Impact of Data Granularity and Distribution Network Modeling on the Energy Community Operation

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***Abstract*—The ongoing energy transition is opening innovative ways in the energy use. The increasingly higher share of Non-Dispatchable Renewable Energy Sources (NDRES) calls on the one hand for matching the loads with the production from NDRES. On the other hand, the trend towards setting up energy communities able to be mostly independent of the main grid requires effective management of the internal grid with the opportunity to offer grid services for proper operation of the main grid. To properly manage the interactions among the energy community members, as well as between the energy community and the main grid, it is necessary to know the correct values of the energy flows, to calculate and allocate the energy losses, and to assess the share between technical and non-technical losses. This paper shows how the presence of data collected at different time intervals and the use of simplified network models may affect the performance of the energy community electrical infrastructure, creating issues in the internal management of the community and in the interactions with the main grid.**

Keywords—Energy community, Energy Metering, Losses, Three-phase power flow.

I. Introduction

A. Motivation

The energy transition is a reality: the recent UN Climate Change Conference (also known as 26th Conference of the Parties', COP26) in Glasgow (UK) highlighted the necessity to act on the current power sector, because globally it accounts alone about 25% of greenhouse gas (GHG) emissions [1]. The actions surely imply the variation of the current energy mix (basically, the main source of those emissions is due to the coal use); however, this is not sufficient. In fact, the substitution plants that exploit fossil fuels are expected to be, at least in Europe, mainly based on installation and operation of renewable energy sources (RES), in particular, non-dispatchable renewable energy sources (NDRES) like wind and solar. In fact, unlike the rest of the world, most of the countries composing the European Union do not consider nuclear power plants as a possible asset in the future energy system[1], even though the CO_2 and other pollutant emissions are zero for these plants during operation. The main issue of an electricity system aiming to be 100% RES-based is that most of the sources are non-dispatchable, i.e., non-controllable by the system operator. This introduces several challenges, because of the power system operation requires the instantaneous balance between load and generation [2][3] and the physics of the electrical system does not allow, unlike the gas system, the electricity storage by simply using the grid infrastructure. Hence, the role of the load *cannot be passive anymore*, but must be an active player for the operation of the electricity grid. The European Commission, with the "Clean Energy Package for all Europeans" [4][2], sets out ambitious goals for the future European energy system[3], with four Directives and four Regulations[4]: Energy Performance in Buildings [5], Renewable Energy [6], Energy Efficiency [7], Electricity [8] Directives, and Governance of the European Union [9], Electricity [10], Risk preparedness [11], and ACER [12] Regulations.

In particular, within the Package the definitions of two different types of *energy community* (EnC) are introduced:

- *Citizen* energy community (CEC) [8], which is a legal entity controlled by its members, who voluntarily become part of them. The participation is open to natural persons, local authorities (including municipalities), or small enterprises. CEC aims primarily to provide affordable energy to the members, rather than generate financial profits. The Directive empowers the EU Members to allow CECs becoming distribution system operators. The CEC is entitled to arrange the sharing of the produced electricity among its members.
- *Renewable* energy community (REC) [6], which is a legal entity with characteristics in common with CEC, but which must be installed close to the RES projects owned and developed by the REC itself.

For our purposes, the difference between REC and CEC is not fundamental, hence in the following the general concept of EnC will be used. Within the EnC framework, the knowledge of the energy consumption and the losses of the EnC grid become quite important, due to the voluntary aggregation of the members. In fact, if doubts are rising regarding the operation of the EnC and the share of the costs among the members, their implementation could be discouraged. This aspect has been highlighted also in [8], which points out that "regular provision of accurate billing information based on actual electricity consumption, facilitated by smart metering, is important for helping customers to control their electricity consumption and costs". The above statement points out the importance of the smart metering. However, it is necessary to understand which should be the metering characteristics that allow the proper representation of the EnC members' behaviour. If the single member can also produce electricity, it is interesting to know its *net load*, defined for every time step as the load minus the

[1] According to [13], currently the nuclear power plants under construction are 52 (total capacity: about 55 GW), mainly concentrated in Asia (China, India and South Korea).

