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Harmonic Source Detection Methods: A Systematic Literature Review

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ABSTRACT Ensuring the quality of power supply is a main target of the power utility companies worldwide. Harmonic distortion is one of the power quality problems that can result either from upstream (utility side) through background harmonic, downstream (customer's side) through non-linear loads, or renewable energy generators. The detection of harmonic sources at the point of common coupling (PCC) is a major concern for both utilities and customers. Various methods have been proposed since the 1990s to be used for harmonic source detection. These methods have been classified into three categories based on the direction of active power flow, reactive power, and voltage–current ratio. In this paper, a systematic literature review is done on the state of the art of current research on the harmonic source detection methods, in order to select the method that gives better practical and commercial results to be used when multiple customers are connected at the PCC. This systematic literature review recognized that most studies concentrated only on harmonic source detection between a customer and utility but the practical power system has multiple customers connected to the PCC with different load conditions. Therefore, the results obtained from this paper review will be useful for researchers and engineers working in the modern grids, who aim to develop a practical and commercial method to quantify the harmonic contribution for different customers and utility.

INDEX TERMS Harmonic distortion, harmonic source detection, renewable energy sources and distributed power generation.

I. INTRODUCTION

The integration of renewable energy generators and the use of non-linear loads in the modern smart grid may cause power quality disturbances. Various types of disturbances can occur, and among them one of the most important is harmonic distortion; voltage and current waveforms are distorted and consist of different harmonic orders. Power system is affected by the disturbances, monitoring need to be in place to minimize the effects which may include equipment failures resulting from overheating, shorten life expectancy of transformers due to the deterioration of insulation levels, and increases in equipment power losses [1]. Disturbances can be caused by any customer connected within the grid and can influence the customers situated at the remote branches of the power grid.

The network configuration and resonance conditions must be monitored as this leads to high harmonic current multiplication that causes high voltage levels. Utilities do allow a certain level of harmonic emissions into the network as agreed on the electricity supply contract. However, it is responsible to manage the network in such a manner to ensure that the voltage distortions remain within the contracted limits and adhere to the power quality standards pre-scribed by the National Energy Regulator of the specific country. This is achieved by means of power quality contract management. During the planning phase, harmonic studies must be conducted intensively to determine the number of customers connected at the Point of Common Coupling (PCC). This exercise needs to be repeated at any time a new customer applied for the connection, to view the trend once a new installation is connected. Accuracy of simulation studies is achieved when adequate information is available, therefore, it is recommended that customers provide the required information. Today, utilities

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are urged to be vigilant not to assume parameters during harmonic studies as this might cause a long-term challenge that could be mitigated in the planning phase.

There are standards [2]–[4] with the set of limits is used to monitor the individual and total harmonic distortion (THD) levels of current and voltage at the PCC. Reference [2] gave the measurement of electric power quantities definitions under sinusoidal, non-sinusoidal, balanced or unbalanced conditions. The amount of harmonic current a customer allowed to inject into the power network at the PCC is limited as indicated in [3]. Reference [4] indicated the limits of the harmonic voltage distortions a customer can add to the network. These standards must be used during the planning phase for the application of a point of connection for electricity supply to customers by the utilities. In order to develop any method for harmonic distortion evaluation, it is vital to identify the disturbance sources that can be either upstream and/or downstream of the metering point; so, responsibility of harmonic distortion can be from the supply and/or load [5]–[7].

The vital aspect of modern network is to conduct the harmonic management and this can only be achieved once the source of harmonic is identified between the parties involved [8]. Studies are conducted with the theoretical idea in mind that the harmonic distortion at the PCC is solely caused by a customer loads, which is not true on a real-life situation. The amount of harmonic distortion present at the PCC is subjected to the installation of a customer and the background harmonic as part of the utility side [9]. The background voltage distortion can no longer ignored or assumed to be minimal, as in some cases, it caused high harmonic currents at the PCC [10]. Currently, there are no guidelines that is limiting the background harmonic, it becomes a need for the National Regulator to develop a guideline to lead power quality engineers during the planning processes.

Whenever there are high levels of harmonic voltage distortions or current injections on the network, it is imperative that the source of harmonic be identified. This is essential to the utility and the customers concerned for a proper mitigation method and for identifying the responsible parties involved. Once the responsibility is apportioned, the affecting party is required to mitigate its contribution by providing a filter and bearing the costs thereof. However, certain networks have proven to be difficult to manage harmonic levels because the source of harmonic could not be accurately detected. This has necessitated the importance of finding accurate method to identify harmonic emitting sources.

Worldwide, harmonic source detection is an important challenge faced by the utilities and customers. The location of harmonic source detection has been part of research since the 1990's [11] as the non-linear loads became part of the power system. Many methods and techniques have been developed and reported in the literature to detect harmonic source [8], [9], [19]–[26], [10], [12]–[18]. These methods and techniques have been in discussion and scrutinise on certain issues.

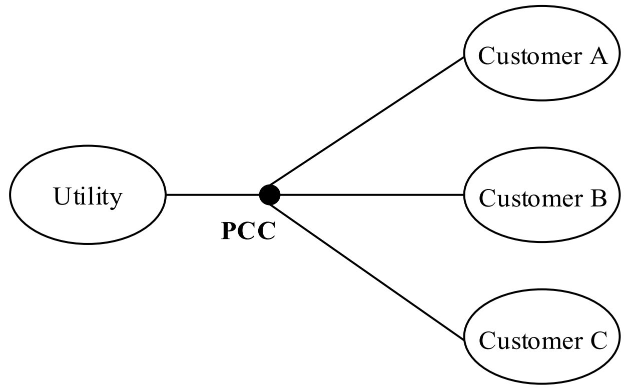

FIGURE 1. **Implementation of harmonic source detection.**

Hence, researchers have done some review and comparison on different methods and techniques [7], [21], [27]–[31].

