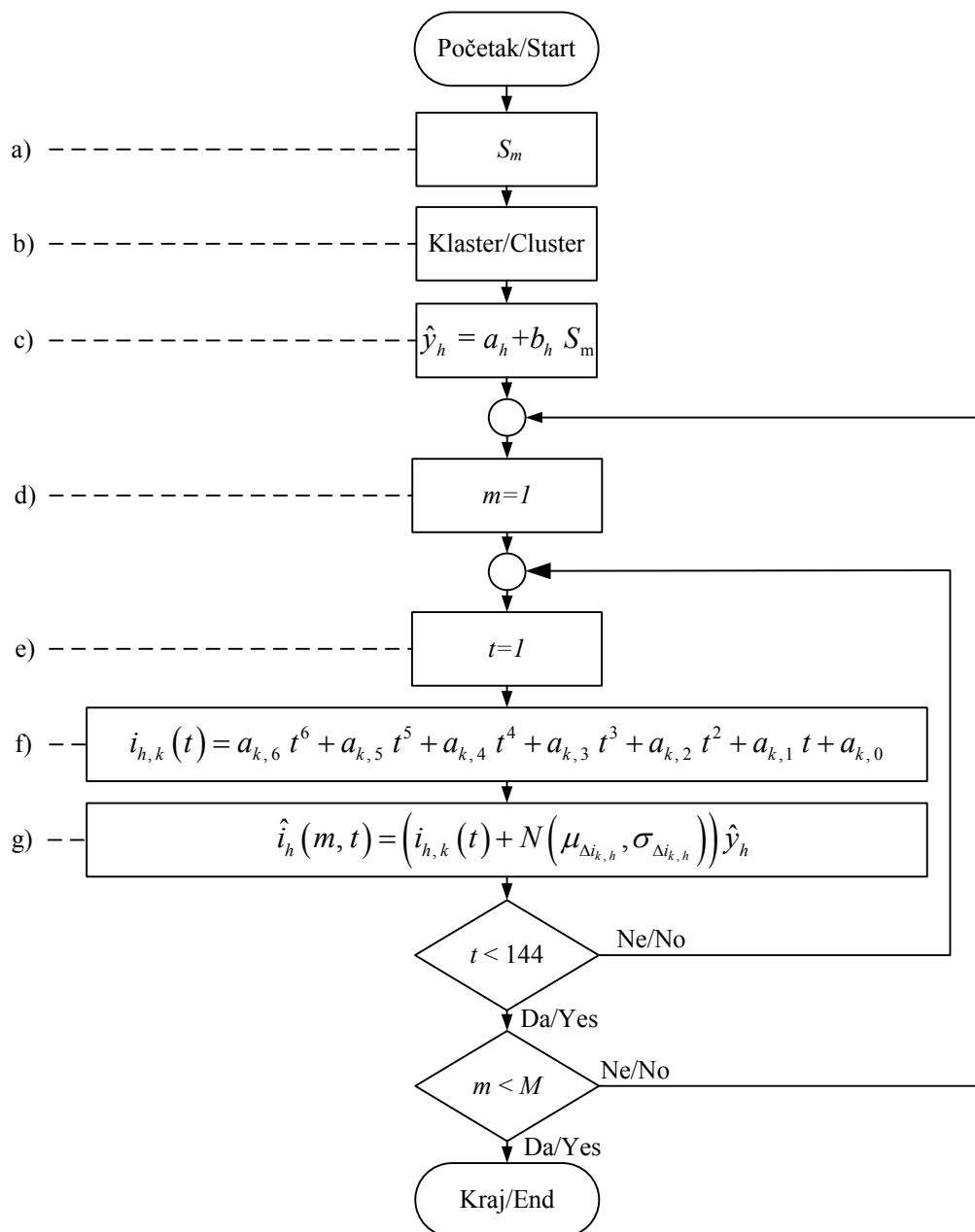
6. STOCHASTIC DETERMINISTIC METHOD OF MONTE CARLO SIMULATION

6.1. Monte Carlo Algorithm of Weekly Harmonic Current Simulation

Knowing two regularly available values, the transformer station peak load and the type of energy consumption, by using the Monte Carlo simulation it is possible to assess the stochastic distribution of harmonic currents weekly values at the MV/LV transformer station. Distribution of the weekly harmonic current values could be assessed by summation of harmonic deterministic and stochastic current component in the Monte Carlo iteration. The deterministic component is an average daily curve of the harmonic current which is determined analytically using (7). The stochastic component is obtained by simulation of values with Normal distribution (18).

