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Generic Model of Coastal Distribution Network for Power System Harmonics Studies

***Abstract**. The paper presents a generic model of typical coastal distribution network developed for power quality studies. Its composition is based on number of measurements performed over long period of time at different connection points in existing distribution network. All relevant elements of the network are fully described and discussed. The generic model can be used for benchmarking results of power system studies, in particular harmonic studies, for coastal regions network including specific types of consumers like hotels, resorts, marinas, airports, apartment buildings, market centres and moderate size industrial plants.*

***Streszczenie.** W artykule zaprezentowano typową nadmorską sieć przesyłową z przeznaczeniem do analizy jakości energii. Opisano dokładnie wszystkie elementy sieci oraz długookresowe wyniki badań. Celem jest analiza takiej sieci z uwzględnieniem jej typowych odbiorców takich jak hotle, centra handlowe, apartamentowce itp. (**Model generyczny nadmorskiej sieci przesyłowej oraz analiza jakości energii w takiej sieci**)*

Keywords: Generic model, Power system harmonics, Power system measurement, Power distribution network modeling, Power quality.
Słowa kluczowe: nadmorska sieć przesyłowa, model generyczny, jakość energii.

1. Introduction

Typical coastal distribution network, a type of distribution network that can be found along the Mediterranean coast and similar coastal regions around the World, is characterized by radial structure with relatively long medium-voltage lines (10kV) and short high-voltage cables (35kV), dispersion of power consumption at low voltage level and relatively short low voltage lines (0.4kV). The main occupations of such a region are services in touristic and related industry. As a result, some of these networks have experienced significant changes, due to intensive tourism development and building. With deregulation and wide spread connections of renewable energy sources (PV, wind generators and similar) as distributed generation at low and medium voltage levels, such networks may increase its complexity even more.

The loads are mainly concentrated in individual buildings, big or small hotels, airports, commercial centers (shopping malls), marinas, light industry and other facilities. Their demand is variable during the year, mainly two-seasonal: during the summer there is very high demand, while during the winter these networks operate at low capacity (except for some exceptional days, like New Year eve or similar). Further typical characteristic of these networks are relatively high level of reactive power, low power factor (cosφ) and possible large unbalance.

Some of the loads typically found in these networks are highly nonlinear and well known as power system harmonic sources (air conditioning, public lighting, electric supply of yachts in marinas, commercial and entertainment centers, leisure facilities, low power electronics, audio and video devices, PCs and similar). They cause numerous undesirable effects, such as resonances, capacitor bank failures, insulation overheating, short-circuit in cables, etc. The situation may become even more challenging in the future due to expected large increase in the use of electric vehicles in urban transportation as those will require construction of fast charging battery stations along main traffic corridors and in car parks. These devices, being highly nonlinear, will contribute further to increase in network harmonic levels. To be able to analyze different scenarios in such networks, especially for power quality purposes, a generic model of network is needed.

Today, there is relatively small number of validated generic network models. These models are mainly oriented towards describing typical urban, rural or industrial, small or large network topologies [1,2,3,4]. Some of them are used for better understanding of behavior of physical network parameters, studying of phenomenon which is characteristic for specific operating states, etc [1,2]. Some were created based on real network with very specific characteristics for application in certain distribution system [3,4]. Some are used for studying specific scenarios [22,23], such as operating network with wind turbines [20,21] or solar panels included [6,7,8], or for analyzing some technical, as well as very specific non-technical (e.g., economic) issues [5,9]. Also, some strictly technical issues, e.g., reconfiguration of distribution networks, lead to creating generic network models [5,10,24,25].

In creating these models, the authors have distinguished several different approaches: stochastic-probabilistic, deterministic or combined one. Stochastic-probabilistic approach is based on comprehensive harmonic measurements and analysis using relevant probabilistic methods [11]. In deterministic approach the authors have applied knowledge based on research of relatively small number of units. Small deterministic systems are easy to visualize, but are necessarily linked to the real life scenario by an initial cause and/or final effect. The downside of this approach is that it does not fully cover the fact that there is a whole range of possible outcomes some of which are more probable and some less [6]. Combined approach uses mixture of the aforementioned approaches. In this case, conclusions are derived from stochastic model (based on relevant number of results of measurement) initially developed on a small number of samples [12].

However, none of above mentioned generic models refers to the coastal distribution network. Availability of validated generic network would facilitate benchmarking of power system studies, including power quality related ones, as well as studies related to connection of renewable generation. Further reason for developing generic distribution network for coastal area is the specific configuration of such a network involving, typically long radial feeders with predominantly small and medium loads, customers with predominantly non-linear load, enabling climate conditions for deployment of renewable energy sources (wind, solar, marine), typically large seasonal variation in load and constant demand for high quality and reliability of supply.

In order to facilitate credible results of simulation studies the model of the network must be based on real network with realistic parameters. The parameters of all network elements (transformers, cables, bus-bars, loads, etc.), their connection and interface have to be derived from realistic network elements and based on long term measurements in real networks [2].

This paper presents a generic model of a coastal distribution network for power quality, or more specific, harmonic studies. The model has been validated through harmonic measurements performed over a long period of time (since April 2004), according to international standards (EN 50160, IEC and IEEE standards) and using verified measurement equipment.

