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“Voltage-Current Ratio Difference” Concept for identifying the dominant harmonic source

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ABSTRACT

This paper proposes a new concept for identifying the harmonic dominant side. The proposed concept is named as “voltage-current ratio difference” for determining the dominant equivalent harmonic voltage source and “current-voltage ratio difference” for determining the dominant equivalent harmonic current source. In contrast to most previous methods, the proposed concept does not require the equivalent harmonic impedance (or admittance) of the utility and customer sides as input data. Indeed, this concept requires the measured harmonic voltage as well as current at the point of common coupling in two states: in normal operation and in operation with the installation of a known serial impedance (or parallel admittance) between the utility and customer. The methodology and application of this concept are thoroughly presented in this paper. In addition, some practical issues about the implementation of the concept are discussed. In this regard, requirements for the serial impedance (or parallel admittance) at the fundamental frequency and at each harmonic order are defined to yield reliable results.

1. Introduction

Harmonic distortion problems have become an important concern in the power system [1]. Identifying the dominant harmonic source is one of the most controversial issues for the evaluation of harmonic distortions [2]. To limit the harmonic distortions in the power system and ensure a high quality of power delivery, various national and international standards set specific harmonic current emission limits for customers [3]. The current emission limits are usually calculated based on the allocated harmonic voltage to each customer. Having a method to determine the harmonic voltage contribution of customers, it can be directly proved whether the customer complies with its allocated harmonic voltage (without needing any further step, namely: harmonic current emission calculation). For the case that the standards insist on harmonic evaluation using current emission, the influence of the utility (background distortion) on customer current emissions should be considered. For this purpose, having a method to determine the harmonic current contribution of utility is essential [4]. This work deals with a method to determine the contribution of utility and customer to harmonic distortion. In addition, the identification of dominant harmonic source is addressed. In this regard, the meaning of the dominant side has been fundamentally challenged in [5,6]. Here, two different definitions for the harmonic dominant side at each harmonic order have been discussed:

- Dominant equivalent harmonic “voltage source;”
- Dominant equivalent harmonic “current source.”

In [5,6], the common methods for determining the dominant equivalent harmonic source at the point of common coupling (PCC) have been categorized in three general concepts based on these two different definitions for the dominant side. These there concepts are based on the direction of active power flow [7–9], reactive power [10,11], and “voltage-current ratio” [5,6,12,13]. These three concepts can be classified as noninvasive methods. Noninvasive methods, since they do not need to cause any disturbance in the investigated system. However, most of them need the equivalent harmonic impedance (or admittance) of utility and customer, which is a crucial point.

The method based on the direction of active power flow needs the measured harmonic voltage and current at the PCC as input data to provide statement about the dominant side [7–9]. Although in original work [7], it is not declared what the dominant side exactly means, this method for both the presented definitions of the dominant side, i.e., the dominant equivalent harmonic voltage and current source, has been

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Nomenclature

Variables

C	Capacitance
G_{iv}	Current-voltage ratio
I	Current
L	Inductance
m	Arbitrary constant
n	Arbitrary integer number
P	Active power
Q	Reactive power
R	Resistance
R_{vi}	Voltage-current ratio
V	Voltage
Y	Admittance
Z	Impedance
ΔG_{iv}	Current-voltage ratio difference
ΔR_{vi}	Voltage-current ratio difference
π	3.14 radian
∞	Infinity

Subscripts and Constants

c	Associated with the customer side
hvrt	Associated with the HVRT test container
lvrt	Associated with the LVRT test container
par	Associated with the parallel admittance
pcc	Associated with the point of common coupling
ser	Associated with the serial impedance
u	Associated with the utility side
I	Associated with the State I (normal operation)
II	Associated with the State II (operation with the installation of a known serial impedance or parallel admittance between the utility and customer)

Notation

$\underline{A}$	Complex number
A	Scalar or magnitude of the complex number $\underline{A}$
$\mathrm{Arg}(\underline{A})$	Argument of the complex number $\underline{A}$
$\lvert\underline{A}\rvert$	Absolute value of the complex number $\underline{A}$

separately investigated in [5,6]. However, it has been analytically shown that this method can not be always used to provide a valid statement about the dominant equivalent harmonic voltage current source [5,6,14]. Therefore, this method cannot always identify the dominant equivalent harmonic source. In this regard, several papers (e.g., [15,16]) have proposed a set of criteria to ensure the validity of this method.

The method based on reactive power requires the measured harmonic voltage and current at the PCC as well as the equivalent harmonic impedance (or admittance) of the utility and customer sides for determining the dominant equivalent harmonic source. In the original work [10,11], a clear definition about the dominant side has been provided for this method. In this regard, this work has proposed the critical impedance and admittance methods for determining the dominant equivalent harmonic voltage and current source, respectively. In contrast to the method based on the direction of active power flow, the methods based on reactive power provide always valid statements about the dominant equivalent harmonic source assuming having no inaccuracy in its input data. However, these methods cannot determine the harmonic contribution of each side [5,6].

The method based on "voltage-current ratio" requires the same input data as the method based on reactive power, i.e., the equivalent harmonic impedance (or admittance) of the utility and customer sides in addition to the measured harmonic voltage and current at the PCC. This method provides statement about the dominant equivalent harmonic voltage source. In the original work [12,13], this method has not been developed for determining the dominant equivalent harmonic current source, which has been addressed in [5]. This method is based on the current-voltage ratio. In addition to the dominant equivalent harmonic source, this method identifies the harmonic contribution of each side at the PCC.

The physical background of the methods as well as some practical issues about the implementation of the methods have been separately discussed in [6]. Accordingly, both the methods based on reactive power and "voltage-current ratio" require the equivalent harmonic impedance of the utility and customer sides, in addition to the measured voltage and current at the PCC. As long as there is no inaccuracy on the input data, both the methods provide always valid statements. The harmonic impedance estimation is the most crucial issue about the implementation of these methods.

It is very desirable in many applications to directly measure the harmonic impedances [17,18]. Used methods to measure the harmonic impedance can be divided into two types: invasive [19,20] and noninvasive [21,22] methods. Invasive methods estimate the harmonic impedance from the variations of voltage and current which are caused by the injected disturbances or harmonic currents into the power system. Although reliable results can be usually extracted from these methods, the disturbances could have negative impacts on the power system operation and it may be impractical. In contrast, noninvasive methods estimate the harmonic impedance from the natural variations of voltage and current which are caused by variations of operating point in the power system without any external variations [23]. The main concern regarding the implementation of the noninvasive methods is the accuracy and reliability of the estimated harmonic impedance [24]. It should be noted that the utility side harmonic impedance can not be constant for a long time due to stochastic changes in power system and the nature of time-varying harmonics. Hence, errors in estimating the harmonic impedance can not be neglected.

Due to the practical constraints and troubles for measuring the harmonic impedances (or admittances), the application of these concepts for determining the dominant equivalent harmonic source is limited. To overcome this problem, this paper proposes a new concept based on the "voltage-current ratio" concept for identifying the dominant side. The proposed concept utilizes a known serial impedance (or parallel admittance) between the utility and customer in order to cause variations in the harmonic voltage and current at the PCC. Therefore, it can be classified as an invasive method. Indeed, this concept is based on the variation of the "voltage-current ratios" (or "current-voltage ratios") in two states: in normal operation and in operation with the installation of a known serial impedance (or parallel admittance) between the utility and customer. Like other invasive methods, the proposed method is especially proper for the applications in type approval tests, which are intended to be performed occasionally. In general, the invasive methods are not intended for continuous operation and monitoring purposes. It should be noted that the previous methods based on the reactive power direction method and voltage-current ratio [5,6,10–13] are not proper for monitoring purposes either because they need the value of impedances, which can vary over the time [25]. Furthermore, it should be noted that this invasive method as well as the addressed noninvasive methods [5] determine the dominant harmonic source for each harmonic order separately.

In [5], it has been analytically demonstrated that the dominant equivalent harmonic voltage and current source are not identical. Therefore, the concept is proposed for determining the dominant equivalent harmonic voltage source as well as current source. The proposed concept has been named as “voltage-current ratio difference” for determining the dominant equivalent harmonic voltage source and “current-voltage ratio difference” for determining the dominant equivalent harmonic current source. This paper describes the “voltage-current ratio difference” method in Section 2 and the “current-voltage ratio difference” in Section 3, theoretically. Section 4 presents this concept verbally focusing on its physical background. In Section 5, some practical aspects for implementing the method are discussed. Section 6 illustrates the application of the proposed concept using some examples. Section 7 provides a short conclusion.

2. “Voltage-Current Ratio Difference”

In [12,13], the “voltage-current ratio” method has been proposed for evaluation the harmonic interaction between the utility and customer and determining the dominant equivalent harmonic voltage source. For this purpose, the harmonic “voltage-current ratio” at the PCC has been suggested as a new indicator to evaluate the equivalent harmonic voltage source of the utility and customer side. The equivalent harmonic voltages can be investigated using the Thevenin equivalent circuit of both sides as shown in Fig. 1(a). This method can determine the ratio of the equivalent harmonic voltages ($\frac{\underline{V}_{\mathrm{u}}}{\underline{V}_{\mathrm{c}}}$) as a complex number, i.e., this method identifies, besides the magnitude ratio of equivalent harmonic voltages ($\frac{V_{\mathrm{u}}}{V_{\mathrm{c}}}$), the phase-angle difference between the equivalent voltages ($\mathrm{Arg}(\underline{V}_{\mathrm{u}}) - \mathrm{Arg}(\underline{V}_{\mathrm{c}})$). It should be noted that this method requires the utility and customer equivalent harmonic impedance ($\underline{Z}_{\mathrm{u}}$ and $\underline{Z}_{\mathrm{c}}$, respectively). In order to accomplish the mentioned purpose without needing the equivalent harmonic impedances, this paper proposes a new method based on “voltage-current ratio.” In this regard, the measured harmonic voltage and current at the PCC in the two following states are required:

- State I: Normal operation, see Fig. 1(a);
- State II: Operation with the installation of a known serial impedance between the utility and customer, see Fig. 1(b).