[3] The recent released EU Green Deal [14] amends the Directive [6] to implement the ambition of the new 2030 climate target [15]

[4] Regulation: it is a binding legislative act that must be applied in every Member state. Directive: legislative act setting common principles for National regulatory framework [16].

generation. In this case, the time interval granularity on the net metering has an evident effect on the outcomes of the prosumers [17].

B. Literature review

The EnCs can be seen as an evolution of the concept of community [18]: as the initial urban environments, with their own complex structure, allowed to guarantee benefit to their members (e.g., protections from external attacks thanks to army and the presence of walls), at the same way the EnCs aims to react against the climate change and, at the same time, to protect their members from possible network collapse and from the increase of the energy prices. Hence, EnCs based on the exploitation of small energy assets has been recognized as one of the most interesting tools to implement the *energy transition*. The concept of EnCs emphasizes the relation among the member and their involvement towards the actual implementation of sustainable energy systems [19]. In particular, the role of the citizens groups (and their interactions, for example on internet forums properly moderated) becomes fundamental to accelerate their actual implementation (e.g., investment collection) [20]. The stress about sustainability led to introduce in literature the definition of *clean EnC*, defined as "social and organizational structures formed to achieve specific goals of its members primarily in the cleaner energy production, consumption, supply, and distribution, although this may also extend to water, waste, transportation, and other local resources" [21]. The ownership and the management of the EnC electricity infrastructure is important to properly manage energy flows among the members, but also to understand if any potential charges do exist and must be shared among the EnC members [22]. As shown in [23] and [24], the EnCs may be bounded or not bounded. In the first case, the energy community is composed of members insisting on the same property. The energy is consumed/used within the property boundaries: if able to be completely self-sufficient, the energy community could avoid any interaction with the public distribution system. In case of non-bounded EnCs, the interaction with the public grid is unavoidable: in this case, the resources to be accessed may be relatively close (i.e., neighbouring-based EnCs) or relatively far (i.e., distributed EnCs). The EnC becomes "virtual", in the sense that there is no infrastructure belonging to the EnC able to connect all the members.

Usually, the EnC design and operation is based on optimisation problem, aiming to reach economic, environmental, technical and social impact [18]. In particular, several indicators refer to the *operation* of the EnC and are based on energy measurements: as example, energy bill (economic impact), self-consumption, self-sufficiency, electricity import/export (technical impact).

However, which is the nature of the data used to feed the optimisation problem and the control system? Is their time granularity good enough to represent the phenomena happening in the system and to properly address the potential issues that can be arisen? The data granularity impacts both the network losses estimation and on the average power peak magnitude and duration, as shown in [25] in case of a public distribution system feeder. In that case, new approaches based on event-based metering showed to overcome the estimation achievable using the usual measurement time intervals (higher or equal 15 minutes).

Moreover, also the choice of the network model implemented can contribute to a wrong estimation of the network losses. Loss estimation is a main point for an EnC. In general, losses are partitioned into *technical* (referring to networks and evaluated from the power flow calculation, because of their non-linear dependence on the demand) and non-technical (depending for example on measurement errors, isolation faults or frauds). Non-technical losses are difficult to be identified and are typically estimated from the energy balance determined over a given time interval, as the difference between the measured energy input from the supply point of the grid and the sum of the measured demand and the estimated technical losses. However, accurate measurements at the grid supply side and at the demand side are needed, as well as a suitable network model, to obtain the non-technical losses in an accurate way. If the technical losses are underestimated, the estimated non-technical losses would increase, also leading to the wrong perception of possible frauds and energy theft in the EnC, thus undermining the trust among the members. For the development of EnCs, trustworthiness is essential, for avoiding negative perceptions from the EnC members. However, there are many causes of possible underestimation of the technical losses that depend on the time granularity of the measurements and network modelling. This paper aims to investigate these aspects, by showing with illustrative examples how important is the nature of the data to properly operate EnCs based on the RES exploitation.

The next sections are organized as follows. Section II presents analytical considerations on time granularity and energy losses, together with calculations carried out on exemplificative two-node systems. Section III shows the results of a case study executed on a distribution system. Section IV contains the concluding remarks.