2. Modelling of the network

Distribution network used for development of generic model is located in small Mediterranean town with a population of slightly over 14,000 people and about 9,000 customers. The network serves several big customers with very different characteristics. There are residential apartment buildings and individual houses for permanent and temporary residence (holiday homes), schools, nursery, markets, restaurants, shopping center, modern Mediterranean marina, small industry plants, hotels etc. There are about 50 km of cables connecting substations and different customers. Total installed power of network transformers is 23.5 MVA while, total demand is below 16 MVA with typical power factor of cosφ = 0.92.

For creating generic model, only one part of the network is used, i.e., part with two substations (TS) 35kV/10kV and TS 10kV/0.4kV. The 110 kV part of the network was modeled with Thevenin equivalent based on short current level, power level (P, Q, S), and voltages. The 110kV network was modeled as an equivalent voltage source. Each line was modeled with standard SINCAL line model, as a π-equivalent circuit [13]. Medium voltage, 35/10kV, transformers were modeled with standard two-winding transformer model available in SINCAL. All cables are modeled using real parameters (distance, conductor material, cross section, resistance, admittance, etc.).

The reduced model of the network is validated through load flow studies and comparison of results with measurements performed in a real network. All relevant network parameters used in the model, as well as corresponded parameters for each of elements are listed in Tables V-XI in the Appendix.

Each load, described in this paper, is modeled as harmonic current source. For developing harmonic load models standards IEC 61000-2-4 class 1, IEC 61000-2-4 class 2 and IEC 61000-2-4 class 3 were used. Based on measurements performed in the network, harmonic characteristics of loads are developed.

Measurements were performed on a marine for mega yachts, hotels and a hotel complex, an airport, a shopping center, a business trade center, on a group of individual households, apartment buildings with some business offices at ground floor, an industrial plant, a sports hall, a water supply plant, a commercial port and a school and a kindergarten. Each of these customers has more or less specific load profile and harmonic characteristic. This is shown in detail in Chapter 3.

Input settings data for network elements, as well as harmonic characteristics for all loads are given in the Appendix (Tables VIII and XI).

Figure 1 shows typical load models used in modeling. The negative power value is used to represent the load. Load current is represented with (1), and load impedance with (2):

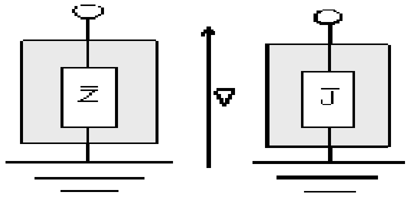

Fig. 1. Equivalent load model

(1) $$\bar{J} = \left(\frac{P_{Ntotal} + jQ_{Ntotal}}{\bar{V}} \right)^{*}$$

(2) $$\bar{Z} = \frac{V_N^2}{P_{Ntotal} - jQ_{Ntotal}}$$

where: J – load current, Z – load impedance, V – voltage. Both parameters are given as complex values.

3. Results of harmonic measurement

All measurements in the network were carried out according to IEC 61000 and EN 50160 and for each characteristic load separately [14,15,16,17]. Based on measurements in real network and in real operating conditions, different specific load models have been identified. Notation C1 to C15 was used for labeling each of different load types. The key information about harmonic characteristics of these loads related to measurements performed in the field, are presented in the sequel.

A. Mediterranean marine - C1

A complex of highly nonlinear loads considered in preparation of generic model is a see-side marina. The boats and yachts represent specific combination of nonlinear loads like rectifiers for charging batteries, small navigation radars, TV, audio devices and other electronic equipment, lighting, navigation instruments etc. Besides that, there are some office buildings, shops, residential apartments, street public lighting, traffic installations and other linear and non-linear loads supplied from the same point of common coupling (PCC).

Measurement, used for developing the model of marina, was performed from September 17-24, 2009 [17]. The results for each of three phases are shown in Fig 2. Total harmonic distortion of recorded current (THDI), as well as three dominant harmonics are presented. Measured values are given as 95% values (values which have not been exceeded during 95% of time). High percentage of the 5th harmonics and large unbalance can be noted.

B. Hotel complex - C2

The hotel complex is part of marina, equipped with high tech devices for air conditioning, video surveillance, smart lifts, smart rooms, modern kitchen equipment, internal TV system, etc. Measurements were performed from July 6 - 15, 2009. Figure 3 shows THDI as well as some individual harmonics.

C. Business and residential complex - C3

This is typical example of modern urban building with residential and business units. Measurement was performed in period of August 17-24, 2008. The results are shown in Fig 4. The 5th harmonic is dominant and large unbalance between phases (in terms of harmonic distortion) can be observed.

