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Aggregated Load Modelling Approach to Study Impact of Heat Pumps Harmonic Distortion on the Low Voltage Distribution Network

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ABSTRACT

The electrification of heating and cooling resources such as Heat Pumps has increased its share in the electricity consumption throughout the world. Furthermore, the utilization of domestic HPs is increasing within the Europe especially in Italy; however, the increased use of heat pumps along with other domestic loads can have a significant impact on the low voltage distribution network in terms of its harmonics injection to the network. This problem needs to be addressed properly by means of suitable models. This paper presents an aggregated load modelling approach to address the harmonic injections of heat pumps into low voltage distribution networks. For this study simulations are conducted in co-simulation environment of OpenDSS and MATLAB implementing the Iterative Harmonic Analysis considering a simple scenario of three independent houses connected to the distribution system. The results are presented in the form of generated harmonic currents, voltages, and percentage errors between considered models for the study. Frequency domain modelling approach appeared to be the best performing model in terms of tradeoff between accuracy and computational time.

1. INTRODUCTION

In the past couple of decades, a dramatic increase has been noticed in the number of consumer electric devices connected to the low voltage distribution network (LVDN) by means of power electronic converters. Heat pumps (HP), televisions, refrigerators, computers, and lighting etc. add significant burden over LVDN. All of these devices are resulting in distorting the shape of voltage and current of the power supplied by LVDN. Distorted power is leading to losses and heating of cables and components in the electrical network reducing the LVDN capacity. The electrification of heating and cooling resources such as Heat Pumps (HPs) has increased its share in the electricity consumption throughout the world. Furthermore, the utilization of domestic HPs is increasing within the Europe especially in Italy because of the high demand being capable of dual functionality i.e., cooling in summers and heating in winters. The trend is expected to increase in next decade worldwide. However, the increased use of heat pumps along with other domestic loads can have a significant impact on the LVDN in terms of its harmonic injection to the network due to their non-linear behavior [1-4].

One of the main issues in analyzing, modelling, and simulating LVDN is the fact of having a huge number of components or devices. Therefore, there is a need to reduce the large number of devices to make its modelling and analysis convenient [4, 5]. Modelling the electrical network in the presence of only linear loads is a common practice but when non-linear loads increase their penetration it may get complicated. This problem needs to be addressed properly by means of suitable models. Therefore, dedicated attention is needed to come up with a compensative solution for this problem to have less or no harmonic injection through HPs in to the LVDN.

This research paper presents an aggregated approach for modelling the components of LVDN for its harmonic analysis in steady state conditions. For this purpose, a test case of a typical LVDN branch is considered having three houses connected to each phase of the network. The houses have different kind of loads such as HPs, lighting, television, cellphones, computers, ironing, dishwasher, and washing machines etc. For this the total load of the house is divided in to two clusters. The first cluster consists of solely HPs of the house and the second cluster consists of combined rest of the loads. Detailed power flow analysis is performed and afterwards the impact of harmonics generated by HPs on the LVDN is computed numerically implementing the Iterative Harmonic Analysis (IHA) through co-simulation of MATLAB and OpenDSS comparing their results with a reference model implemented in SIMULINK.

Section II of the manuscript discusses the aggregated load modelling in detail. Section III enlightens methodology adapted for this research study along with system model in detail. Section IV elaborates results and discussion. Conclusion and future research are detailed in section V.

2. AGGREGATED LOAD MODELLING

The aggregated load modelling is usually utilized for the analysis of the power systems in the steady state. This modelling approach is grounded on the standard constant impedance, constant current, and constant power representation of load component in static mode, while only some other loads (e.g. induction motors) is represented in dynamic mode. Guo et al. [2, 3] have proposed an aggregated load modelling approach (ALMA) for residential consumers for its harmonic study. In the study [2], previous time-domain model (TDM) was utilized in terms of aggregated TDMs. Dedicated analysis is undergone for harmonic cancellation effects among loads of same and diverse categories. The authors then converted same study to frequency domain model (FDM) representation in admittance matrices in coupled harmonic state. ALMA is proposed [4] where equivalent load model is derived for the representation of load characteristics of a specific area within the electrical network. Particle swarm optimization (PSO) technique is used for identification of unknown parameters within the system and IEEE 14-bus and IEEE 57-bus systems were employed for conducting simulation study. Different load models were thoroughly studied for aggregating residential loads considering its non-linear behavior for assessment of harmonic levels injected into LVDN [5]. A simple IEEE 4-bus and IEEE Europe LV test feeder systems were utilized for simulation study.