The algorithm of the Monte Carlo simulation of the weekly harmonic current is shown in Figure 7. The algorithm consists of the following steps:

- For the considered MV/LV transformer station, it is necessary to determine the peak load S_m . This value is used in medium voltage network planning as an input value for load flow calculation where, if measurements aren't available, it is assessed from the number and the type of consumers connected to low voltage network.
- The transformer station is classified into one of the clusters.
- On the basis of the simple linear regression model, Table 3, from the transformer station peak load, the peak value of the average daily harmonic curve \hat{y}_h is assessed.
- Start of the Monte Carlo simulation.
- Start of the calculation of the normalized average daily harmonic curve.
- On the basis of polynomial coefficients, Table 1, for the time interval t , the value of the normalized average daily harmonic curve is calculated (13).
- With the Inversion Transformation Method, the values of the stochastic component of the normalized weekly harmonic current are calculated. The summation of normalized values of the stochastic and the deterministic component of the weekly harmonic curve multiplied by the assessed peak value of the average daily harmonic curve results in the set of simulated values of the weekly harmonic curve:



Slika 7. Algoritam Monte Carlo simulacije vrijednosti tjedne krivulje h-tog strujnog harmonika na SN/NN transformatorskoj stanici

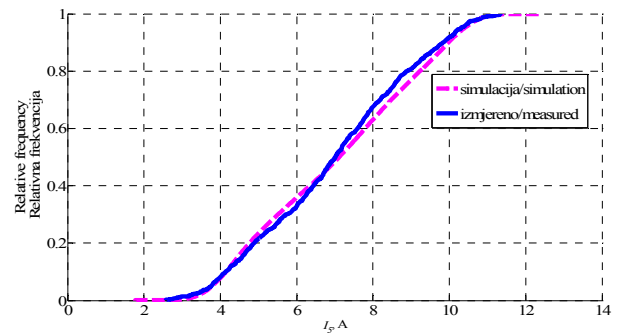
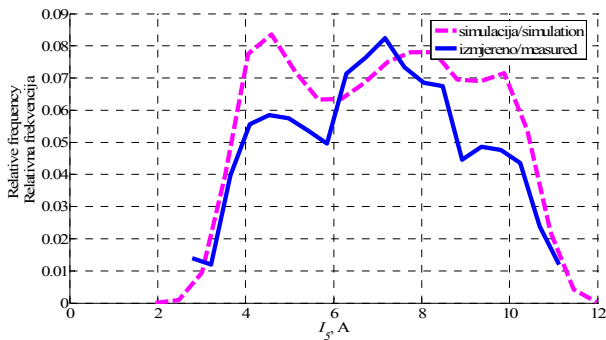
Figure 7. Algorithm of the Monte Carlo simulation of the weekly curve of the harmonic current at the MV/LV transformer station

6.2. Primjer Monte Carlo simulacije tjedne krivulje strujnog harmonika

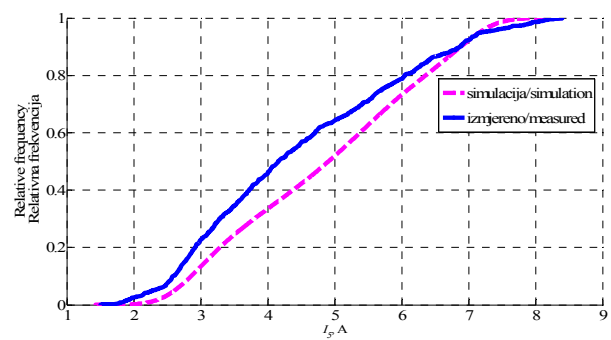
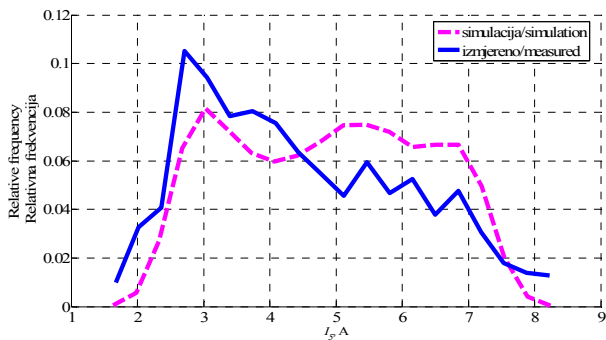
6.2 An example of the Weekly Harmonic Current Simulation

Na temelju opisanog algoritma napravljena su dva primjera Monte Carlo simulacije vrijednosti tjedne krivulje 5. strujnog harmonika. Prikazana je usporedba razdiobe izmjerenih i simuliranih vrijednosti tjedne krivulje 5. strujnog harmonika, slike 8 i 9.

On the basis of the described algorithm, two examples of Monte Carlo simulation of the weekly 5th harmonic current simulation are made. A comparison between measured and simulated values of the weekly 5th harmonic current is shown, Figures 8 and 9.