II. Time Granularity and Energy Losses

This section introduces a set of illustrative examples for investigating the way the energy losses depend on the time granularity with which the average active and reactive power values are available. Simple exemplificative cases are provided for the three-phase model of a two-node system by resorting to analytic formulations. Further cases are then solved by using a three-phase power flow executed with time-dependent load profiles.

A. Reference analytic formulation

Let us consider a two-node system (Fig. 1) with line impedance $\bar{Z} = R + jX$ and assigned complex power load $P + jQ$. The equation at the receiving node is

$$P + jQ = \bar{V}_2 \bar{I}^* = V_2 \frac{(V_1 e^{-j\delta} - V_2)}{R - jX} \quad (1)$$

Some elaborations are carried out by separating the real and imaginary parts of (1), so that:

$$RP + XQ + V_2^2 = V_1 V_2 \cos\delta \quad (2)$$

$$XP - RQ = V_1 V_2 \sin\delta \quad (3)$$

from which the two equations are squared and summed up with each other, to obtain the voltage V_2^2 from the solution of the resulting biquadratic equation:

$$V_2^2 = \frac{V_1^2}{2} - (RP + XQ) \pm \sqrt{\frac{V_1^4}{4} - (RP + XQ)V_1^2 - (XP - RQ)^2} \quad (4)$$

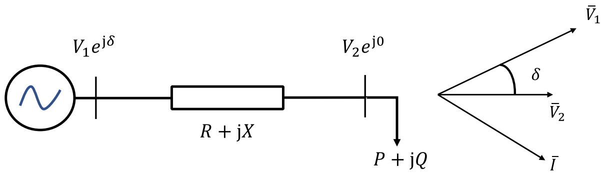

Fig. 1. Circuit scheme of the two-node system and phasor diagram.

The voltage V_2 is then determined as the square root of (4). In addition, the angle δ is calculated from (3):

$$\delta = \sin^{-1}\left(\frac{XP - RQ}{V_1 V_2}\right) \tag{5}$$

The current $\bar{I}$ is then found as

$$\bar{I} = \frac{(\bar{V}_1 - \bar{V}_2)}{R+jX} \tag{6}$$

and the power losses are computed as $\Delta P = R\, I^2$.

B. Three-phase two-node system with two time intervals

Let us consider a three-phase system with assigned power loads. For the system loads, let us take two time steps of duration τ each. For the numerical calculations, let us consider an example for a three-phase line with ideal neutral, with data expressed in per units (pu): $V_1 = 1$ pu, $R = 0.011$ pu, $X = 0.035$ pu, $P = 0.1$ pu, and $Q = 0.05$ pu. The single time step is half-hourly ($\tau = 0.5$ h). Some illustrative examples are discussed below.

B.1. Balanced load at the two time steps with ideal neutral

The first comparison is given for a balanced three-phase system taken in two cases, characterised by having the same average load calculated over the two time steps for every phase, hence with the same total average three-phase power:

- *Case A0*: Equal complex average power $\bar{S} = P + jQ$ in every phase at both time steps (balanced three-phase system, without any measured difference from the two time steps). The current $\bar{I}_{A0}$ is calculated from (6) by using $V_1 = E$, P and Q, and the total energy losses in the two time steps are determined as $\Delta W^{(A0)} = 2\tau \cdot 3RI_{A0}^2$.
- *Case A1*: Equal complex average power in every phase, but with measured differences detected in the two time steps, i.e., $\bar{S}/2$ at the first time step, and $3\bar{S}/2$ at the second time step. The currents $\bar{I}_{A1,1}$ and $\bar{I}_{A1,2}$ are calculated from (6) by using $V_1 = E$, while P and Q are given at each time step from the corresponding complex average power. The total energy losses $\Delta W^{(A1)} = \tau \cdot 3R(I_{A1,1}^2 + I_{A1,2}^2)$ in the two time steps are indicated in Table I. The load is indicated in the table with its active power (the power factor is constant).