Muhssin et al. [6] investigated an aggregated load approach and proposed a simplified model for residential HPs. An algorithm based on decentralized temperature was utilized for controlling the ON-OFF cycle of HPs. Seven different case-studies were interpreted for identification of suitable number of HP model to be represented as total number of heat pumps verified with MATLAB simulations through aggregation of 5000 HPs. Wang et al. [7] proposed an impedance based method for the analysis and modelling of harmonic interaction among grid and aggregated loads. It was proposed that limits of impedances must be specified and to be used as additional design parameter for limiting the load's harmonic distortion impact on distribution network. Analytical models were reviewed in the study [8] for representing aggregated linear loads in the distortion and harmonic propagation studies. The results demonstrated higher sensitivity of harmonic distortion to the type of model used for representation of the load. At peak periods, residential appliances can be controlled by means of an aggregator in the form of a single representation for reduction of it aggregated energy consumption [9] through Gaussian mixture model and gaussian copula function.

The researchers aim to investigate the effects of linear aggregated loads [10] for its harmonic analysis. Different load models were utilized for checking the systems' sensitivity to harmonic voltages and impedance. Athiappan et al. [11] have proposed an aggregated frequency coupling matrix model based on artificial disturbances utilizing sources of distributed generation. The study [12] details the impact of harmonic current cancellation of the aggregated load currents illustrating impact over the network through demonstration of a comparison among harmonics generated by measurements and mathematical calculations. Collin et al. [13] presented a component-based technique for building an improved aggregated load model having capability of preservation of electrical characteristics enabling its utilization in the analysis of power flows, harmonic and voltage profile analysis. Salles et al. [14] presented a probabilistic harmonic analysis technique grounded on modelling residential loads' random harmonic injections through simulation of its random states. A generic methodology for the development of an ALMA is presented [15] for power systems analysis in steady state utilizing the UK residential load sector for the purposes of simulation.

3. METHODOLOGY AND SYSTEM MODEL

This research study incorporates the co-simulation environment of two software i.e., SIMULINK/MATLAB and OpenDSS. OpenDSS is an open-source software specifically designed for supporting complex analysis through customizable and flexible platform for meeting current and future challenges attributed to distribution systems.

A simple LVDN is shown in Figure 1 with a 3-φ voltage source of 20kV connected to a step-down $\Delta - Y$ transformer with neutral (20kV/400V). A 3-φ line with neutral is connecting bus-A with B. Three single phase lines are connecting bus B with C, D, and E. The buses C, D, and E represents the connecting points of the houses. Each house is connected to a phase line and neutral line. Each house is supposed to have nominal voltage at 230V line to neutral.

The load of houses is modelled with an ALMA i.e. the loads are divided in to two main clusters. The first cluster consists of HPs only as distinct loads and rest all of the loads of the houses such as refrigerator, television, hair dryer, microwave, lighting, and chargers etc. are combined together as single aggregated load. The specifications of LVDN are given in Table 1. Harmonic spectrum of first 10 odd harmonics from 1-19 is considered for the study.

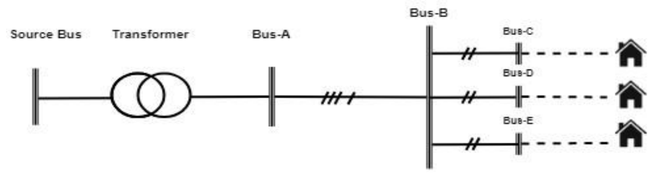

Figure 1. Low voltage distribution network [16]

Table 1. LVDN specification

Entity	Value with Units
Voltage Source	20kV
Transformer	20kV-230V
Impedance Line A-B	R_1=0.12Ω, R_0=0.342Ω, X_1=0.072Ω, X_0=0.089Ω
Length Line A-B	1km
Impedance Line B-C,D,E	R_1=1.15Ω, R_0=1.2Ω, X_1=0.083Ω, X_0=0.083Ω
Length Line B-C,D,E	0.01km