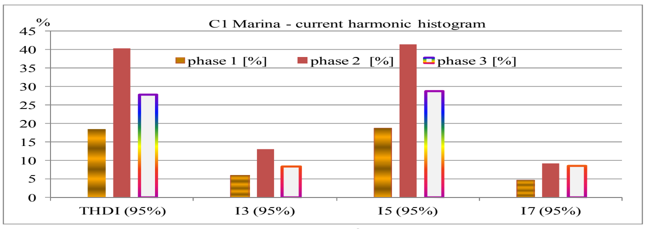

Fig. 2. THDI and current harmonics of a Mediterranean marina

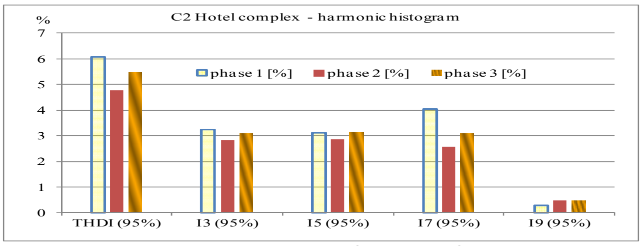

Fig. 3. THDI and current harmonics of a group of hotels

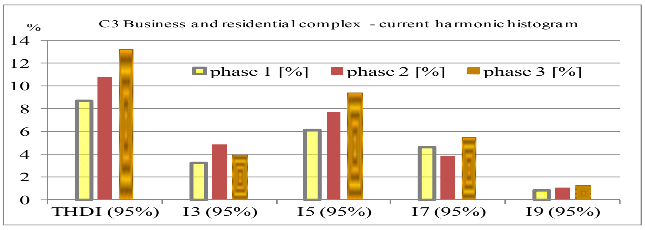

Fig. 4. THDI and current harmonics of a business complex

D. *Shopping center - C4*

A shopping center model has been developed based on measurements performed during August 11-18, 2009. The shopping center contains sophisticated air conditioning and heating systems, strong internal and external lighting systems, video surveillance and control systems, lifts, escalators and other nonlinear devices. Typical harmonics are presented in Figure 5. In addition, operation of large number of small single phase loads results in unbalance.

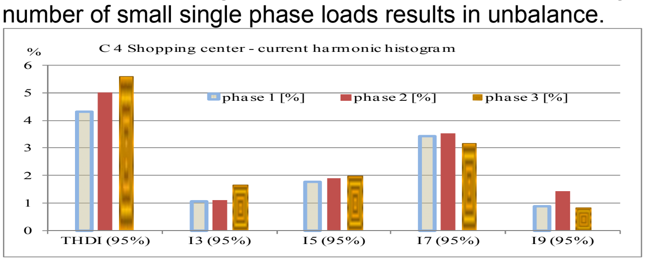

Fig. 5. THDI and current harmonics of a shopping center

E. *Airport - C5*

A significant load in coastal distribution network may be an airport. Measurement at the PCC, i.e. TS 10/0.4 kV "Airport", of the international airport Tivat was performed from Jun 24-28, 2005. The results are shown in Figure 6. Similar data was recorded at another airport in Montenegro, the Airport Podgorica, during period Jun 29 - July 6, 2009.

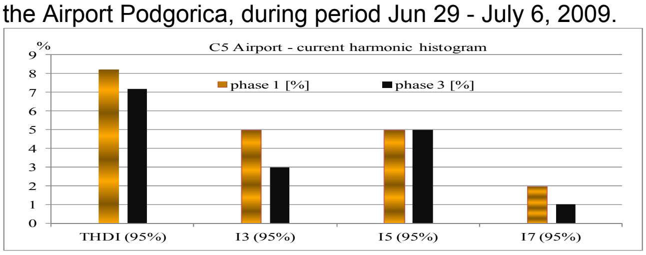

Fig. 6. THDI and current harmonics of a small airport Tivat

F. *Equivalent individual household - C6*

Model of a household is based on measurements performed from July 16-23, 2010. This was a group of over 150 individual houses connected at 10/0.4kV, 400 kVA substation. Figure 7 presents recorded THDI spectrum during the monitoring period. The 3rd harmonic was dominant, as measurement took place in a period that coincides with the broadcasting of the Football World Cup 2010, and a huge number of TV sets were simultaneously connected to the grid.

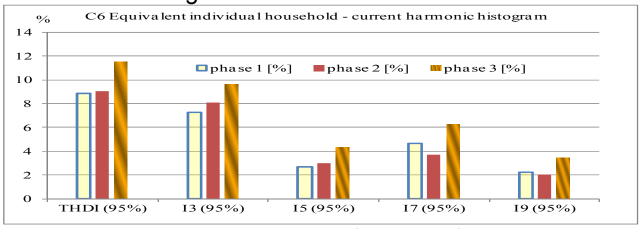

Fig. 7. THDI and current harmonics of a group of individual houses

G. *Apartment (multi flat) building - C7*

Model of typical apartment building (with around 10 apartments) was based on harmonic measurements carried out at TS 10/0.4 kV from May 4-11, 2004. Typical current harmonic spectrum for apartment building is shown in Figure 8. Figure 9 shows recorded THDU during monitoring period. Public lighting contributes to unbalanced phase 3. High level of THDU during the evening hours can be noticed, when it was close to 7%. The highest contribution is coming from the 5th and the 7th harmonic.

The lower levels of THDI for group of individual houses (customer C6) compared to apartment building (customer C7) are the consequents of attenuation due to much larger cable lengths in the former case.

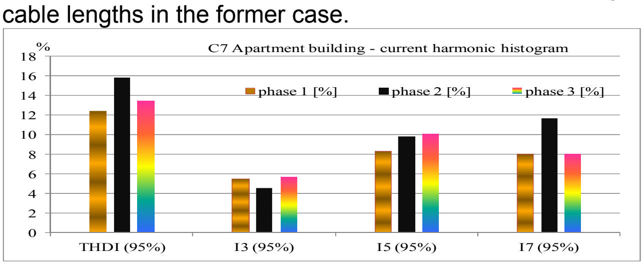

Fig. 8. THDI and current harmonics of a multi flat building

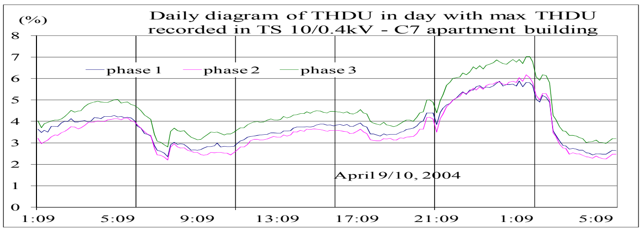

Fig. 9. THDU measured at TS 10/0.4kV

H. *Industrial plant - C8*

A large industrial plant has been picked for monitoring and taken into account for modeling of the network. It is a metal-refining factory that produces plain bearings for automotive industry, with electrolysis unit, electro-induction stove, press, bore unit and others. All measurements were performed from Apr. 23 to May 4, 2004. Figure 10 shows THDI and current harmonic spectrum. More results are given in [15].