In this paper, it is assumed that the measurements in mentioned states are performed consecutively and without any interruptions. As a result, the measurements are accomplished in a specific operating point of the utility and customer at the fundamental frequency. This assumption allows to consider a same value for model parameters (i.e., the equivalent harmonic voltage sources and impedances) in both states because the harmonic behavior of the utility and customer can generally depend on their operating point at the fundamental frequency. However, the changes in the operating point of the utility and customer sides over a long time is inevitable. Therefore, this assumption are valid only for relatively short measurement time.

In both mentioned states, the “voltage-current ratio” at the PCC ($\underline{R}_{\mathrm{vi}}$) for each harmonic order can be calculated from measurement data as follows:

$$\underline{R}_{\mathrm{vi}} = \frac{\underline{V}_{\mathrm{pcc}}}{\underline{I}_{\mathrm{pcc}}}. \tag{1}$$

“Voltage-current ratio” ($\underline{R}_{\mathrm{vi}}$) can be defined as a Möbius transformation of equivalent harmonic voltage ratio ($\frac{\underline{V}_{\mathrm{u}}}{\underline{V}_{\mathrm{c}}}$) [12]. Under normal operation (State I), the “voltage-current ratio” can be formulated according to Fig. 1(a) as follows:

$$\underline{R}_{\mathrm{vi-I}} = \frac{\underline{V}_{\mathrm{pcc-I}}}{\underline{I}_{\mathrm{pcc-I}}} = \frac{\underline{Z}_{\mathrm{c}}\left(\frac{\underline{V}_{\mathrm{u}}}{\underline{V}_{\mathrm{c}}}\right) + \underline{Z}_{\mathrm{u}}}{-\left(\frac{\underline{V}_{\mathrm{u}}}{\underline{V}_{\mathrm{c}}}\right) + 1}. \tag{2}$$

Under operation with the installation of a known serial impedance between the utility and the PCC (State II), the “voltage-current ratio” can be formulated according to Fig. 1(b) as follows:

$$\underline{R}_{\mathrm{vi-II}} = \frac{\underline{V}_{\mathrm{pcc-II}}}{\underline{I}_{\mathrm{pcc-II}}} = \frac{\underline{Z}_{\mathrm{c}}\left(\frac{\underline{V}_{\mathrm{u}}}{\underline{V}_{\mathrm{c}}}\right) + (\underline{Z}_{\mathrm{u}} + \underline{Z}_{\mathrm{ser}})}{-\left(\frac{\underline{V}_{\mathrm{u}}}{\underline{V}_{\mathrm{c}}}\right) + 1}. \tag{3}$$

Based on (2) and (3), this paper proposes a new indicator for determining the dominant equivalent harmonic voltage source. This indicator is named “voltage-current ratio difference” at the PCC ($\Delta\underline{R}_{\mathrm{vi}}$) and can be calculated as follows for each harmonic order:

$$\Delta\underline{R}_{\mathrm{vi}} = \underline{R}_{\mathrm{vi-II}} - \underline{R}_{\mathrm{vi-I}} = \frac{\underline{Z}_{\mathrm{ser}}}{-\left(\frac{\underline{V}_{\mathrm{u}}}{\underline{V}_{\mathrm{c}}}\right) + 1}. \tag{4}$$

Eq. (4) describes also the “voltage-current ratio difference” at the PCC ($\Delta\underline{R}_{\mathrm{vi}}$) as a Möbius transformation of the complex variable $\frac{\underline{V}_{\mathrm{u}}}{\underline{V}_{\mathrm{c}}}$ (equivalent harmonic voltage ratio). As can be seen in (4), this Möbius transformation is independent of $\underline{Z}_{\mathrm{u}}$ and $\underline{Z}_{\mathrm{c}}$. Therefore, determining of the $\frac{\underline{V}_{\mathrm{u}}}{\underline{V}_{\mathrm{c}}}$ and consequently determining the dominant equivalent harmonic voltage source is independent of $\underline{Z}_{\mathrm{u}}$ and $\underline{Z}_{\mathrm{c}}$ as well, in contrast to the method based on reactive power and “voltage-current ratio.” In other words, this Möbius transformation depends only on the known $\underline{Z}_{\mathrm{ser}}$, which is the most important advantage of this method in comparison to the previous methods.

Generally, two foci analogous to two extreme cases can be defined for each Möbius transformation. For (4), these extreme cases can be characterized as follows:

- Case A: $\frac{\underline{V}_{\mathrm{u}}}{\underline{V}_{\mathrm{c}}} \to \infty$. In this case, the “voltage-current ratio difference” ($\Delta\underline{R}_{\mathrm{vi}}$) approaches zero (i.e., $\Delta\underline{R}_{\mathrm{vi}} \to 0$);
- Case B: $\frac{\underline{V}_{\mathrm{u}}}{\underline{V}_{\mathrm{c}}} \to 0$. In this case, the “voltage-current ratio difference” ($\Delta\underline{R}_{\mathrm{vi}}$) approaches the serial impedance (i.e., $\Delta\underline{R}_{\mathrm{vi}} \to \underline{Z}_{\mathrm{ser}}$).

In order to investigate the interaction between the utility and customer, the position of the “voltage-current ratio differences” ($\Delta\underline{R}_{\mathrm{vi}}$) should be compared with the above-mentioned foci (0 and $\underline{Z}_{\mathrm{ser}}$) in the complex plane (Fig. 3). For this purpose, two families of Apollonian circles can be used as isolines in the complex plane:

- Each circle in the first family of the Apollonian circles is correlated with a specific magnitude of the equivalent harmonic voltage ratio, i.e., $\frac{V_{\mathrm{u}}}{V_{\mathrm{c}}} = m$ (see the blue circles in Fig. 3). It determines the locus of “voltage-current ratio differences” ($\Delta\underline{R}_{\mathrm{vi}}$) such that the ratio of distances from $\Delta\underline{R}_{\mathrm{vi}}$ to 0 and to $\underline{Z}_{\mathrm{ser}}$ equals m. In extreme case A, the corresponding circle approaches 0, while in extreme case B, the

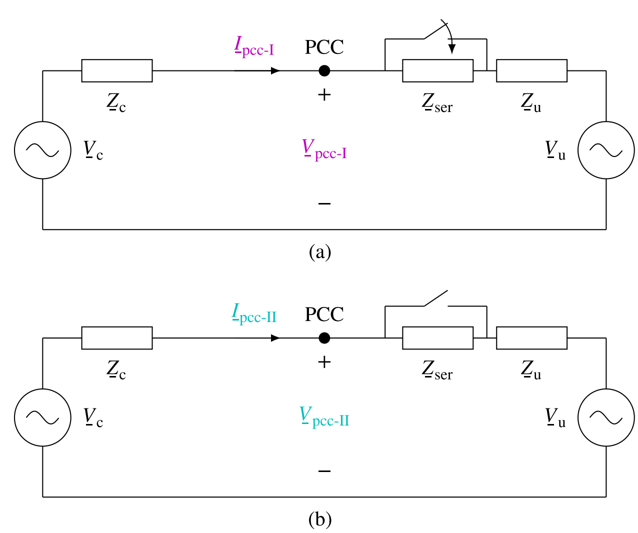

Fig. 1. Thevenin equivalent circuit to explain the harmonic voltage source detection: (a) in normal operation; and (b) in operation with the installation of a known serial impedance between the utility and customer.

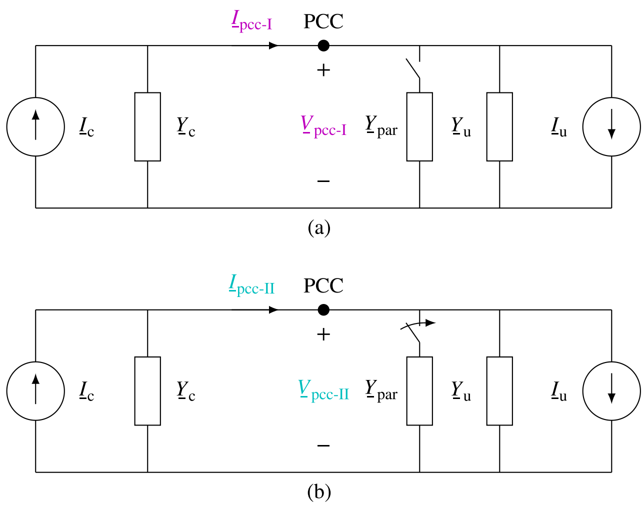

Fig. 2. Norton equivalent circuit to explain the harmonic current source detection: (a) in normal operation; and (b) in operation with the installation of a known parallel admittance between the utility and customer.