A co-simulation iterative algorithm between OpenDSS and MATLAB implementing the Iterative Harmonic Analysis adapted for this study is presented in Figure 2. In the first iteration the LVDN is implemented in OpenDSS and simulated under undistorted conditions. The fundamental harmonic current is given 100% amplitude with phase angle 0^0 and is then fed to OpenDSS for the load connected to 1st phase and repeated for the other two phases but with phase angles as -120° and 120°. The resultant fundamental and harmonic voltages acquired from OpenDSS are then fed to the frequency domain harmonic model (FDM) having loads of both clusters. For the representation of the aggregated load of each house, the HP model is taken from the study [17] as a generalized

Norton equivalent whereas aggregated load is modelled with a parallel RL circuit. The resultant fundamental and harmonic currents generated by the aggregated FDM model are then fed to OpenDSS. A while loop is run for the iteration till computed total harmonic distortion (THD) is less than considered threshold. This modelling approach is called IHA_{FDM} in next section.

For verification purposes the aggregated FDM model of each house is substituted by means of an equivalent SIMULINK model within the IHA algorithm called (IHA_{SMK}) in the next section.

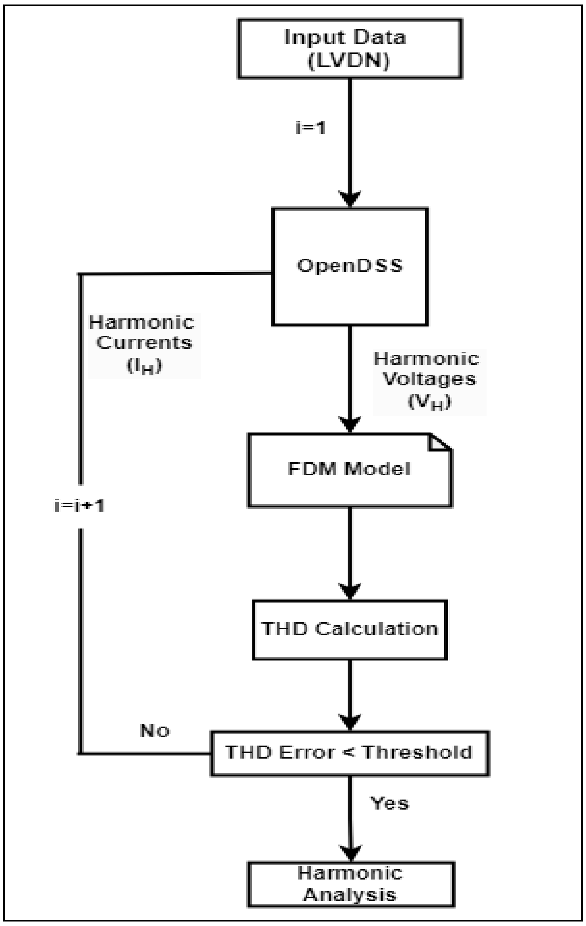

Figure 2. Co-simulation IHA algorithm

4. RESULTS AND DISCUSSION

Load profile of two different days (Table 2) of a week are selected i.e. working day and a weekend day in order to properly analyze the HP generated harmonics impact on LVDN.

For verification purposes a reference model is developed in SIMULINK and reference simulations are computed with load profiles of both selected days. Afterwards, the simulations done through IHA_{FDM} and IHA_{SMK} methods are compared with that of the developed reference model. Percentage error is also computed for the generated current and voltage harmonics.

For the sake of simplicity only a single hour is selected i.e. 17:00 to show the results for the resultant generated harmonic currents and voltages with both IHA implementations in comparison to the reference model. A single hour is taken so as to simplify the analysis because the load profiles at the same hour are different for both working day and weekend.

Table 2. Load profiles

Hour	Working Day Aggregated Load	Working Day Heat Pump	Weekend Day Aggregated Load	Weekend Day Heat Pump
00	1.611	0.72	1.985	0.87
01	1.159	0.72	1.874	0.72
02	1.001	0.72	0.856	0.72
03	0.8	0.87	0.8	0.72
04	0.8	0.87	0.8	0.87
05	0.8	0.87	0.8	0.87
06	1.896	0.72	1.001	1.07
07	1.958	0.72	1.236	1.07
08	2.395	0.87	2.395	1.07
09	2.55	1.07	2.546	1.13
10	2.969	1.07	2.998	1.13
11	2.856	1.13	3.546	1.22
12	3.965	1.13	3.856	1.22
13	4.025	1.13	4.015	1.22
14	3.568	1.33	4.658	1.33
15	3.158	1.33	4.972	1.33
16	2.568	1.33	5.103	1.33
17	1.698	1.22	5.103	1.33
18	2.365	1.22	5.103	1.33
19	2.898	1.33	5.012	1.22
20	4.856	1.33	4.698	1.22
21	3.103	1.33	4.125	1.07
22	3.001	1.13	3.985	1.07
23	2.654	1.13	3.354	0.87