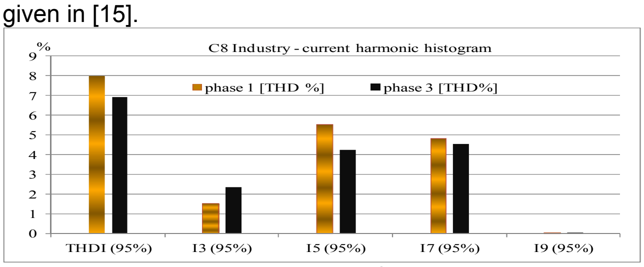

Fig. 10. THDI and currents harmonics of an Industrial plant

I. Sports hall - C9

Measurements at the PCC of a sports hall were performed from March 23-29, 2005. The results are shown in Figure 11.

Major loads in the hall were lighting, air conditioning, and recreation and catering types of loads. THDU and THDI time variations are presented in Figure 12. The THDI has familiar pattern of high values during light loads with peaks around the 20%.

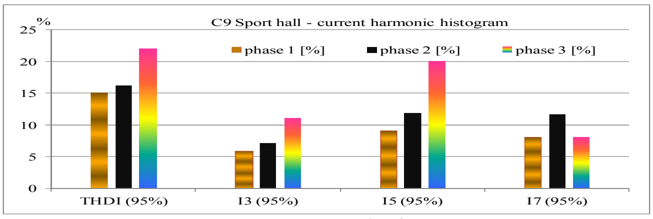

Fig. 11. THDI and current harmonics of a Sport hall

Low values of THDI are the result of operation of electric heaters during training period in the hall. When the heaters are turned off, fluorescent lighting becomes the dominant load and the level of THDI is higher. The THDU is far below the 5% limit [18].

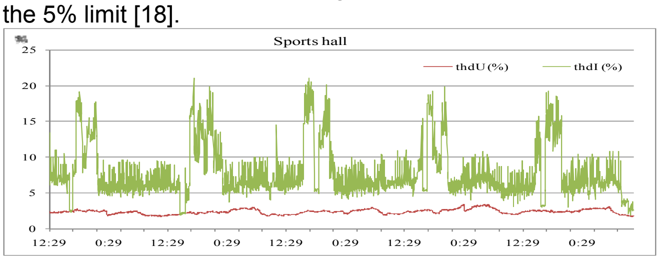

Fig.12.THDU and THDI variation recorded during monitoring period

J. A small hotel - C10

Harmonic spectrum of a small hotel is more or less similar to that recorded for a hotel complex (C2). Still, there are some differences (Figure 13). The measurements were carried out from Jun 29 - July 6, 2008 at 10kV. The main difference is that THDI is slightly lower and that the 5th harmonic dominates harmonic spectrum with higher values.

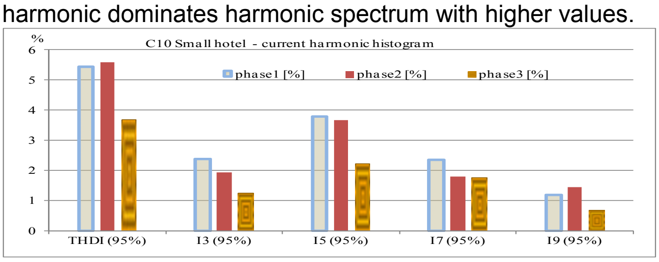

Fig. 13. THDI and individual current harmonics – a small hotel

K. Business trade center - C11

During period November 12 – 22, 2008 measurements for this specific customer were performed. Figure 14 shows harmonic spectrum and THDI during period of measurements. The higher values of THDI then in case of a shopping center can be observed. Also, a significant harmonic unbalance indicates the effects of large number of non-linear single-phase loads unequally distributed in the center.

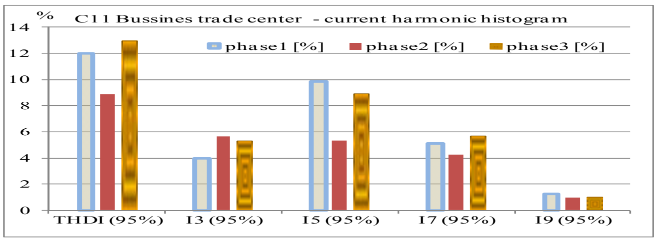

Fig. 14. THDI and current harmonics – a business trade center

L. School and kindergarten - C12

Harmonics measurements at a PCC of a primary school and a child care center were carried out from May 5-12, 2010. Main impact on current distortion comes from two computer clusters inside primary school, and air conditioning system. One computer cluster contains 25 PCs and 10 printers. Simultaneous operations of these devices can cause significant impact on power quality [19]. Recorded harmonic spectrums are presented in Figure 15.