The ratio between the total energy losses obtained if there is a measured difference over different time steps (Case A1), with respect to Case A0 with equal average power load is:

$$r_W^{(A1)} = \frac{\Delta W^{(A1)}}{\Delta W^{(A0)}} = \frac{(I_{A1,1}^2 + I_{A1,2}^2)}{2I_{A0}^2} \tag{7}$$

In the numerical case considered, $r_W^{(I)} = 5.87/3.96 = 1.48$. The practical meaning of this result is that the calculation of the energy losses carried out with more detailed knowledge of the loads during time provides less underestimated results, in the specific case with a remarkable 48% increase in the total energy losses.

TABLE I. Losses with Different Loads and Equal Average Load in the Two Time Steps

Time Step	Power (pu)			Losses (pu·h) · 10^{-3}			
	Phase A	*Phase B*	*Phase C*	*Phase A*	*Phase B*	*Phase C*	*Total*
Case A0							
t_1	0.10	0.10	0.10	0.66	0.66	0.66	1.98
t_2	0.10	0.10	0.10	0.66	0.66	0.66	1.98
Total	0.20	0.20	0.20	1.32	1.32	1.32	3.96
Case A1							
t_1	0.05	0.05	0.05	0.12	0.12	0.12	0.36
t_2	0.15	0.15	0.15	2.17	2.17	2.17	5.51
Total	0.20	0.20	0.20	2.29	2.29	2.29	5.87
Case A2							
t_1	0.20	0	0.10	5.56	0	0.66	6.22
t_2	0.10	0	0.20	0.66	0	5.56	6.22
Total	0.30	0	0.30	6.22	0	6.22	12.44

B.2. Different load unbalances at the two time steps with ideal neutral

In the distribution networks, loads are generally unbalanced. In the calculation of the energy losses, the effect of unbalance is combined with the data granularity and provides further contributions that need to be considered to avoid the energy losses underestimation that could occur by modelling the system as balanced. For the sake of simplicity, let us consider an unbalanced case for the three-phase system, with the following characteristics:

- *Case A2*: Complex average powers $2\bar{S}$, 0 and $\bar{S}$ in the three phases at the first time interval, and 0, $2\bar{S}$, and $\bar{S}$ in the three phases at the second time interval. These values have been chosen in such a way that the sum of the three-phase average power in the three phases over the two time steps is the same as in Case A0. The energy losses in the phase with load $2\bar{S}$ are $\Delta W' = \tau R\, I'^2$, where $\bar{I}'$ is determined from (6) by using $V_1 = E$, $P = \mathrm{Re}(2\bar{S})$ and $Q = \mathrm{Im}(2\bar{S})$ in the calculation of V_2. The energy losses in the phase with load $\bar{S}$ are $\Delta W'' = \tau R\, I''^2$, where $\bar{I}''$ is calculated from (6) by using $V_1 = E$, $P = \mathrm{Re}(\bar{S})$ and $Q = \mathrm{Im}(\bar{S})$. In the two time steps, the energy losses are $\Delta W^{(A2)} = 2(\Delta W' + \Delta W'') = 4\tau R(I'^2 + I''^2)$. Table I shows the specific results.

Comparing the two cases, numerically it holds $I'' = I_{A0}$, so that the ratio between the total energy losses with respect to the balanced three-phase system is:

$$r_W^{(A2)} = \frac{\Delta W^{(A2)}}{\Delta W^{(A0)}} = \frac{(I'^2 + I_{A0}^2)}{3I_{A0}^2} = \frac{1}{3}\left(1 + \left(\frac{I'}{I_{A0}}\right)^2\right) \tag{8}$$

From the results indicated in Table I for the three-phase line indicated, the ratio $r_W^{(A2)}$ is as high as 12.44/3.96 = 3.1457. This result means that considering the unbalanced loads in the individual time steps gives total line losses more than three times higher than considering a balanced average load in the two time steps. This remarkable difference gives another clear indication on the importance of calculating the line losses in an accurate way concerning both time steps and network modelling.