4.1 Load profile of working day

Figures 3 and 4 illustrate the comparison of harmonic voltages and currents in between reference, IHA_{FDM} and IHA_{SMK} models for a working day. During the working day, the HP load is 1.22kW and the aggregated load is 1.698kW. It is depicted in figures that for the considered odd harmonics, generated voltages and currents are almost equivalent to that of the reference model for both IHA_{FDM} and IHA_{SMK}. However, there is a little difference between assumed to be because of the control scheme selected for the non-linear load i.e., heat pump.

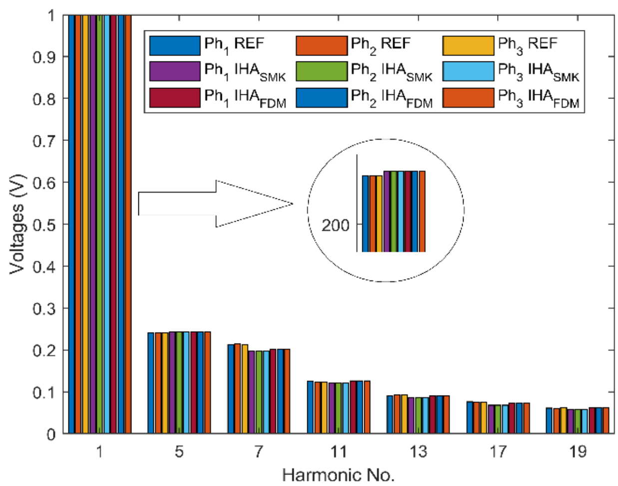

Figure 3. Comparison of harmonic voltages between reference, IHA_{FDM}, and IHA_{SMK} models for working day

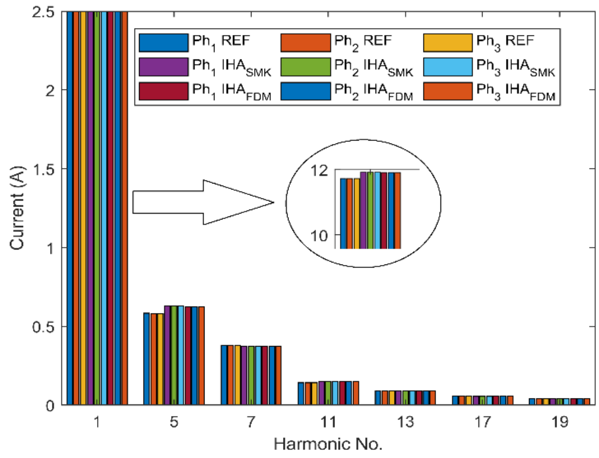

Figure 4. Comparison of harmonic currents between reference, IHA_{FDM}, and IHA_{SMK} models for working day

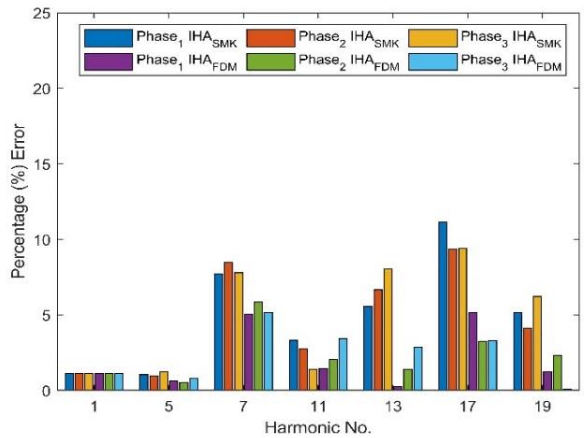

Figure 5. Comparison of percentage errors between fundamental and harmonic voltages obtained by IHA_{FDM}, and IHA_{SMK} models compared with reference for working day