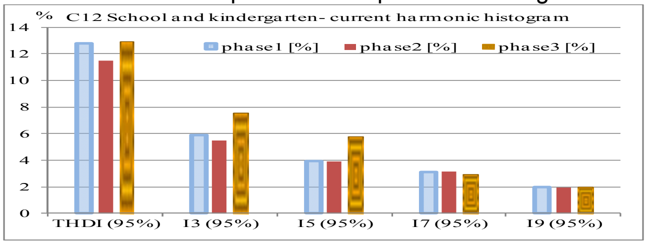

Fig. 15. Current harmonics of a school and child care center

M. Administrative building - C13

Harmonics measurements at an administrative building were performed in period of September 4 -7, 2009. Corresponding harmonic spectrum is shown in Figure 16. Results show significant presence of large number of single phase nonlinear devices as the 3rd harmonic is dominant.

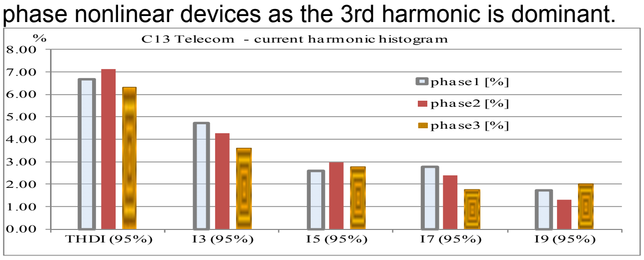

Fig. 16. THDI and individual current harmonics

N. Water supply plant - C14

A water supply company has been included in measurements as pump drives are usually equipped with nonlinear frequency converter for motor start and speed control. Measurements were performed from September 7-15, 2008. 10kV transformer side was selected as measuring point. THDI and current spectrum are shown in Figure 17.

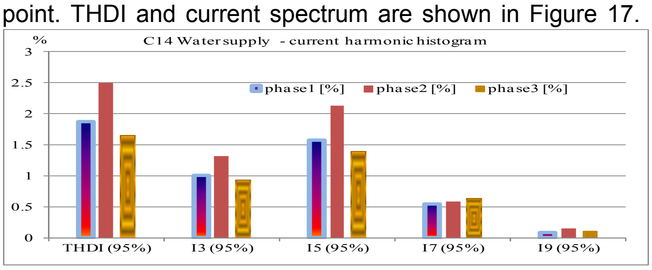

Fig. 17. THDI and individual current harmonics

O. Commercial Port - C15

This load is a medium size civil commercial port on Mediterranean, with a large number of different non-linear loads mainly three-phase connected. Measurements were performed from September 8 – 17, 2010. THDI and current harmonics are shown in Figure 18.

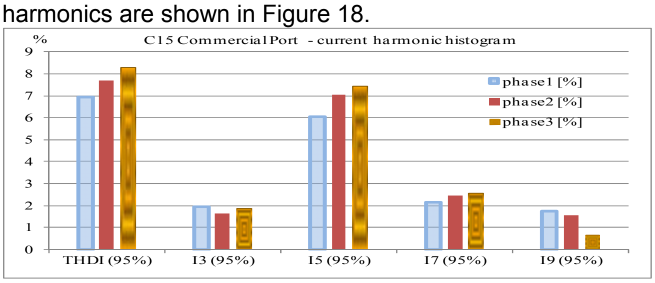

Fig. 18 THDI and individual current harmonics

4. Generic model description

For building the generic network model, collected measurement data were statistically processed and two characteristic values of harmonic indices have been used for setting up the model: the 95% and Average values. After all characteristics of individual loads have been modeled and incorporated in the overall network model, several case studies were carried out. Some of the results are shown in Appendix – Table VII. Harmonic characteristics for each harmonic load model are listed in Table XI in the Appendix.

The network model was built using PSS SINCAL 6.0, as representative computing application software for modeling electricity supply network and systems [13]. Developed generic network model consists of 23 nodes, 12 transformers, 15 lines including both, underground cables and overhead lines and covers 4 voltage levels. It contains one 110kV/35kV substation, two 35kV/10kV substations and five 10kV/0.4kV substations. All 15 load types C1 to C15 (Appendix Table IX) are used and incorporated in considered generic model. The single line diagram of the generic network is shown in Figure 19.

5. Simulation results

The simulations were carried out for several network operating points to ensure robustness of conclusions. It is important to notice that simulation took into account the worst possible case, namely that the phase angles are equal for all harmonics. This was necessary to do, as the phase angles have not been recorded during the monitoring campaign due to the limitations of used PQ monitoring equipment.

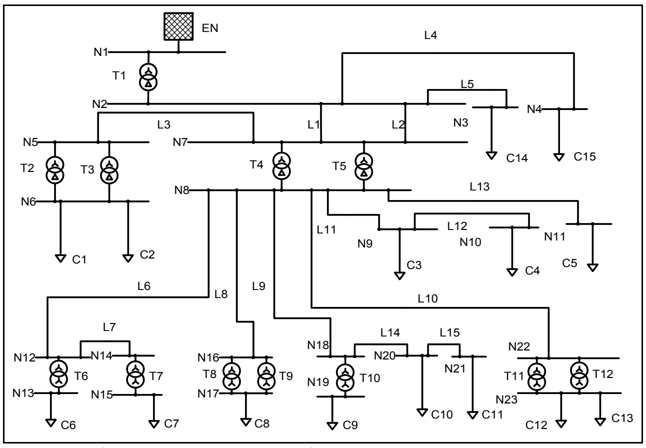

Fig. 19. Single line diagram of generic distribution network (N – node, T – transformer, L – line, C – customer)

In reality, one would expect to record different phase angles between currents and voltages for different harmonic components. When added up, these different phase angles would lead to vector addition of harmonic components and such to attenuation of total harmonic distortion. So, the realistic situation would be much better in terms of harmonic distortion than the assumed condition.