B.3. Different load unbalances at the two time steps with real neutral

For assessing the results in a more realistic case, the unbalanced line model provided by Kersting [26] is considered, in which the neutral is not ideal, and the phase impedances are also slightly different. The solutions are calculated by using three-phase power flow calculations, where the loss partitioning in the three phases is determined as explained in [27]. Table II shows the results in two cases with load settings identified with a similar rationale as the ones shown in Section II.B.1 (Case B1 with balanced load, and Case B2 with unbalanced load such that the total average power in the three phases is the same as in Case B1 in both time steps). The results indicate a ratio $r_W^{(B2)}$ = 45.478/19.390 = 2.345, that confirms the remarkable difference obtained in the total losses resulting when the difference among the data in the two single time steps is detected.

TABLE II. LOSSES WITH DIFFERENT LOAD UNBALANCES AND EQUAL AVERAGE LOAD IN THE TWO TIME STEPS

Case B1							
Time Step	**Power (kW)**			**Losses (kWh)**			
	Phase A	***Phase B***	***Phase C***	***Phase A***	***Phase B***	***Phase C***	***Total***
t_1	500	500	500	6.396	6.442	6.552	19.390
t_2	500	500	500				
Case B2							
t_1	1000	0	500	19.693	19.323	6.463	45.478
t_2	0	1000	500				

B.4. Different load and generation unbalances at the two time steps

When the system contains both load and generation connected to different phases, the determination of a single average power over the three phases is no longer meaningful, because the average power would be affected by the compensation that occurs in the sum of positive and negative values. As an extreme example, let us consider a three-phase system with complex average powers $\bar{S}$, 0, and -$\bar{S}$, in the three phases at a given time interval, while in the successive time interval the complex average powers are -$\bar{S}$, 0, and $\bar{S}$ in the three phases. Let us denote this case as Case B3. The total average power is null in this case either on the line (at each single time step) and phase-by-phase in the two time steps, so that a comparison case with a balanced three-phase system cannot be constructed.

The results are shown in Table II. This example looks quite extreme as it has been constructed; however, the possibility of switching from $\bar{S}$ to -$\bar{S}$ (or vice versa) in successive time steps could practically occur when the same prosumer has both local generation and load, for example with load 2$\bar{S}$ connected only in one time instant and local generation that gives the contribution -$\bar{S}$ to the net load and is connected in both time steps.

Another conceptual result that arises from the results shown in this section is that a phase-by-phase comparison (i.e., considering the losses on each phase rather than on the three phases of a given line) is not meaningful when the system contains both local generation and load. In fact, the losses depend on the square of the current (both when the current is taken from the grid or is injected into the grid) at each phase, while in the average power balance carried out on multiple time steps there are terms that are compensated and as such lead to reduced inputs to the power flow calculations. The losses in phase A and phase C are different when the load power is the same, because the three-phase system is also slightly structurally unbalanced due to the location of the conductors [26].

TABLE III. DIFFERENT LOAD UNBALANCE RESULTS (AVERAGE POWER AND ENERGY LOSSES) WITH LOAD AND LOCAL GENERATION ON TWO PHASES

Case B3							
Time Step	**Power (kW)**			**Losses (kWh)**			
	Phase A	***Phase B***	***Phase C***	***Phase A***	***Phase B***	***Phase C***	***Total***
t_1	1000	0	-1000	32.782	0	27.570	60.352
t_2	-1000	0	1000	28.826	0	33.347	60.173
Total	0	0	0	59.608	0	60.917	120.525

A variant of the previous case is presented as Case B4, in which the local generation and load are connected to only one phase in different time intervals. The results are shown in Table III. Again, there is no possible comparison with the balanced case, nor with the total behaviour averaged on a single phase in the two time steps.