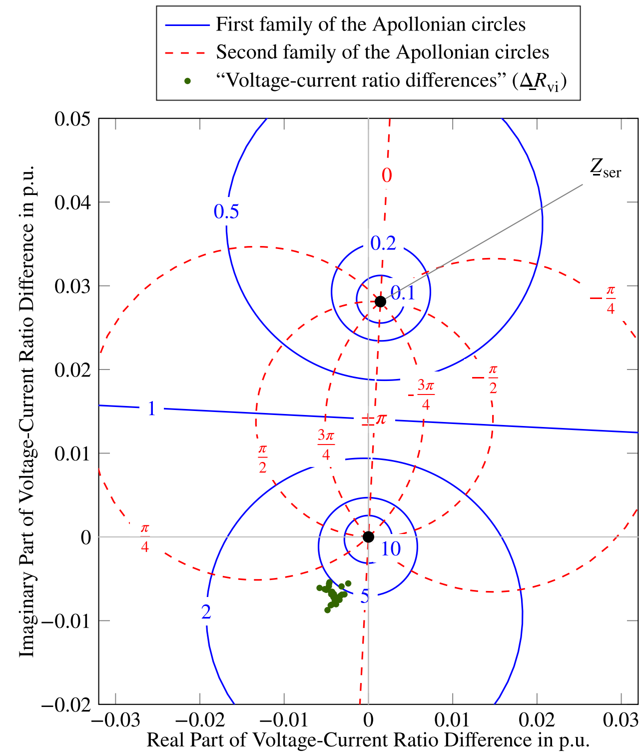

Fig. 3. Graphical representation of the "voltage-current ratio differences" method.

corresponding circle approaches $\underline{Z}_{\text{ser}}$. For the specific intermediate case $\frac{V_u}{V_c} = 1$, the circle degenerates into the perpendicular bisector of the line segment between 0 and $\underline{Z}_{\text{ser}}$;

- Each circle in the second family of the Apollonian circles corresponds to the specific angles of the equivalent harmonic voltage ratio, i.e., $\text{Arg}(\frac{\underline{V}_u}{\underline{V}_c}) = \text{Arg}(\underline{m}) + n\pi$, where n can be 0, ±1, ±2, .. (see the red circles in Fig. 3). Any point on a circle of this family forms an inscribed angle, equal to $\text{Arg}(\underline{m}) + n\pi$, by two chords with the aid of that this point as the common end point as well as 0 and $\underline{Z}_{\text{ser}}$. The circles of the second family intersect the isolines of the first family at right angles.

The magnitude of the equivalent harmonic voltage ratio ($\frac{V_u}{V_c}$) as well as its phase angle ($\text{Arg}(\frac{\underline{V}_u}{\underline{V}_c})$) can be determined by comparing the position of the "voltage-current ratio differences" ($\Delta\underline{R}_{\text{vi}}$) with these circle families.

By comparing the position of the "voltage-current ratio differences" ($\Delta\underline{R}_{\text{vi}}$) with the perpendicular bisector of the line segment between 0 and $\underline{Z}_{\text{ser}}$ (i.e., the intermediate case $\frac{V_u}{V_c} = 1$), the dominant equivalent harmonic voltage source can be determined. Indeed,

- If the "voltage-current ratio difference" ($\Delta\underline{R}_{\text{vi}}$) is closer to 0 (i.e., $|\Delta\underline{R}_{\text{vi}}| < |\Delta\underline{R}_{\text{vi}} - \underline{Z}_{\text{ser}}|$), then the equivalent harmonic voltage source of the utility side is dominant ($\frac{V_u}{V_c} > 1$);
- If the "voltage-current ratio difference" ($\Delta\underline{R}_{\text{vi}}$) is closer to $\underline{Z}_{\text{ser}}$ (i.e., $|\Delta\underline{R}_{\text{vi}}| > |\Delta\underline{R}_{\text{vi}} - \underline{Z}_{\text{ser}}|$), then the equivalent harmonic voltage source of the customer side is dominant ($\frac{V_u}{V_c} < 1$);
- If the "voltage-current ratio difference" ($\Delta\underline{R}_{\text{vi}}$) is located at the perpendicular bisector of the line segment between 0 and $\underline{Z}_{\text{ser}}$ (i.e., $|\Delta\underline{R}_{\text{vi}}| = |\Delta\underline{R}_{\text{vi}} - \underline{Z}_{\text{ser}}|$), then both the voltage sources have the same magnitude ($\frac{V_u}{V_c} = 1$).

In order to assist in the implementation of this method, its algorithm for a specific harmonic order is presented as a flowchart in Fig. 4. This algorithm can be used for each harmonic order.

As shown in Fig. 1, the serial impedance is installed at the utility side (between the utility and the PCC). It should be noted that installing the serial impedance at the customer side (between the customer and the PCC) does not change the main idea of this method, but it results in different formulations. In order to avoid duplication of the description, this case is not presented in this paper.

3. "Current-Voltage Ratio Difference"

The "current-voltage ratio" method has been proposed in [6] for determining the dominant equivalent harmonic current source. In this work, the harmonic "current-voltage ratio" at the PCC has been suggested as a new indicator to evaluate the equivalent harmonic current source of the utility and customer side. The equivalent harmonic currents can be investigated using the Norton equivalent circuit of both sides as shown in Fig. 2(a). This method can determine the ratio of the equivalent harmonic currents ($\frac{\underline{I}_u}{\underline{I}_c}$) as a complex number, i.e., this method determines,besides the magnitude ratio of equivalent harmonic currents ($\frac{I_u}{I_c}$), the phase-angle difference between the equivalent currents ($\text{Arg}(\underline{I}_u) - \text{Arg}(\underline{I}_c)$). It should be noted that this method requires the utility and customer equivalent harmonic admittance ($\underline{Y}_u$ and $\underline{Y}_c$, respectively). In order to accomplish the mentioned purpose without needing the equivalent harmonic admittances, this paper proposes a new method based on "current-voltage ratio." In this regard, the measured harmonic voltage and current at the PCC in the two following states are required:

- State I: Normal operation, see Fig. 2(a);
- State II: Operation with the installation of a known parallel admittance between the utility and customer, see Fig. 2(b).

In this paper (similar to the Section 2), it is assumed here that the measurements in mentioned states are performed consecutively and without any interruptions. This assumption allows to consider a same value for model parameters (i.e., the equivalent harmonic current sources and admittances) in both states. In both the mentioned states, the "current-voltage ratio" at the PCC ($\underline{G}_{\text{iv}}$) for each harmonic order can be calculated from measurement data as follows:

$$\underline{G}_{\text{iv}} = \frac{\underline{I}_{\text{pcc}}}{\underline{V}_{\text{pcc}}}. \tag{5}$$

"Current-voltage ratio" ($\underline{G}_{\text{iv}}$) can be defined as a Möbius transformation

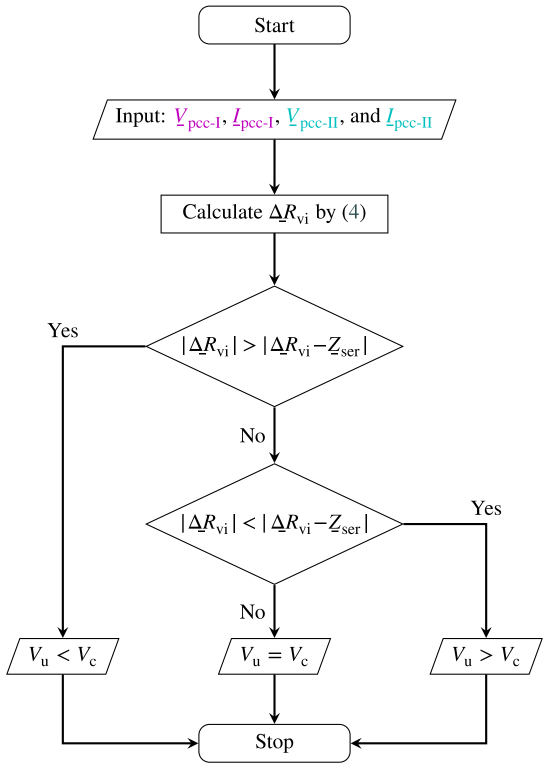

Fig. 4. Flowchart of the "voltage-current ratio differences" method for determining the dominant equivalent harmonic voltage source.

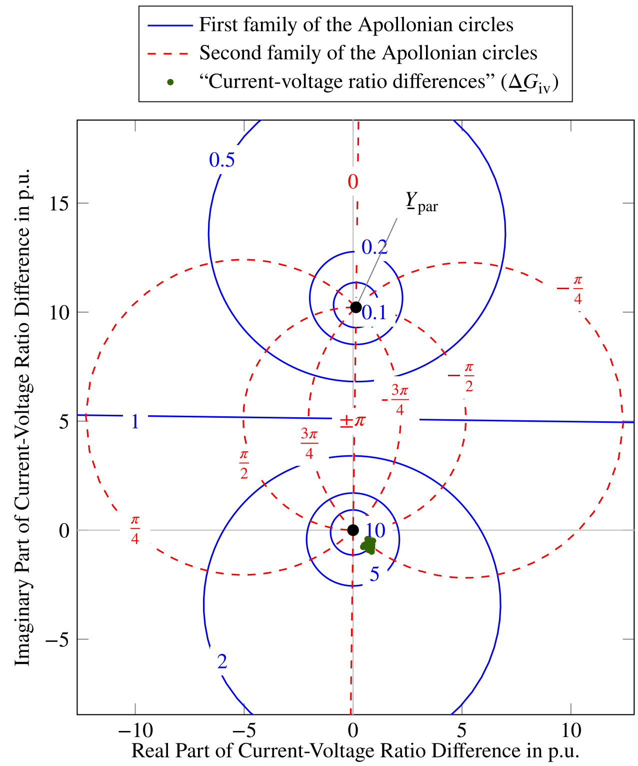

Fig. 5. Graphical representation of the "current-voltage ratio" method.