Furthermore, as frequencies of considered harmonics are less than 450Hz, dependence of resistances and inductance on frequency has not been taken in account.

Based on the long-term measurements of network parameters at consumer and the other nodes, the data base is formed. The relevant statistical values of the data in this database (σ - standard deviation, min - min value, max - max value, μ – average value, 0.95 - 95% probability of appearance, 0.05 - 5% probability of appearance, Me – median function, Mo – mode function) are determined.

Only two operating conditions are selected as typical: one corresponding to 95% probability (the value appears 95% of the time during the year) and the other corresponding to average values of measured quantities (U, I, P, Q, and related harmonic components).

Before running the simulations all the above parameters are set to average values in the first case and to 95% probability values in the second. Simulations are performed with corresponding parameter values and the results of simulations compared with measured values at the key buses. Load flow and harmonic analysis has been carried out for both operating conditions and the values of current, voltage, power and harmonic components at the node N2 (35 kV side of transformer 110/35 kV) are obtained. Real measurements at this point were performed during period May 18 – 30, 2004.

Based on the load flow simulation, the currents at 35 kV side of the transformer at the node N2 are obtained.

The aim was to identify the time period during field measurements when the current value was very close or equal to value obtained in simulations in both cases (95% settings and average settings). Following this the other measured parameters (P, Q, S, harmonic components) obtained during corresponding time period were identified and compared with those obtained in the simulations.

Table I. Results obtained by simulation

Parameter node N2 (35 kV side TR 110/35 kV)	Simulation - 95% probability	Simulation - AVERAGE
P [kW]	7061.68	5395.12
Q [kVAr]	3123.59	2239.06
S [kVA]	7720.00	5840.00
I [A]	126.52	95.39
I3 [A]	0.70	2.02
I5 [A]	5.27	3.52
I7 [A]	2.28	2.88
U [kV]	34.26	34.47
U3 [%]	0.62	0.63
U5 [%]	1.63	2.14
U7 [%]	1.01	1.31

Measurements conducted within the specified period included current, voltage, power (active, reactive and apparent) and all harmonic components of currents and voltages up to the 51st. In this analysis, however, only the 3rd, the 5th and the 7th harmonic were considered. Table I shows the results of simulations for node N2.

6. Model verification

Validation of the generic network model is done by comparisons of values of P, Q, I and U and corresponding of current and voltage harmonic components obtained by simulation (by load flow and harmonic analyzes) at node N2 with the values obtained during measurements in the real network for the two operating conditions discussed above. The operating points had similar parameters related to harmonic distortion and the main difference was in the level of demand. So, with average loading in the network, average values for harmonic content of individual sources were entered and simulation was run. The same procedure was repeated with 95% probability of loading and harmonic distortion. Based on statistical analyses of the data obtained during the monitoring period from May 18, 2004 at 14:47h to May 30, 2004 at 21:46h, the measured current and demand values were used to fit Gaussian distribution with parameters given in Table II.

Table II. Results obtained by statistical analyses

Statistical Values for	current 126.52A	current 95.39A
Normal Distribution	0.601	0.173
Mean	119.850	
Standard Deviation	25.940	

For the first operating point (95% of the statistical appearance of measured values) the current at 35 kV side of transformer at node N2 is found to be 126.52A. By comparing with measurement results, it has been determined that this current value appears twice during two days (as 95% value of currents in all three phases): The first time on May 25, 2004 at 13:50 and 14:00, and for the second time on May 28, 2004 at 10:32 and 18:47. Table III shows all these data.

Table III. Comparison of results obtained by measurement and simulation, I=126.52A node N2

I	II	III	IV	V	VI	VII	VIII	IX	X
parameter node N2 (35 kV side TR 110/35 kV)	results by measurement				results by simulation - 95% probability	(II-VI)*100/II related to May 25, 2004 at 13:50	(III-VI)*100/III related to May 25, 2004 at 14:00	(IV-VI)*100/IV related to May 28, 2004 at 10:32	(V-VII)*100/V related to May 28, 2004 at 18:47
	May 25, 2004 at 13:50	May 25, 2004 at 14:00	May 28, 2004 at 10:32	May 28, 2004 at 18:47					
P (kW)	6940.16	6915.35	6947.20	6974.25	7061.68	-1.75	-2.12	-1.65	-1.25
Q (kVAr)	3232.39	3196.42	3372.53	2842.84	3123.59	3.37	2.28	7.38	-9.88
S (kVA)	7655.99	7618.34	7722.53	7531.40	7720.00	-0.84	-1.33	0.03	-2.50
I (A)	126.52	126.52	126.52	126.52	126.52	0.00	0.00	0.00	0.00
I3 (A)	0.68	0.78	0.62	0.69	0.70	-3.48	9.78	-13.50	-1.98
I5 (A)	5.56	5.80	5.74	4.90	5.27	5.15	9.08	8.13	-7.62
I7 (A)	2.30	2.31	2.04	1.91	2.28	0.74	1.17	-11.91	-19.53
U (kV)	35.73	35.77	35.97	34.89	34.26	4.11	4.22	4.75	1.81