Slika 8. Razdioba vrijednosti tjedne krivulje 5. strujnog harmonika na TS 10/0,4 kV TS B. Magovca 38
Figure 8. Distribution of quantities of the 5th harmonic current weekly curve at TS 10/0.4 kV TS B. Magovca 38



Slika 9. Razdioba vrijednosti tjedne krivulje 5. strujnog harmonika na TS 10/0,4 kV TS B. Magovca 44
Figure 9. Distribution of quantities of the 5th harmonic current weekly curve at TS 10/0.4 kV TS B. Magovca 44

7. ZAKLJUČAK

Monte Carlo metodom moguće je simulirati strujne harmonike na SN/NN stanicama. Pritom treba biti zadovoljena pretpostavka vremenske nepromjenjivosti, u smislu odsustva determinističke komponente u izmjerenim vrijednostima strujnih harmonika. Jedna od metoda rješavanja problema vremenske promjenjivosti strujnih harmonika je rastavljanje nestacionarne vremenske serije na stacionarni stohastički proces i determinističku komponentu. Poznavajući dva redovito dostupna podatka, vršno opterećenje i tip potrošnje, moguće je Monte Carlo simulacijom procijeniti statističku razdiobu tjednih vrijednosti strujnih harmonika na SN/NN transformatorskoj stanici. Na temelju opisanog postupka napravljena su dva primjera Monte Carlo simulacije vrijednosti tjedne krivulje 5. strujnog harmonika. Prikazana je usporedba razdiobe izmjerenih i simuliranih vrijednosti tjedne krivulje 5. strujnog harmonika. Prikazani stohastički model SN/NN transformatorske stanice moguće je uključiti u algoritam Monte Carlo proračuna harmonika u srednjonaponskoj mreži.

7. CONCLUSION

Using the Monte Carlo method, it is possible to simulate harmonic currents at the MV/LV transformer stations. In doing so, the definition of time invariability has to be fulfilled, in the sense of the absence of the deterministic component from measured values of harmonic currents. One of the methods for solving the problem of harmonic currents time variability is the decomposition of time series into the stationary stochastic process and the deterministic component. Knowing the two regularly available values, the transformer station peak load and the type of consumption, by using Monte Carlo simulation it is possible to assess stochastic distribution of the harmonic currents weekly values at the MV/LV transformer station. On the basis of the described algorithm, two examples of the Monte Carlo simulation of the weekly 5th harmonic current are made. The comparison between measured and simulated values of the weekly 5th harmonic current is shown. It is possible to include the presented stochastic model of the MV/SN transformer station in the Monte Carlo algorithm for harmonic calculation in medium voltage networks.

8. POPIS OZNAKA

struja harmonika u fazi L1	$I_{L1,h}$	A
tjedna krivulja harmonika struje dan u tjednu	$I_{h,tj}$	A
red harmonika	d	
vremenski interval	h	
dnevna krivulja harmonika struje	t, h	
normirana dnevna krivulja struje	I_h, A	
stohastička komponenta harmonika struje	$I_{h,n}$	A
objekt u klaster analizi	$S_{h,tj}$	kW
točka krivulje centroida	\mathbf{x}	
centroid	c_h	
broj krivulja u klasteru	C_h	
procijenjena vrijednost struje harmonika	n_k	
procijenjena vrijednost zavisne varijabla	\hat{i}_h	A
koeficijenti polinoma	\hat{y}_h	
odstupanja polinoma od klastera	$a_{k,p}$	
srednja vrijednost odstupanja	$\Delta i_{h,k}$	
standardna devijacija odstupanja	$\mu_{\Delta i_{h,k}}$	A
nezavisna varijabla	$\sigma_{\Delta i_{h,k}}$	A
zavisna varijabla	x_i	
procijenjeni parametar regresije	y_i	
procijenjeni parametar regresije	$\hat{\alpha}$	
koeficijent determinacije	$\hat{\beta}$	
koeficijent korelacije	r^2	
procijenjena vrijednost struje harmonika	r	
Normalna razdioba	\hat{i}_h	A
	N	

8. LIST OF SYMBOLS

harmonic current in phase L1	
weekly current harmonic curve	
day of the week	
harmonic order	
time interval	
daily current harmonic curve	
normalized daily current curve	
stochastic component of harmonic current	
object in cluster analysis	
point of centroid curve	
centroid	
number of curves in cluster	
estimated value of the harmonic current	
estimated value of depended variable	
polynomial coefficients	
residual values of polynomial curves from cluster	
mean value of residuals	
standard deviation of residuals	
independent variable	
dependent variable	
estimated regression parameter	
estimated regression parameter	
determination coefficient	
correlation coefficient	
estimated value of harmonic current	
Normal distribution	

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