of equivalent harmonic current ratio ($\frac{\underline{I}_{\text{u}}}{\underline{I}_{\text{c}}}$) [5]. Under normal operation (State I), the "current-voltage ratio" can be formulated according to Fig. 2(a) as follows:

$$\underline{G}_{\text{iv-I}} = \frac{\underline{I}_{\text{pcc-I}}}{\underline{V}_{\text{pcc-I}}} = \frac{\underline{Y}_{\text{c}}\left(\frac{\underline{I}_{\text{u}}}{\underline{I}_{\text{c}}}\right) + \underline{Y}_{\text{u}}}{-\left(\frac{\underline{I}_{\text{u}}}{\underline{I}_{\text{c}}}\right) + 1}. \tag{6}$$

Under operation with the installation of a known parallel admittance between the utility and the PCC (State II), the "voltage-current ratio" can be formulated in consonance with Fig. 1(b) as follows:

$$\underline{G}_{\text{iv-II}} = \frac{\underline{I}_{\text{pcc-II}}}{\underline{V}_{\text{pcc-II}}} = \frac{\underline{Y}_{\text{c}}\left(\frac{\underline{I}_{\text{u}}}{\underline{I}_{\text{c}}}\right) + (\underline{Y}_{\text{u}} + \underline{Y}_{\text{par}})}{-\left(\frac{\underline{I}_{\text{u}}}{\underline{I}_{\text{c}}}\right) + 1}. \tag{7}$$

Based on (6) and (7), this paper proposes a new indicator for determining the dominant equivalent harmonic current source. This indicator is named "current-voltage ratio difference" at the PCC ($\Delta \underline{G}_{\text{iv}}$) and can be calculated as follows for each harmonic order:

$$\Delta \underline{G}_{\text{iv}} = \underline{G}_{\text{iv-II}} - \underline{G}_{\text{iv-I}} = \frac{\underline{Y}_{\text{par}}}{-\left(\frac{\underline{I}_{\text{u}}}{\underline{I}_{\text{c}}}\right) + 1}. \tag{8}$$

Eq. (8) describes also the "current-voltage ratio difference" at the PCC ($\Delta \underline{G}_{\text{iv}}$) as a Möbius transformation of the complex variable $\frac{\underline{I}_{\text{u}}}{\underline{I}_{\text{c}}}$ (equivalent harmonic current ratio). As can be seen in (8), this Möbius transformation is independent of $\underline{Y}_{\text{u}}$ and $\underline{Y}_{\text{c}}$. Therefore, determining of the $\frac{\underline{I}_{\text{u}}}{\underline{I}_{\text{c}}}$ and consequently determining the dominant equivalent harmonic current source is independent of $\underline{Y}_{\text{u}}$ and $\underline{Y}_{\text{c}}$ as well. In other words, this Möbius transformation depends only on the known $\underline{Y}_{\text{par}}$, which is the most important advantage of this method in comparison to the previous methods.

For (8), the corresponding extreme cases can be characterized as follows:

- Case A: $\frac{\underline{I}_{\text{u}}}{\underline{I}_{\text{c}}} \to \infty$. In this case, the "current-voltage ratio difference" ($\Delta \underline{G}_{\text{iv}}$) approaches zero (i.e., $\Delta \underline{G}_{\text{iv}} \to 0$);
- Case B: $\frac{\underline{I}_{\text{u}}}{\underline{I}_{\text{c}}} \to 0$. In this case, the "current-voltage ratio difference" ($\Delta \underline{G}_{\text{iv}}$) approaches the parallel admittance (i.e., $\Delta \underline{G}_{\text{iv}} \to \underline{Y}_{\text{par}}$).

In order to investigate the interaction between the utility and customer, the position of the "current-voltage ratio differences" ($\Delta \underline{G}_{\text{iv}}$) should be compared with the above-mentioned foci (0 and $\underline{Y}_{\text{par}}$) in the complex plane (Fig. 5). For this purpose, two families of Apollonian circles can be used as isolines in the complex plane:

- Each circle in the first family of the Apollonian circles corresponds to a specific magnitude of the equivalent harmonic current ratio, i.e., $\frac{I_{\text{u}}}{I_{\text{c}}} = m$ (see the blue circles in Fig. 5). It determines the locus of "current-voltage ratio differences" ($\Delta \underline{G}_{\text{iv}}$) such that the ratio of distances from $\Delta \underline{G}_{\text{iv}}$ to 0 and to $\underline{Y}_{\text{par}}$ equals m. In extreme case A, the corresponding circle approaches 0, while in extreme case B, the corresponding circle approaches $\underline{Y}_{\text{par}}$. For the specific intermediate case $\frac{I_{\text{u}}}{I_{\text{c}}} = 1$, the circle degenerates into the perpendicular bisector of the line segment between 0 and $\underline{Y}_{\text{par}}$;
- Each circle in the second family of the Apollonian circles is correlated with the specific angles of the equivalent harmonic current ratio, i.e., $\text{Arg}(\frac{\underline{I}_{\text{u}}}{\underline{I}_{\text{c}}}) = \text{Arg}(\underline{m}) + n\pi$, where n can be 0, ±1, ±2, .. (see the red circles in Fig. 5). Any point on a circle of this family forms an inscribed angle, equal to $\text{Arg}(\underline{m}) + n\pi$, by two chords with the aid of that this point as the common end point as well as 0 and $\underline{Y}_{\text{par}}$. The circles of the second family intersect the isolines of the first family at right angles.

The magnitude of the equivalent harmonic currents ratio ($\frac{I_{\text{u}}}{I_{\text{c}}}$) as well as its phase angle ($\text{Arg}(\frac{\underline{I}_{\text{u}}}{\underline{I}_{\text{c}}})$) can be determined by comparing the position of the "current-voltage ratio differences" ($\Delta \underline{G}_{\text{iv}}$) with these circle families.

By comparing the position of the "current-voltage ratio differences"

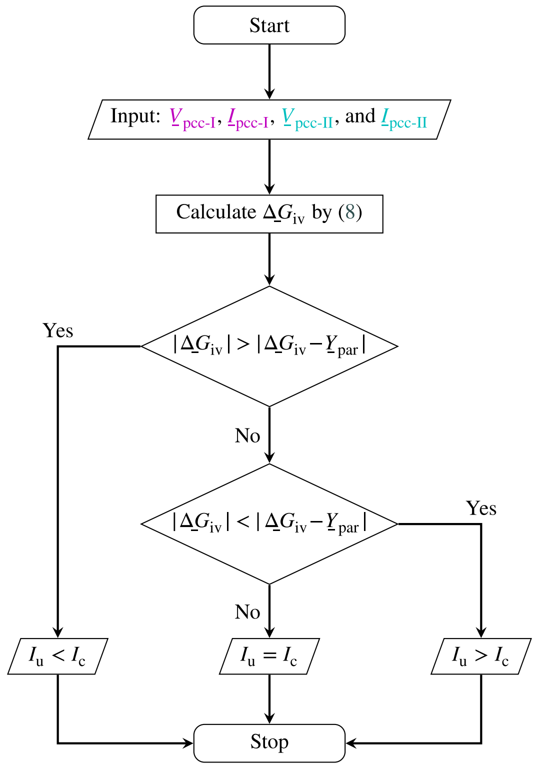

Fig. 6. Flowchart of the "current-voltage ratio" method for determining the dominant equivalent harmonic current source.

($\Delta\underline{G}_{\text{iv}}$) with the perpendicular bisector of the line segment between 0 and $\underline{Y}_{\text{par}}$ (i.e., the intermediate case $\frac{I_{\text{u}}}{I_{\text{c}}} = 1$), the dominant equivalent harmonic current source can be determined. Indeed,

- If the "current-voltage ratio difference" ($\Delta\underline{G}_{\text{iv}}$) is closer to 0 (i.e., $|\Delta\underline{G}_{\text{iv}}| < |\Delta\underline{G}_{\text{iv}} - \underline{Y}_{\text{par}}|$), then the equivalent harmonic current source of the utility side is dominant ($\frac{I_{\text{u}}}{I_{\text{c}}} > 1$);
- If the "current-voltage ratio difference" ($\Delta\underline{G}_{\text{iv}}$) is closer to $\underline{Y}_{\text{par}}$ (i.e., $|\Delta\underline{G}_{\text{iv}}| > |\Delta\underline{G}_{\text{iv}} - \underline{Y}_{\text{par}}|$), then the equivalent harmonic current source of the customer side is dominant ($\frac{I_{\text{u}}}{I_{\text{c}}} < 1$);
- If the "current-voltage ratio difference" ($\Delta\underline{G}_{\text{iv}}$) is located at the perpendicular bisector of the line segment between 0 and $\underline{Y}_{\text{par}}$ (i.e., $|\Delta\underline{G}_{\text{iv}}| = |\Delta\underline{G}_{\text{iv}} - \underline{Y}_{\text{par}}|$), then both the current sources have the same magnitude ($\frac{I_{\text{u}}}{I_{\text{c}}} = 1$).

In order to assist in the implementation of this method, its algorithm for a specific harmonic order is presented as a flowchart in Fig. 6.

As shown in Fig. 2, the parallel admittance is installed at the utility side (between the utility and the PCC). It should be noted that installing the parallel admittance at the customer side (between the customer and the PCC) does not change the main idea of this method, but it results in different formulations. In order to avoid duplication of the description, this case is not presented in this paper.