Table IV. Comparison of results obtained by measurement and simulation, I=95.39A node N2

I	II	III	IV	V	VI	VII	VIII	IX	X
parameter node N2 (35 kV side TR 110/35 kV)	results by measurement				results by simulation-AVERAGE	(II-VI)*100/II related to May 19, 2004 at 5:58	(III-VI)*100/III related to May 22, 2004 at 4:12	(IV-VI)*100/IV related to May 23, 2004 at 5:08	(V-VI)*100/V related to May 23, 2004 at 5:09
	May 19, 2004 at 5:58	May 22, 2004 at 4:12	May 23, 2004 at 5:08	May 23, 2004 at 5:09					
P (kW)	5345.96	4465.35	5230.49	5249.96	5395.12	-0.92	-20.82	-3.15	-2.77
Q (kVAr)	2771.82	4523.41	3224.97	3162.60	2239.06	19.22	50.50	30.57	29.20
S (kVA)	6021.82	6356.15	6144.79	6128.95	5840.00	3.02	8.12	4.96	4.71
I (A)	95.39	95.39	95.39	95.39	95.39	0.00	0.00	0.00	0.00
I3 (A)	1.73	1.81	1.61	1.60	2.02	-16.84	-11.67	-25.55	-26.33
I5 (A)	3.76	3.40	4.92	4.64	3.52	6.51	-3.39	28.55	24.24
I7 (A)	2.40	2.76	2.89	2.81	2.88	-20.13	-4.46	0.24	-2.60
U (kV)	35.45	38.47	37.19	37.10	34.47	2.76	10.40	7.31	7.09

Table IV shows the data corresponding to this operating condition. Second operating point is represented by the settings for consumer nodes corresponding to statistical average of the measured values. In this operating state, current value obtained by simulation at 35 kV transformer side at node N2 was 95.39A. Measurement results show such current value repeating four times during the measurement interval. For the same current level in both cases shown in tables above, independently of operating conditions, the same level of P, Q, S and harmonic components were obtained. The difference between the measured and simulated values of powers (P, Q, S) is within the acceptable limit.

In the first case (May 25, 2004 and May 28, 2004 according 95% probability settings), by comparing P, Q and S from Table I and Table III it can be seen that the difference in values is typically within acceptable ±10% tolerance. The differences are much smaller than this in vast majority of the cases. The similar conclusion applies to current harmonic components, i.e., differences much less than 10% in large majority of cases.

It the second case, however, these differences are higher (on average between 10% and 15%) as the matching between measured and simulated operating conditions was much more difficult to achieve at the first place since the average parameters were used. If, the harmonic phase angles were taken into account during the setting of harmonic characteristics of loads one would expect the results to be much more accurate due to attenuation of harmonics.

7. Conclusion

The generic model of coastal distribution network is presented and validated. Application is foreseen for analysis, planning and development of such distribution networks. The model is characterized by relatively small level of demand (up to 20MVA in total), number of nodes (up to 100) and several concentrated points of consumption (up to 10 with level of demand per customer up to 10% of the total). Furthermore, developed generic network enables detailed studies of impact of nonlinear loads on distribution network performance, development of appropriate mitigating solutions, as well as, detailed studies related to connection of renewable energy sources, which employ significant portion of nonlinear power electronic components known to be both sources and casualties of poor power quality in the network.

Appendix

Table V. Input settings data - characteristics of network TR units

Element Name	Network Level	Vr1 [kV]	Vr2 [kV]	Sn [MVA]	vk [%]	VecGrp
T1	110kV	110	35	20	10.7	YD5
T2	35 kV	35	10	4	5.96	YD5
T3	35 kV	35	10	4	5.96	YD5
T4	35 kV	35	10	8	7	YD5
T5	35 kV	35	10	8	7	YD5
T6	10kV	10	0.4	1	8	DYN5
T7	10kV	10	0.4	1	8	DYN5
T8	10kV	10	0.4	1	8	DYN5
T9	10kV	10	0.4	1	8	DYN5
T10	10kV	10	0.4	1	8	DYN5
T11	10kV	10	0.4	0.63	8	DYN5
T12	10kV	10	0.4	0.63	8	DYN5

Table VI. Input settings data - parameters of network lines

Element Name	q [mm²]	l [km]	r [Ohm/km]	x [Ohm/km]	c [nF/km]	Vr [kV]	Ith [kA]	r0 [Ohm/km]	x0 [Ohm/km]	c0 [nF/km]	q0 [mm²]
L1, 35 kV	150	3.75	0.2	0.095	0.1206	35	0.32	0.8	0.92	0	35
L2, 35kV	150	3.75	0.2	0.095	0.1206	35	0.32	0.8	0.92	0	35
L3, 35kV	95	2.1	0.224	0.103	0.1206	35	0.3	0.712	0.302	227.8826	35
L4, 35kV	95	2.1	0.224	0.103	0.1206	35	0.3	0.712	0.302	227.8826	35
L5, 35kV	95	2.1	0.224	0.103	0.1206	35	0.3	0.712	0.302	227.8826	35
L6, 10kV	150	1.88	0.0655	0.1024	495	10	0.245	0.7	0.279	496.196	0
L7, 10kV	120	0.72	0.1568	0.091	550	10	0.215	0.7	0.279	306	10
L8, 10kV	120	1.66	0.1568	0.091	550	10	0.215	0.7	0.279	306	10
L9, 10kV	150	2.2	0.0655	0.1024	495	10	0.245	0.7	0.279	496.196	0
L10, 10kV	150	1.7	0.0655	0.1024	495	10	0.245	0.7	0.279	496196	0
L11,10kV	150	1.1	0.0655	0.1024	495	10	0.245	0.7	0.279	496.196	0
L12, 10kV	120	0.45	0.1568	0.091	550	10	0.215	0.7	0.279	306	10
L13, 10kV	150	3.7	0.0655	0.1024	495	10	0.245	0.7	0.279	496196	0
L14, 10kV	120	0.77	0.1568	0.091	550	10	0.215	0.7	0.279	306	10
L15, 10kV	120	0.85	0.1568	0.091	550	10	0.215	0.7	0.279	306	10