TABLE IV. DIFFERENT LOAD UNBALANCE RESULTS (AVERAGE POWER AND ENERGY LOSSES) WITH LOAD AND LOCAL GENERATION ON ONE PHASE

Case IV							
Time Step	**Power (kW)**			**Losses (kWh)**			
	Phase A	***Phase B***	***Phase C***	***Phase A***	***Phase B***	***Phase C***	***Total***
t_1	1000	0	0	26.584	0	0	26.584
t_2	-1000	0	0	21.869	0	0	21.869
Total	0	0	0	48.453	0	0	48.453

A further example that indicates the effect of the unbalance given by the presence of different loads and local generations in the single phases is constructed by considering the following situation, in all cases with constant power factor (equal to 0.9):

- Phase A: parametric analysis with variable net active power load, from negative values (prevailing local generation) to positive values (prevailing load)
- Phase B: constant active power (100 kW)
- Phase C: constant active power (100 kW)

Fig. 2 shows the losses in the three phases, as well as the voltage magnitude, to confirm that the cases reported are feasible concerning node and phase voltages. The presence of the (non-ideal) neutral maintains the voltages inside acceptable ranges. The variation of the losses clearly indicates the transition from the situation with prevailing local generation to the one with prevailing load.

C. Lessons Learned

From the results of the cases presented in Section II.B, three main issues arise:

1. *Time granularity* issue: by solving the power flow with load power values averaged over relatively long time intervals, the total losses could be largely underestimated.

2. *Network modelling* issue: For unbalanced systems, when the network contains only loads (without local generation), the total energy losses in the unbalanced case could increase significantly compared with a balanced three-phase system with the same average power load.
3. *Net power issue*: for comparisons among cases with different time steps in a common time horizon, the total energy losses ratios make sense when the network model contains only loads (no local generation), otherwise there is a compensation between load and local generation in the determination of the net power across the phases and the time interval that makes the comparison biased; the extreme case with null net power load in the overall time interval has been shown.

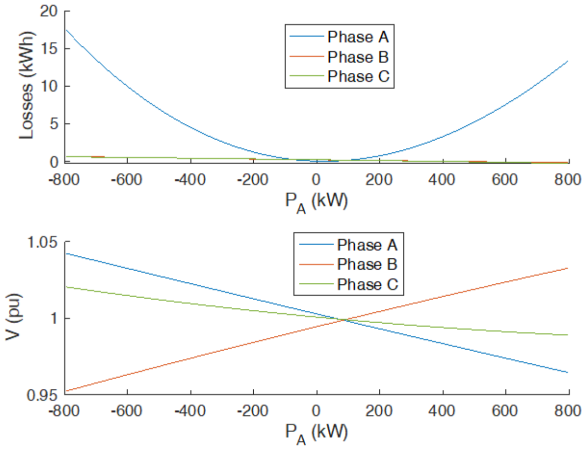

Fig. 2. Phase line losses and voltage magnitude when the net load power at phase A changes.

III. Results on a Distribution Network

The results shown in the previous section have highlighted the need to consider time steps shorter than hour to obtain more significant results for the calculation of the energy losses. However, which is a suitable time step for this analysis? The main concepts indicated below could leave the impression that better and better representation is obtained when the time step becomes shorter and shorter, virtually until one cycle (20 ms). However, when the time step becomes very short, the power patterns include fluctuations with smaller energy content, which are compensated among different loads in the system. An important information is the typical variability of the electrical demand that is connected to the electrical networks. For interval metering with regular time step, one minute time step has been indicated as a reasonable compromise for time granularity between the number of data and the accuracy of representation [25][28]. Significant results are obtained by using non-regular data gathering such as event-driven energy metering [29], that provides remarkably good representativeness of the power patterns [25].

The case study reported in this section considers the model of the IEEE European Low Voltage Test Feeder [30][31], composed of 906 nodes and 55 1-minute loads.

The system contains only loads, with no local generation. Thereby, it is possible to calculate the ratios between energy losses for unbalanced and balanced load cases.

The load data used in this section are available at one-minute time step. The calculation of the energy losses in the network is carried out with a three-phase power flow solver coded in Matlab©. Two situations are compared, in which the load power at each node is:

a) available at 1-minute time step from [31];
b) averaged at 15 minutes for each load from the above-indicated data at 1-minute time step.