4. Physical background of the methods

The main aim here is to illustrate the physical background of the "voltage-current ratio difference" concept. For this purpose, the "voltage-current ratio difference" method is verbally described in this section. This method is developed based on the two extreme cases, in which one of the utility and customer equivalent harmonic voltage sources is much larger than the other. In these cases, the equivalent harmonic voltage source of the not-dominant side can be neglected. Therefore, this side shows a passive behavior like an impedance. In these cases, the "voltage-current ratio difference" at the PCC can be obtained as follow:

- If the equivalent harmonic voltage source of the utility side is negligible, then the "voltage-current ratio" in normal operation ($\underline{R}_{\text{vi}-\text{I}}$) is expected to be equal to $\underline{Z}_{\text{u}}$, see Fig. 1(a). In this case, the "voltage-current ratio" in operation with the installation of a known serial impedance ($\underline{R}_{\text{vi}-\text{II}}$) is expected to be equal to $\underline{Z}_{\text{u}} + \underline{Z}_{\text{ser}}$, see Fig. 1(b). As a result, the "voltage-current ratio" difference at the PCC ($\Delta\underline{R}_{\text{vi}} = \underline{R}_{\text{vi}-\text{II}} - \underline{R}_{\text{vi}-\text{I}} = \underline{Z}_{\text{u}} + \underline{Z}_{\text{ser}} - \underline{Z}_{\text{u}} = \underline{Z}_{\text{ser}}$) is expected to be $\underline{Z}_{\text{ser}}$;
- If the equivalent harmonic voltage source of the customer side is negligible, then the "voltage-current ratio" in normal operation ($\underline{R}_{\text{vi}-\text{I}}$) is expected to be equal to $-\underline{Z}_{\text{c}}$, see Fig. 1(a). In this case, the "voltage-current ratio" in operation with the installation of a known serial impedance ($\underline{R}_{\text{vi}-\text{II}}$) is also expected to be equal to $-\underline{Z}_{\text{c}}$, see Fig. 1(b). As a result, the "voltage-current ratio difference" at the PCC ($\Delta\underline{R}_{\text{vi}} = \underline{R}_{\text{vi}-\text{II}} - \underline{R}_{\text{vi}-\text{I}} = -\underline{Z}_{\text{c}} + \underline{Z}_{\text{c}} = 0$) is expected to be 0.

Generally, the interaction between the equivalent harmonic voltage sources determines the position of the "voltage-current ratio difference" in the complex plane. The harmonic interaction can be figuratively interpreted in the following way. While the equivalent harmonic voltage source of the utility side attempts at "pushing" the "voltage-current ratio difference" to zero, the equivalent harmonic voltage source of the customer side attempts at "pushing" the "voltage-current ratio difference" to the known serial impedance ($\underline{Z}_{\text{ser}}$). In this situation, it can be concluded: the larger the equivalent harmonic voltage magnitude of the side is, the stronger the push of that side is.

In a similar way, the physical background of the "current-voltage ratio difference" can be described. In order to avoid duplication of the description, the physical background of the "current-voltage ratio difference" is not presented in this section.

5. Practical aspects

The aim of the proposed concept is to determine the ratio of the equivalent harmonic voltages ($\frac{\underline{V}_{\text{u}}}{\underline{V}_{\text{c}}}$) or the ratio of the equivalent harmonic currents ($\frac{\underline{I}_{\text{u}}}{\underline{I}_{\text{c}}}$) without having the exact value of impedances, which is the most important advantage of this concept in comparison to the methods based on the reactive power and the voltage-current ratio. For this purpose, only the harmonic voltage and current at the PCC in two states (see Section 2 or 3) are required. Another advantage of the proposed concept compared to other methods (methods based on the direction of active power flow and the reactive power) is its ability to determine the contribution of both sides to the harmonic distortions at the PCC. Indeed, using this method makes it possible not only to identify the side with the main contribution to harmonic distortions (dominant equivalent harmonic source) but also to determine the ratio of the equivalent harmonic sources. As discussed in [5], the ratio of the equivalent harmonic voltages (or ratio of the equivalent harmonic currents) is equal to the ratio of the harmonic current contributions (or ratio of the harmonic voltage contributions) of each side at the PCC. Hence, the proposed concept also determines the contribution ratio of each side to harmonic distortions. Here, in addition to the magnitude of the harmonic contribution ratio, the angle of this ratio can be determined. Knowing this angle is useful to investigate whether the utility and customer harmonic contributions weaken or reinforce each other. The proposed concept is compared with other methods in Table 1 from different points of view (input data, validity, etc.).

Some practical issues regarding the selection and implementation of the serial impedance (or parallel admittance) are discussed in the following sections.

Table 1
Overview of the Relevant Methods for Evaluation the Harmonic Interaction between the Utility and Customer.

Method	Input Data	Method Statement	Valid	Disadvantage
Direction of active power flow [7–9]	$\underline{V}_{\mathrm{pcc}}$, $\underline{I}_{\mathrm{pcc}}$	• Identifying the dominant equivalent harmonic voltage and current source	Not always	Invalid statement in some cases
Reactive power (critical impedance and critical admittance) [10,11]	$\underline{V}_{\mathrm{pcc}}$, $\underline{I}_{\mathrm{pcc}}$, $\underline{Z}_{\mathrm{u}}$, $\underline{Z}_{\mathrm{c}}$	• Identifying the dominant equivalent harmonic voltage and current source	Always	Requiring the utility and customer equivalent harmonic impedance
Voltage-current ratio and current-voltage ratio [5,12,13]	$\underline{V}_{\mathrm{pcc}}$, $\underline{I}_{\mathrm{pcc}}$, $\underline{Z}_{\mathrm{u}}$, $\underline{Z}_{\mathrm{c}}$	• Identifying the dominant equivalent harmonic voltage and current source • Determining the magnitude of the harmonic voltage and current contributions ratio • Determining the angle of the harmonic voltage and current contributions ratio	Always	Requiring the utility and customer equivalent harmonic impedance
Voltage-current ratio difference and current-voltage ratio difference (proposed methods)	$\underline{V}_{\mathrm{pcc}}$, $\underline{I}_{\mathrm{pcc}}$ (in two states, see Sections 2 and 3)	• Identifying the dominant equivalent harmonic voltage and current source • Determining the magnitude of the harmonic voltage and current contributions ratio • Determining the angle of the harmonic voltage and current contributions ratio	Always	Requiring an additional installation

5.1. Requirement for the impedance and admittance at the fundamental frequency

The harmonic behavior of the utility and customer can generally depend on their operating point at the fundamental frequency. In this paper, the operating point is defined as follows:

- Active power at the fundamental frequency (P);
- Reactive power at the fundamental frequency (Q);
- Voltage amplitude at the fundamental frequency (V).

Here, it is assumed that the measurements (in the both states) are performed in a specific operating point of the utility and customer. To realize this assumption, besides the consecutive performance of the measurements, the installation of the serial impedance (or parallel admittance) between the utility and customer should not significantly change the operating point. For this purpose, the right choice of the serial impedance (or parallel admittance) plays an important role for the implementation of "voltage-current ratio difference" (or "current-voltage ratio difference") method. In this regard, the following points can be addressed:

- In case of the serial impedance applied to the "voltage-current ratio difference" method, installation of an inductive or resistive-inductive impedance should be used to yield more reliable results. An inductive or resistive-inductive impedance has a small magnitude at the fundamental frequency (depending on its inductance) comparing to higher harmonic orders. Consequently, the influence of this impedance on the operating point of the utility and customer at the fundamental frequency can be neglected;
- In an analogous way, in case of the parallel admittance applied to the "current-voltage ratio difference" method, a capacitive or resistive-capacitive admittance should be used to yield more reliable results. A capacitive or resistive-capacitive admittance has a small magnitude at the fundamental frequency (depending on its capacitance) comparing to higher harmonic orders. In this way, a notable change in the operating point at fundamental frequency can be avoided.

5.2. Requirement for the impedance and admittance at each harmonic order

In this section, requirements for the serial impedance (or parallel admittance) at each harmonic order, in addition to the fundamental frequency, are defined to yield reliable results. The "voltage-current ratio difference" (or "current-voltage ratio difference") method is based on the variation of the "voltage-current ratios" (or "current-voltage ratios") in two states (see Section 2 or Section 3). This variation results from installation of the serial impedance (or parallel admittance) between the utility and customer. An appropriate range of this variation performs an essential role to achieve the valid method statements. The desired variation range can be reached by the suitable selection of a serial impedance (or parallel admittance). In this regard, the following points should be considered by implementation of the methods:

- The serial impedance (or parallel admittance) should not be much smaller than the combined utility and customer equivalent harmonic impedance, $\underline{Z}_{\mathrm{u}} + \underline{Z}_{\mathrm{c}}$, (or combined utility and customer equivalent harmonic admittance, $\underline{Y}_{\mathrm{u}} + \underline{Y}_{\mathrm{c}}$). Otherwise, the resulted variation due to the installation of the serial impedance (or parallel admittance) in the "voltage-current ratios" (or "current-voltage ratios") is subtle. This subtle variation is invisible in measurement data;
- The serial impedance (or parallel admittance) should not be much larger than the combined utility and customer equivalent harmonic impedance, $\underline{Z}_{\mathrm{u}} + \underline{Z}_{\mathrm{c}}$, (or combined utility and customer equivalent harmonic admittance, $\underline{Y}_{\mathrm{u}} + \underline{Y}_{\mathrm{c}}$). Otherwise, the harmonic current

(or voltage) at the PCC after installation of the serial impedance (or parallel admittance) is relatively small and, therefore, probably has a low signal-to-noise ratio. Accordingly, the resulted "voltage-current ratio" (or "current-voltage ratio") can not be reliably determined.