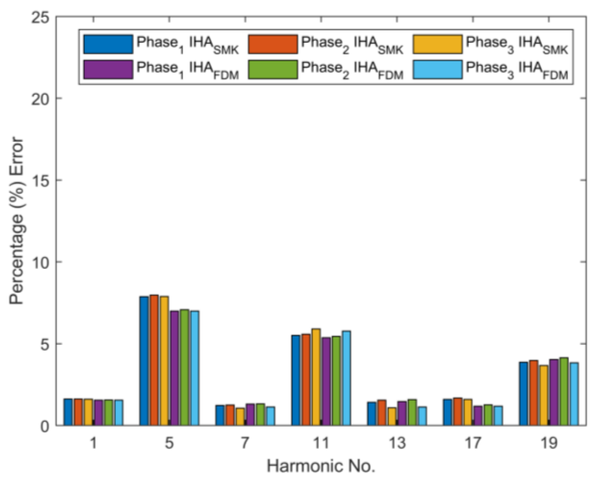

Figure 6. Comparison of percentage errors between fundamental and harmonic current obtained by IHA_{FDM}, and IHA_{SMK} models compared with reference for working day

Figures 5 and 6 show the percentage error between reference and IHA_{SMK} model as well as reference and IHA_{FDM} model in terms of harmonic voltages and currents for a working day. It can be seen that for the fundamental and 5th harmonics are showing minimum errors of under 2%. Overall, for all considered harmonics the percentage error in voltages is less than acceptable range i.e. 10%. Whereas, in currents the harmonics for 5th, 11th, and 19th are a little higher but overall, the percentage error is in acceptable range.

4.2 Load profile of weekend day

Figures 7 and 8 illustrate the harmonic voltage comparison of reference, IHA_{FDM}, and IHA_{SMK} models for a holiday or weekend. During the day at 17:00 hours, the HP load is 1.33kW and the aggregated load is 5.103kW. It can be noticed in figures that for considered odd harmonics, generated voltages and currents are almost equivalent to that of the reference model for both IHA_{FDM} and IHA_{SMK}. However, there is a little difference between assumed to be because of the control scheme selected for the non-linear load i.e., heat pump.

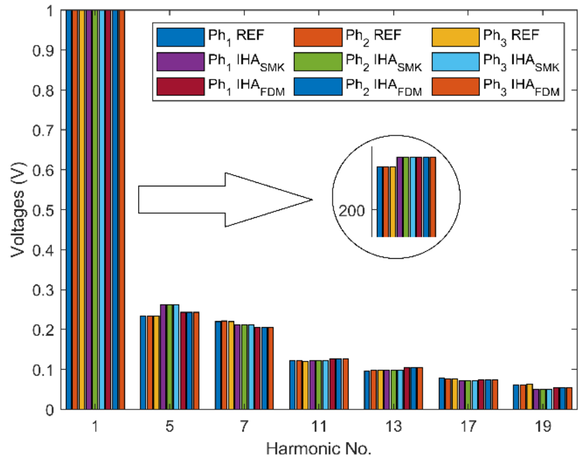

Figure 7. Comparison of harmonic voltages between reference, IHA_{FDM}, and IHA_{SMK} models for weekend day

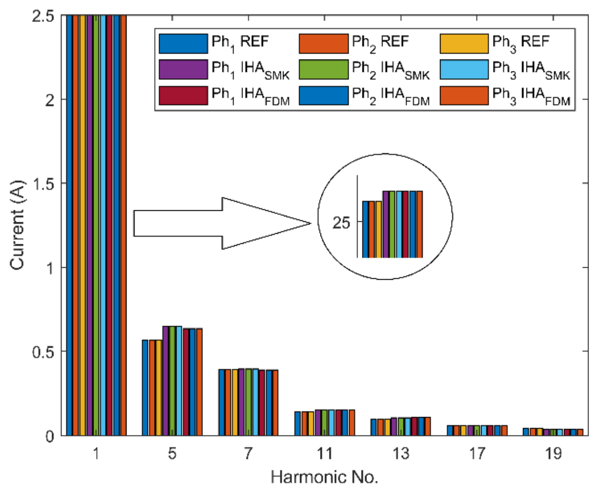

Figure 8. Comparison of harmonic voltages between reference, IHA_{FDM}, and IHA_{SMK} models for weekend day

Figures 9 and 10 show the percentage error between reference and IHA_{FDM} model as well as reference and IHA_{SMK} model in terms of harmonic voltages and currents for a weekend day. It can be seen that the fundamental harmonic has minimum error of under 3%. Overall, for all considered harmonics except 19th, the percentage error in voltages is less than acceptable range i.e. 10%. Whereas, in currents the harmonics for 5th, 11th, 13th, and 19th are a little higher but overall the percentage error is in acceptable range. The high percentage error in currents is because of peak load.