Table VII. Load flow analysis results for few network elements - 95% settings

Element Name	P [MW]	Q [MVAr]	S [MVA]	cosφ	Sb [MVA]	S/Sb [%]
T1	7.04	2.61	7.51	0.94	20.00	37.54
T2	0.54	0.23	0.59	0.92	4.00	14.75
L1	2.51	0.72	2.61	0.96	19.40	13.44
L2	2.51	0.72	2.61	0.96	19.40	13.44
EN	7.06	3.12	7.72	0.91	10.00	77.22
C1	-0.40	-0.30	0.50	0.80	0.53	94.69
C2	-0.69	-0.16	0.71	0.97	0.75	94.69

Table VIII. Input settings data – in-feeder

Node 1	Sk" MVA	v	LF Type	R0 [Ω]	X0 [Ω]	Vmin [%]	Vmax [%]
110 kV	1258	1.1	P,Q	70	12	98	103

Table IX. Input settings data – loads

Load Name	Network Level	P [kW]	Q [kVAr]	V [kV]
C1	10kV	420	315	10
C2	10kV	726.666	173.333	10
C3	10kV	384	56	10
C4	10kV	2136	456	10
C5	10kV	295	182	10
C6	0.4kV	175.2	49.333	0.4
C7	0.4kV	330.587	85	0.4
C8	0.4kV	360	340	0.4
C9	0.4kV	28	10	0.4
C10	10kV	142.4	74	10
C11	10kV	108.8	40	10
C12	0.4kV	74.146	16.746	0.4
C13	0.4kV	203.893	59.467	0.4
C14	35 kV	772.332	389.666	35
C15	35 kV	1246	784	35

Table X. Input settings data – nodes

Network Level	Name	Short Name	Node Type	Ik" [kA]
110kV	110 kV TRANSMITION	N1	Busbar	5947
35 kV	35 kV TRANSMITION	N2	Busbar	2623
35 kV	WATHER SUPLLAY PLANT	N3	Busbar	2122
35 kV	PORT	N4	Busbar	2122
35 kV	COMPLEX 35	N5	Busbar	2457
10kV	MARINA 10	N6	Busbar	3419
35 kV	DISTRIBUTION 35	N7	Busbar	2489
10kV	DISTRIBUTION 10	N8	Busbar	2633
10kV	BUSINESS AND RESIDENTIAL COMPLEX10	N9	Busbar	3260
10kV	SHOPPING MALL10	N10	Busbar	2725
10kV	AIRPORT 10	N11	Busbar	2538
10kV	HOUSEHOLD IND. 10	N12	Busbar	3256
0.4kV	HOUSEHOLD IND.0.4	N13	Busbar	13873
10kV	BUILDING AND SCHOOL 10	N14	Busbar	2629
10kV	INDUSTRY 10	N16	Busbar	2465
0.4kV	BUILDING AND SCHOOL 0.4	N15	Busbar	7472
0.4kV	INDUSTRY 0.4	N17	Busbar	9579
10kV	SPORTS HALL 10kV	N18	Busbar	3371
0.4kV	SPORTS HALL 0.4kV	N19	Busbar	8898
10kV	SMALL HOTEL 10kV	N20	Busbar	2889
10kV	BUSINESS TRADE CENTER 10kV	N21	Busbar	2291
10kV	KINDERGARTEN I SCHOOL10kV	N22	Busbar	2465
0.4kV	KINDERGARTEN AND SCHOOL 0.4kV	N23	Busbar	11469

Table XI. Customer's harmonic characteristic settings

n[1]	C1 I [A]	C2 I [A]	C3 I [A]	C4 I [A]	C5 I [A]
1	27.3	41	24	127.6	19.2
3	2.1	2.37	1.301	0.28	0.8
5	3.9	3.05	3.74	2.89	1.12
7	1.75	0.23	1.62	0.38	0.3
9	0.7	0.91	0.03	0.05	0.2
n[1]	C6 I [A]	C7 I [A]	C8 I [A]	C9 I [A]	C10 I [A]
1	274.67	506.67	130	50	9.13
3	3.32	16.67	19.67	2.67	1.85
5	5.34	26.67	28	4	2.23
7	0.88	0.022	12	0.23	0.36
9	0.58	0.02	5.33	0.02	0.1
n[1]	C11 I [A]	C12 I [A]	C13 I [A]	C14 I [A]	C15 I [A]
1	6.64	107.47	318.4	15.17	23.63
3	0.37	3.31	9.21	0.922	0.92
5	3.03	5.21	23.79	3.49	4.645
7	1.04	1.05	1.31	1.42	1.62
9	0.08	1.96	0.7	0.11	0.33

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