On the basis of experience in several test-bench measurements, the following range for the serial impedance and parallel admittance at each harmonic order has been selected:

$$0.2 \leqslant \frac{Z_{ser}}{|\underline{Z}_{\mathrm{u}}+\underline{Z}_{\mathrm{c}}|} \leqslant 5,$$
$$0.2 \leqslant \frac{Y_{\mathrm{par}}}{|\underline{Y}_{\mathrm{u}}+\underline{Y}_{\mathrm{c}}|} \leqslant 5. \tag{9}$$

Consequently, a rough estimate of the combined utility and customer equivalent harmonic impedance or admittance is enough to yield more reliable results. Although selection of a serial impedance or parallel admittance in the mentioned range is proposed, it does not imply that the selection of a serial impedance or parallel admittance outside of the proposed range leads necessarily to invalid statements. In other words, selecting the serial impedance (or parallel admittance) outside of the proposed range can have an adverse effect on the reliability of the results. This range is, at present, tentative and may be modified in follow-up studies. For example, it may be possible to determine a proper range based on some characteristics of utility and customer (e.g. voltage level, short-circuit power at the PCC, nominal power of customer). According to this idea, a case-specific choice of the serial impedance and parallel admittance can be possible.

It should be noted that creating a resonance between the serial impedance (or parallel admittance) and the existing impedance (or admittance) should be avoided by suitable selection of a impedance (or admittance).

5.3. Implementation feasibility of the "Voltage-Current Ratio Difference" Concept in onsite measurement

The main challenge with respect to implementation of this concept is the achievement of measurements data in operation state with the installation of a known serial impedance (or parallel admittance). Performing such measurement for a small customer in low voltage level is not difficult. However, these measurements can be a challenge for customers in medium and high voltage level. A practical idea can be the application of existing test equipment which are certificated for such tests. For example, low-voltage ride-through (LVRT) and high-voltage ride-through (HVRT) test containers can be used for this purpose (see Fig. 7). These test containers are usually applied to investigate and prove the LVRT and HVRT capability of large-scale generating plants [28–30]. These test-containers can also be applied for harmonic studies [31]. It should be noted that the LVRT and HVRT containers are designed and certificated for on-site measurements [26]. Therefore, the proposed concept can be realized in on-site measurements using these test containers:

- The "voltage-current ratio difference" method can be implemented using the LVRT test container. In such a case, the requirements of the corresponding measurement can be satisfied using the serial inductor of the LVRT test container ($L_{\mathrm{lvrt-ser}}$ in Fig. 7). The value of this serial inductor should be selected so that the mentioned requirements in Section 5.1 are fulfilled. It can be done by selecting the proper tap of serial inductors. As in Section 5.1 mentioned, by proper selection of serial inductor, no significant voltage drop at the PCC is expected. Therefore, performing the measurement causes no negative impacts on the power system operation. It should be noted that the parallel inductor of the LVRT test-container ($L_{\mathrm{lvrt-par}}$ in Fig. 7) is not required and, therefore, is not connected.
- The "current-voltage ratio difference" method can be implemented using the HVRT test-container. In this case, the capacitor in the parallel branch of the HVRT test-container ($C_{\mathrm{hvrt-par}}$ in Fig. 7) can satisfy the requirements of the corresponding measurement, which are described in Section 5.1. The additional resistor in the parallel branch ($R_{\mathrm{hvrt-par}}$ in Fig. 7) prevents the uncontrolled oscillation of voltage at the PCC. In case of the "current-voltage ratio difference" method, the serial inductor of the HVRT test-container ($L_{\mathrm{hvrt-par}}$ in Fig. 7) is not required and, therefore, is short-circuited.

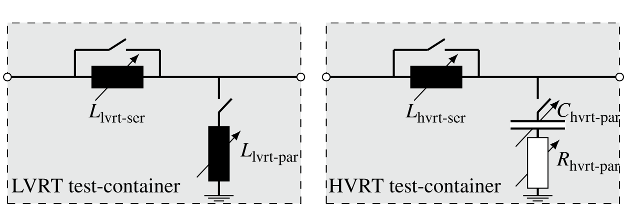

Fig. 7. Configuration of LVRT and HVRT test containers [26,27].

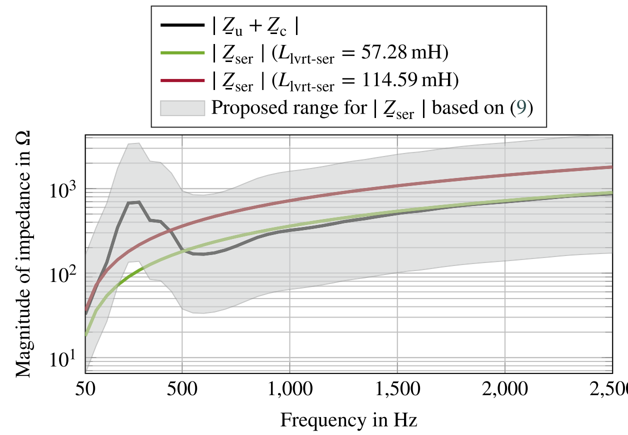

Fig. 8. Magnitude of the combined utility and customer equivalent harmonic impedance regarding an exemplary measurement campaign in comparison to different serial impedance.

As described in this section, the proposed concept can be implemented in the real power system using well-established equipment. The first experience in this regard is reported here. The proposed concept has been implemented for a customer in medium voltage level. In this measurement campaign, the magnitude of the combined utility and customer equivalent harmonic impedance ($\underline{Z}_{\mathrm{u}} + \underline{Z}_{\mathrm{c}}$) is calculated over the frequency with the aid of a noninvasive method to estimate the harmonic impedance [25,31]. The calculated harmonic impedance is shown in Fig. 8 up to 2.5 kHz. Based on the value of this impedance, the proposed range for the serial impedance by (9) is presented in this figure as a gray zone. In this measurement campaign, the measurements are performed in three states: in normal operation ($L_{\mathrm{lvrt-ser}} = 0$), in operation with the installation of a 57.28-mH serial inductor ($L_{\mathrm{lvrt-ser}} = 57.28\,\mathrm{mH}$), and a 114.59-mH serial inductor ($L_{\mathrm{lvrt-ser}} = 114.59\,\mathrm{mH}$). As shown in Fig. 8, the harmonic impedance of these two inductors is located within the gray zone (except in a narrow range of frequency in case of the 57.28-mH serial inductor). It means that the mentioned requirements in (9) can be satisfied using these two inductors almost for whole frequency range up to 2.5 kHz. Accordingly, it is expected that the resulted variation in the harmonic "voltage-current ratio" due to the installation of these two inductors can be sensible in measurement data.

Fig. 9 shows the magnitude and angle of "voltage-current ratios" for the fundamental frequency and exemplary for the 7$^{\mathrm{th}}$ harmonic order in the three mentioned states. For each of these states, the "voltage-current ratios" have been calculated over 100 time windows. Each time window had approximately a width of 200 ms. As shown in Fig. 9, a notable variation in the "voltage-current ratios" for the 7$^{\mathrm{th}}$ harmonic order can be reached using both the two inductors. It should be noted

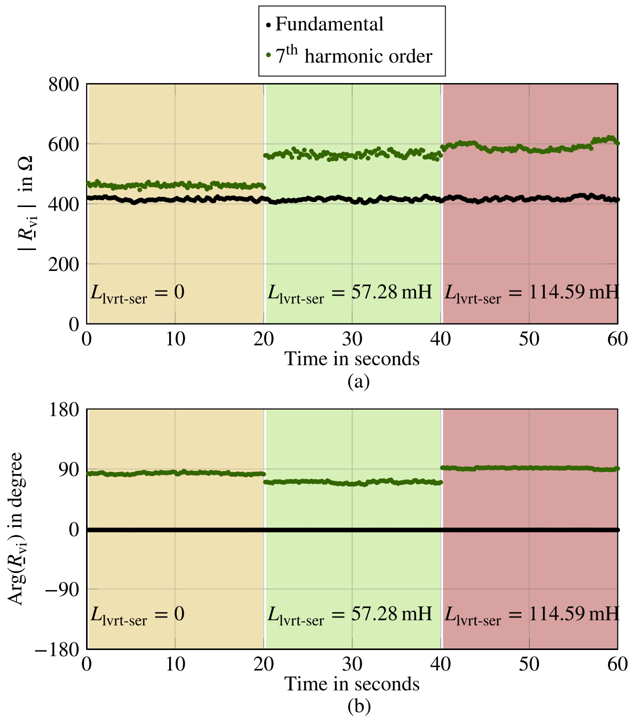

Fig. 9. "Voltage-current ratios" for the fundamental frequency and 7th harmonic order with three serial inductor ($L_{lvrt-ser}$) regarding an exemplary measurement campaign: (a) magnitude; and (b) angle.

that this variation can be observed in the magnitude and/or angle of "voltage-current ratios." Based on the mentioned requirements in Section 5.1, the installation of the serial impedance should not significantly change the operating point at the fundamental frequency in order to avoid a negative influence on the power system operation. Fig. 9 shows a subtle variation in the "voltage-current ratios' for the fundamental frequency due to the installation of both the inductors. In addition, Fig. 10 shows the active power, reactive power, and voltage amplitude for the fundamental frequency over the measuring time. The installation of these inductors does not significantly change the operating point. Indeed, the influence of these inductors on the operating point of the utility and customer can be neglected.