The losses in the lines and the total losses are calculated for each quarter of hour. From the results shown in Fig. 3, the 15-minute total losses obtained by using the data at 1-minute time step are always higher than the losses computed from the average load at 15 minutes. As in the previous cases, the differences are due to the effect of time granularity. Considering the total losses in the individual phases (for a given line, i.e., line 32), Fig. 4 shows the corresponding phase losses ratio, which shows the impact of unbalance in addition to time granularity. When the individual lines are considered, the line losses ratio is calculated as the ratio between the total losses (summed up over the three phases at each line) evaluated from 1-min data and the corresponding total losses computed from the 15-min average power data. The results are presented in boxplot form in Fig. 5. The boxplot shows the statistics of the 906 lines at each quarter of hour. Most values are close to unity; however, very high values appear in some lines with high variations during time.

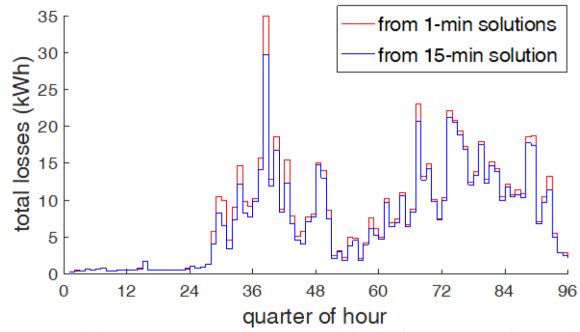

Fig. 3. Total line losses at each quarter of hour from power flow solutions calculated with 1-min and 15-min average power loads.

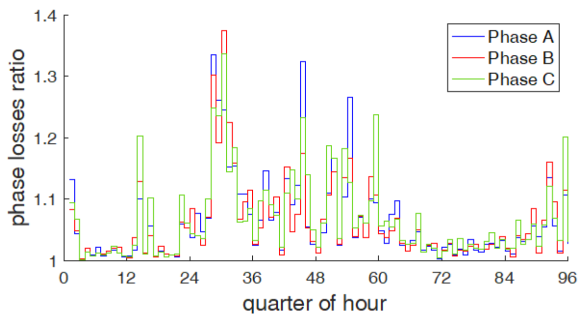

Fig. 4. Phase losses ratio at each quarter of hour from power flow solutions calculated with 1-min and 15-min average power loads (line 32).

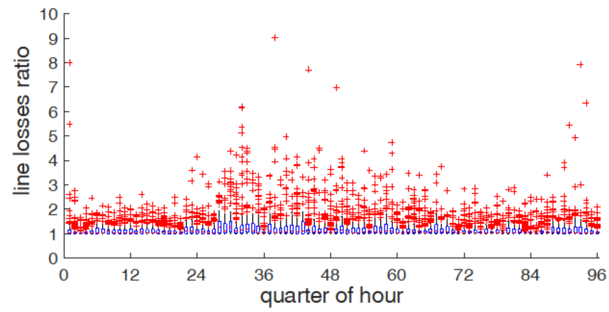

Fig. 5. Boxplot of the line losses ratio at each quarter of hour.

IV. Conclusions

This paper has provided various insights concerning the calculation of the energy losses in a distribution network, which depend on the load data representation and the network modelling. Three issues have been identified, due to the time granularity of load representation at different time steps, the network modelling, and the role of the net power. About time granularity, the solutions used at present with interval metering at 15 min, 30 min or 1 hour are poorly suitable and provide a remarkable underestimation of the total losses. Data gathered from one-minute interval metering or event-driven metering with good representativeness of the power patterns would provide better information to be used inside accurate three-phase modelling and power flow calculations.

These aspects demonstrate that approaching the problem of EnC implementation only through a simple *energy balance* is not enough. The electrical infrastructure plays an important role, and the nature of the collected data is fundamental. Low quality data can lead to wrong energy balance, undermining the collaboration and reciprocal trust relationships on the basis of the EnC concept. The regulatory bodies have to consider all the above implications, by acting with an effective work of revision of the current data collection and management practices, and by pushing forward innovative approaches. At the same time, an important dissemination work has to be initiated, because only improving the citizens' awareness about EnCs pros and cons can really make possible the EnC widespread implementation.

Future works will investigate how new measurement paradigms and data collection methodologies manage and solve the issues raised in this paper, making it possible to implement operation strategies that incorporate the actual grid conditions into the studies on the development of EnCs.

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