It can be noticed from the results that IHA_{FDM} model presents better results when compared to IHA_{SMK} model.

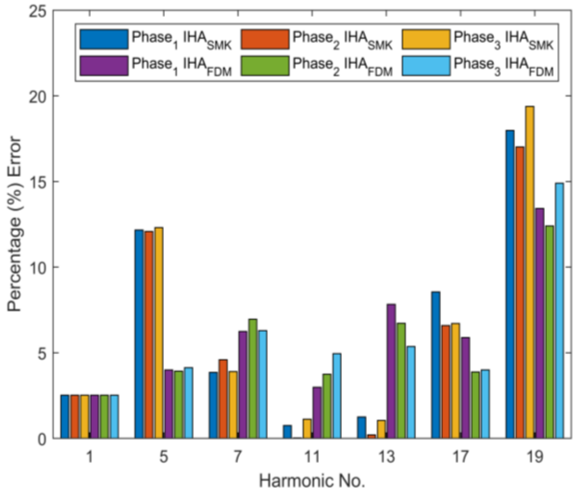

Figure 9. Comparison of percentage errors between fundamental and harmonic voltages obtained by IHA_{FDM}, and IHA_{SMK} models compared with reference for weekend day

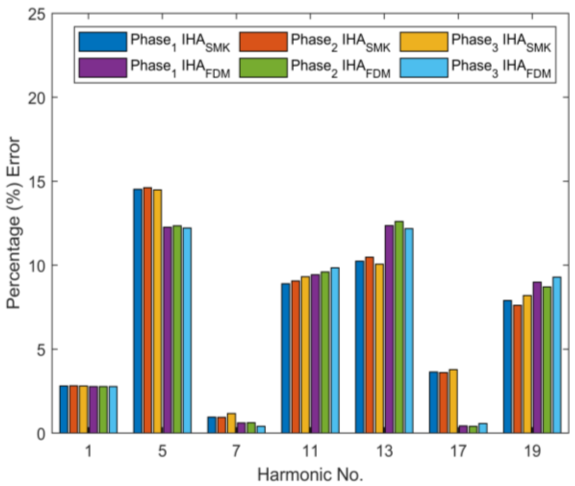

Figure 10. Comparison of percentage errors between fundamental and harmonic current obtained by IHA_{FDM}, and IHA_{SMK} models compared with reference for weekend day

4.3 Computation times

Finally, it is important underlining that the computation of IHA_{FDM} model is way faster than reference and IHA_{SMK} models. IHA_{FDM} model takes almost 15 times lesser time for the computation when compared to reference and IHA_{SMK} model.

5. CONCLUSION AND FUTURE WORK

This study comprised of an aggregated load modelling approach for studying the harmonic impact produced by non-linear loads such as heat pumps on the low voltage distribution network. Along with modelling a reference model for the study, two other iterative models IHA_{FDM} and IHA_{SMK} are developed. The generated harmonics in currents and voltages acquired with reference model are verified through developed iterative models comparing the results with a reference model fully developed in SIMULINK. The little difference at each harmonic order is because of the approximations introduced by the developed models and control scheme adapted for the heat pump. It is noticed that the computation of IHA_{FDM} model is almost 15 times faster than reference and IHA_{SMK} models. Furthermore, the results achieved with IHA_{FDM} model are better when compared to IHA_{SMK} model.

The future work comprises of expanding the current low voltage distribution network (LVDN) by adding more branches containing additional houses. Furthermore, the loads within the houses may also be considered diverse i.e., considering other types of electrical loads usually used in houses. Also, the simulations are to be performed based on yearly load profile instead of daily load profile. The expansion of study will help to analyze the impact of harmonic distortions generated by heat pump into LVDN in a better way.

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NOMENCLATURE

LVDN	Low voltage distribution network
HP	Heat pump
ALMA	Aggregated load modelling approach
TDM	Time domain modelling
FDM	Frequency domain modelling
THD	Total harmonic distortion
IHA	Iterative harmonic analysis
FCM	Frequency coupling matrix

Greek symbols

ϕ	Phase
Ω	Ohms