6. Application of the proposed concept on examples

In this section, the proposed concept is applied to some examples in order to illustrate its performance for identifying the dominant equivalent harmonic. In this regards, the applicability of proposed

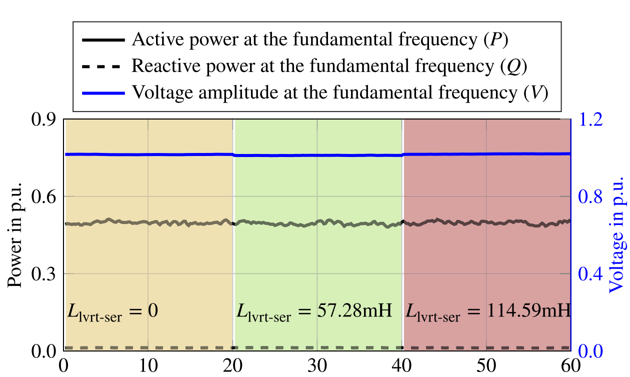

Fig. 10. Variation of the utility and customer operating point with two serial inductors ($L_{lvrt-ser}$) regarding an exemplary measurement campaign.

Table 2
Overview of Test-Bench and On-Site Measurements.

Measurement campaigns	Customer type	Available measurement data	Applicable methods	Inapplicable methods
I (test-bench)	LED lamp (low voltage (level)	● Voltage and current at the PCC in normal operation ● Voltage and current at the PCC in operation with the installation of a serial inductor (13 mH)	● Direction of active power flow ● Voltage-current ratio difference	● Reactive power (critical impedance) ● Voltage-current ratio
		● Voltage and current at the PCC in normal operation ● Voltage and current at the PCC in operation with the installation of a parallel capacitor (4.5 μF)	● Direction of active power flow ● Current-voltage ratio difference	● Reactive power (critical admittance) ● Current-voltage ratio
II (on-site)	Wind turbine (medium voltage level)	● Voltage and current at the PCC in normal operation ● Voltage and current at the PCC in operation with the installation of a serial inductor (114 mH)	● Direction of active power flow ● Voltage-current ratio difference	● Reactive power (critical impedance) ● Voltage-current ratio

concept is shown using test-bench and on-site measurements (see Section 6.1). Furthermore, the validity of this concept is proved using the calculation examples (see Section 6.2). In addition, the proposed method is compared to other existing methods.

6.1. Test-bench and on-site measurements

In order to prove the applicability of the proposed concept, results from test-bench and on-site measurements are illustrated in this section. In addition, the great advantage of the proposed concept compared to other methods (methods based on the direction of active power flow, the reactive power, and the voltage-current ratio) is addressed. In this regard, some selected results from two measurement campaigns are illustrated. Table 2 gives an overview of these measurement campaigns.

In Measurement Campaign I, test-bench measurements have been carried out on a LED lamp (see Table 2). For this case, the harmonic voltages and currents at the PCC in each operation state have been measured over 25 time windows. Each time window had approximately a width of 200 ms. In the presentation of the all examples in this paper, all parameters and variables are given in p.u. based on the nominal voltage and power of the customer. Figs. 3 and 5, which are used to introduce the proposed method in Sections 2 and 3, show the results of Measurement Campaign I. Fig. 3 shows the results of the "voltage-current ratio difference" method for the 17$^{\text{th}}$ harmonic order. The value of the used serial impedance ($\underline{Z}_{\text{ser}}$) in the corresponding measurement for this harmonic order is equal to $(0.015 + \text{j}0.28)\,\text{p. u.}$ From this figure, following statements related to harmonic distortions can be concluded:

- The equivalent harmonic voltage source of the utility side is dominant, i.e. $2 < \frac{V_{\text{u}}}{V_{\text{c}}} < 5$;
- The phase-angle difference between two equivalent voltages varies between 0 and $\frac{\pi}{2}$, i.e. $0 < \text{Arg}(\frac{\underline{V}_{\text{u}}}{\underline{V}_{\text{c}}}) < \frac{\pi}{2}$.

Fig. 5 shows the results of the "current-voltage ratio difference" method for the 7$^{\text{th}}$ harmonic order. The value of the used parallel admittance ($\underline{Y}_{\text{par}}$) for this harmonic order is equal to $(0.1 + \text{j}10)\,\text{p. u.}$ In this regards, following statements related to harmonic distortions can be concluded from Fig. 5:

- The equivalent harmonic current source of the utility side is dominant, i.e. $5 < \frac{I_{\text{u}}}{I_{\text{c}}} < 15$;
- The phase-angle difference between two equivalent currents varies between $\frac{-\pi}{4}$ and 0, i.e. $\frac{-\pi}{4} < \text{Arg}(\frac{\underline{I}_{\text{u}}}{\underline{I}_{\text{c}}}) < 0$.

In Measurement Campaign II, on-site measurements have been carried out on a wind turbine. In this case, the measurement campaign has been performed with the help of a LVRT test container at the medium voltage level. The harmonic voltages and currents have been measured over 30 time windows for the two operation states (normal operation and operation with the installation of a known serial impedance). Each time window had approximately a width of 200 ms. Using the serial impedance, it is only possible to determine the dominant equivalent harmonic "voltage" source using these measurement data. For this purpose, the "voltage-current ratio difference" method is applicable. Fig. 11(a) shows the results of this method for the 14$^{\text{th}}$ harmonic order. The value of the used serial impedance ($\underline{Z}_{\text{ser}}$) in the corresponding measurement for this harmonic order is equal to $(0.10 + \text{j}2.75)\,\text{p. u.}$ Based on this concept, the ratio of distances of $\Delta\underline{R}_{\text{vi}}$ to 0 and $\underline{Z}_{\text{ser}}$ is proportional to $\frac{V_{\text{u}}}{V_{\text{c}}}$. Therefore, to determine the dominant equivalent harmonic voltage source, it should be investigated whether $\Delta\underline{R}_{\text{vi}}$ is closer to 0 or $\underline{Z}_{\text{ser}}$. For this purpose, the perpendicular bisector of the line segment between 0 and $\underline{Z}_{\text{ser}}$ divides the complex plane into two zones:

- Dark gray zone: Possible zone for $\Delta\underline{R}_{\text{vi}}$ related to $\frac{V_{\text{u}}}{V_{\text{c}}} > 1$;
- Light gray zone: Possible zone for $\Delta\underline{R}_{\text{vi}}$ related to $\frac{V_{\text{u}}}{V_{\text{c}}} < 1$.

These zones are separated by a blue line in the graphical representation. This line corresponds to the first family of the Apollonian circles having $\frac{V_{\text{u}}}{V_{\text{c}}} = 1$. For better orientation, other information (i.e. other Apollonian circles of the first and second family) is depicted just with low opacity.

Subsequently, the proposed method is compared to the existing methods [5,7,8,11,13]. However, the methods based on the reactive power and the "voltage-current ratio" are inapplicable due to the lack of the equivalent impedance values. Indeed, the main advantage of proposed concept is its independence from the exact value of the utility and customer equivalent harmonic impedances. The method based on the direction of active power flow does not require the equivalent impedance values. Therefore it is also applicable to these measurement data. Fig. 11(b) shows the related results of this method for the same harmonic order. As in Fig. 11(b) shown, this method divides the

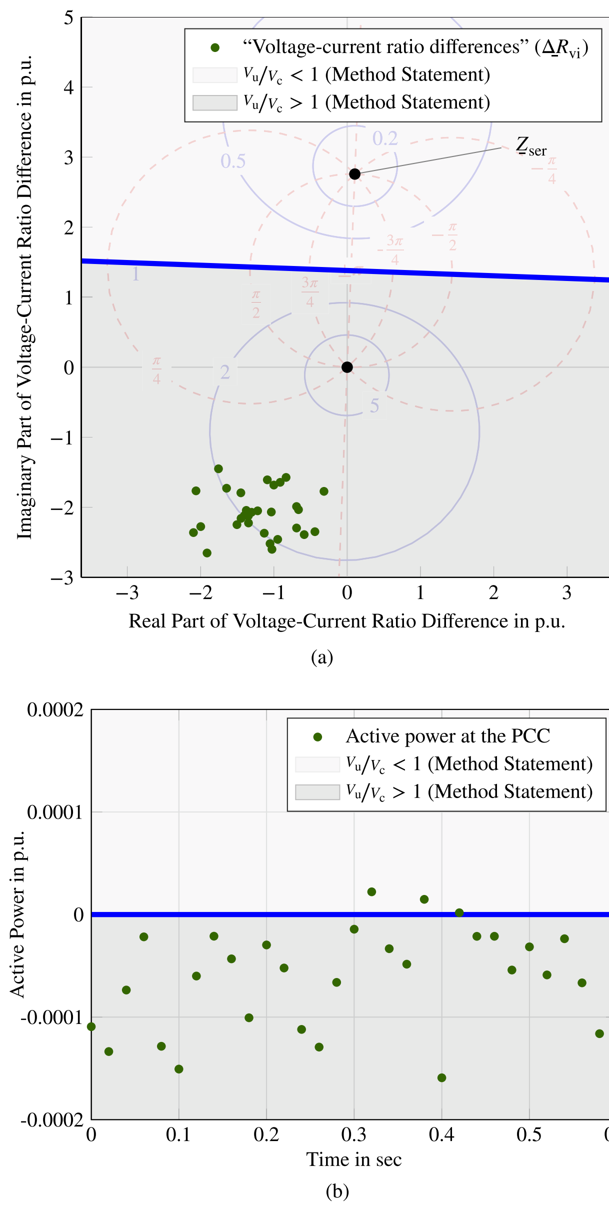

Fig. 11. On-site measurement results – Graphical representation based on: (a) voltage-current ratio difference method; and (b) direction of active power flow method.

possible area for active power at the PCC into two zones [6]:

- Dark gray zone: Possible zone for active power related to $V_u/V_c > 1$;
- Light gray zone: Possible zone for active power related to $V_u/V_c < 1$.

The method based on the direction of active power flow gives the statement that the customer in three of the time windows has the dominant harmonic voltage source. By comparing Fig. 11(a) and (b), it can concluded that this statement is in contradiction to the statements of the proposed method. It is impossible to find out which of these contradictory statements is correct. However, the validity of the method based on the direction of active power flow was called into question [6]. In order to prove the validity of the “voltage-current ratio difference” method, it is applied to some calculation examples in the next section.

6.2. Calculation examples

In comparison to measurement data, calculation examples are more proper to investigate the validity of the methods because measurement inaccuracies make this investigation difficult. In this section, the defined calculation examples in [6] are considered in order to compare the performance of the proposed concept with noninvasive methods (methods based on the direction of active power flow, the reactive power, and the voltage-current ratio). The calculation examples are presented just for identifying the dominant equivalent harmonic “voltage” source although they can be applied for identifying the dominant equivalent harmonic “current” source. In these examples, the utility and customer equivalent harmonic impedance ($\underline{Z}_u$ and $\underline{Z}_c$, respectively) are assumed to be as follows:

$$\underline{Z}_u = (0.005 + j0.01)\,\text{p. u.}, \quad \underline{Z}_c = (0.01 - j0.05)\,\text{p. u.}$$

In order to show the main advantage of the proposed method, equivalent harmonic impedances are assumed to be unknown (in contrast to [6]). However, they are necessary for investigating the validity of this concept. In order to evaluate the validity of the methods, two examples are defined. In the first one, the magnitude of the equivalent harmonic voltage ratio is assumed to vary from 0.1 up to 10 logarithmically, where the angle of the equivalent harmonic voltage ratio remains constant:

$$\underline{V}_u = (0.001\ldots0.1)\,\text{p. u.} \angle\frac{\pi}{2}, \quad \underline{V}_c = 0.01\,\text{p. u.} \angle 0.$$

In the second calculation example, the angle of the equivalent harmonic voltage ratio is assumed to vary from 0 up to 2π, where the magnitude of the equivalent harmonic voltage ratio remains constant:

$$\underline{V}_u = 0.008\,\text{p. u.} \angle(0\ldots2\pi), \quad \underline{V}_c = 0.01\,\text{p. u.} \angle 0.$$

The results of this concept for both the calculation examples are illustrated using graphical representations in Fig. 12. In this figure, the calculated $\Delta\underline{R}_{vi}$ are divided into two parts depending on $\frac{V_u}{V_c}$:

- Green stars: $\Delta\underline{R}_{vi}$ related to $\frac{V_u}{V_c} > 1$;
- Green points: $\Delta\underline{R}_{vi}$ related to $\frac{V_u}{V_c} < 1$.

Based on the method statement, $\Delta\underline{R}_{vi}$ related to $\frac{V_u}{V_c} > 1$ (green stars) should be closer to 0 (i.e. located in the dark gray zone), whereas $\Delta\underline{R}_{vi}$ related to $\frac{V_u}{V_c} < 1$ (green points) should be closer to $\underline{Z}_{ser}$ (i.e. located in the light gray zone).

In Fig. 12(a), results related to the first calculation example, $\frac{V_u}{V_c} = (0.1\ldots10)$, are presented. As shown, the statement of the voltage-current ratio difference method is correct in all cases. It should be noted that all $\Delta\underline{R}_{vi}$ of this calculation example belong to an Apollonian circle from the second family. Therefore, they form a circular arc in Fig. 12(a).

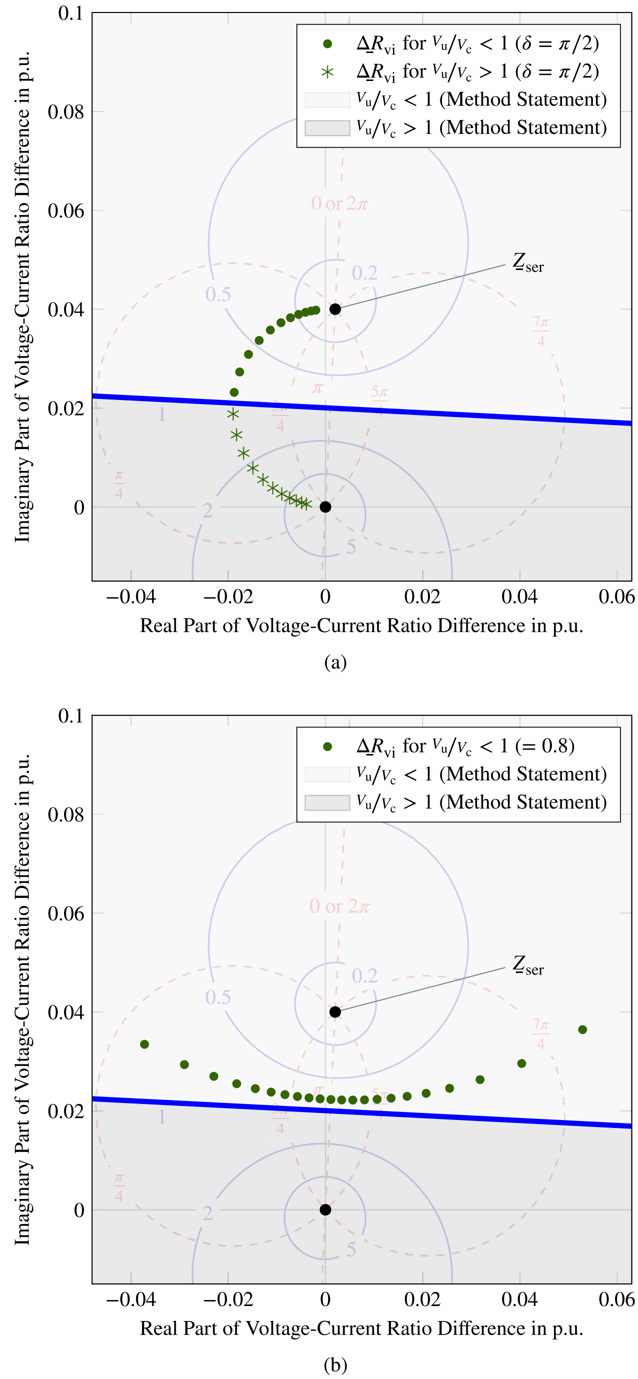

Fig. 12. Method based on voltage-current ratio difference – Graphical representation for: (a) the first calculation example (variation of $\frac{V_u}{V_c}$ from 0.1 up to 10); and (b) the second calculation example (variation of $\text{Arg}(\frac{V_u}{V_c})$ from 0 up to 2π).

In Fig. 12(b), results related to the second calculation example, $\text{Arg}(\frac{V_u}{V_c}) = (0\ldots2\pi)$, are shown. The statements of the voltage-current ratio difference method are correct in all cases as well. All $\Delta \underline{R}_{vi}$ of this calculation example belong to an Apollonian circle from the first family. Therefore, they form a circular arc in Fig. 12(b). Based on this results, the proposed concept gives in all investigated cases valid statements about the dominant equivalent harmonic source.

7. Conclusion

This paper has proposed a new concept for determining the dominant side. In contrast to the most common methods for determining the dominant side, the proposed concept does not require the equivalent harmonic impedance (or admittance) of the utility and customer sides as input data. This concept has been developed into two methods. The key points with regard to these methods are summarized as follows:

- "Voltage-current ratio difference" method: This method provides statement about the dominant equivalent harmonic voltage source. Using this method, besides the magnitude ratio of equivalent harmonic voltages, the phase-angle difference between the equivalent voltages can be determined. For this purpose, the measured harmonic voltage and current at the PCC in two states (normal operation and operation with the installation of a known serial impedance between the utility and customer) are required. The serial impedance should be an inductive or resistive-inductive impedance to yield more reliable results. An inductive or resistive-inductive impedance has a small magnitude at the fundamental frequency (depending on its inductance) compairing to higher harmonic orders. Consequently, the influence of this impedance on the operating point of the utility and customer at the fundamental frequency can be neglected;
- "Current-voltage ratio difference" method: This method provides statement about the dominant equivalent harmonic current source. Using this method, besides the magnitude ratio of equivalent harmonic currents, the phase-angle difference between the equivalent currents can be determined. For this purpose, the measured harmonic voltage and current at the PCC in two states (normal operation and operation with the installation of a known parallel admittance between the utility and customer) are required. A capacitive or resistive-capacitive admittance should be applied to yield more reliable results. A capacitive or resistive-capacitive admittance has a small magnitude at the fundamental frequency (depending on its capacitance) compairing to higher harmonic orders. It ensures that the operating point does not change at the fundamental frequency for the utility and customer.

This paper has thoroughly presented the methodology and application of a new concept. In addition, some practical aspects regarding the implementation of the concept has discussed. In this regard, requirements for the serial impedance (or parallel admittance) at the fundamental frequency and at each harmonic order have been defined to yield reliable results.

CRediT authorship contribution statement

Farhad Safargholi: Methodology, Software, Resources, Data curation, Writing - original draft. **Kaveh Malekian:** Conceptualization, Investigation, Writing - review & editing. **Wolfgang Schufft:** Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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