Reference [9] proposed a benchmark test system representing the MV/LV network to be used to close the gap on evaluating the existing proposed method of harmonic source detection. This is a comprehensive idea as many studies can be done using this benchmark test system with a different power system software packages to test and analyze different developed methods and techniques. Most industries can use software that are available to them to test the benchmark and use it for a real-life situation. Authors concluded that different topologies of the grid to be studied, which include renewable energy generators fed by power electronic inverters were not considered in the proposed benchmark. Therefore, further research was required for the improvement of the benchmark test system. In a steady state normal condition, this benchmark will be of a good tool to be used, although in real-life, a practical grid, the network responsibility and loading condition may change as the need arises as well as harmonic generation from non-linear source can change anytime depending on the load conditions.

A practical method for detecting the harmonic source must be determined to assist the field engineers in apportioning the harmonic fairly to customers. This will be of the best idea for the current and future power system model where renewable energy generators are integrated and multiple customers are connected at PCC. Presented methods concerned harmonic distortion between a utility and a customer, although this does not give a true scenario of a power system. Today, power system is according to Figure 1 where multiple customers are connected at PCC. These customers have different operating conditions that need to be known by power quality engineers during the planning phase.

Therefore, to evaluate the literature research adequately a Systematic Literature Review (SLR) methodology as defined in [32] is used. This study addressed more precisely the following: how to detect the harmonic when multiple customers are connected at the PCC. This is described a general question, the specific questions are as follows: (i) how to determine which customer is contributing more harmonic; (ii) how to quantify the customer's contributions; (iii) how

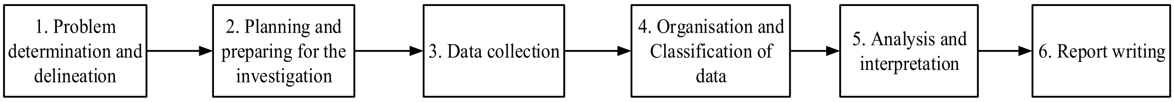

FIGURE 2. Systematic literature review stages.

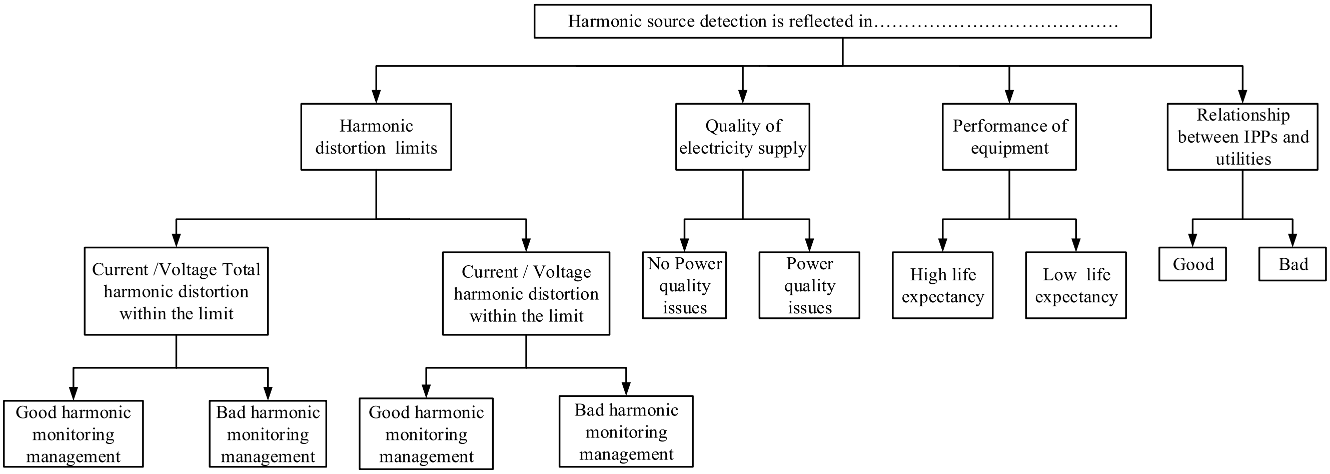

FIGURE 3. Dendrogram of inductive research design.

to improve the harmonic monitoring management (iv) what happen when different customers with operating and load conditions are connected at the PCC; and (v) what are the most common simulation and experimental methodologies used to give a proof of a selected method.

Although various researchers proposed methods for harmonic sources detection, they only focused on the cases of one customer and a utility. Therefore, there is a shortcoming to detect the harmonic source when multiple customers are connected at PCC with different operating and load conditions. The objective of this study is to select and propose a practical and commercial method for harmonic source detection when multiple customers are connected at the PCC.

The rest of this paper is organized as follow: Section 2 presents the systematic literature review methodology used; Section 3 gives the results of the analysis of the reviewed papers; Section 4 discusses the results and indicates the future research framework, and finally, the last section gives the conclusions.

II. METHODOLOGY

A Systematic Literature Review (SLR) is carried out based on a method used mostly in the medicine, social sciences and as well as in other field such as education, supply chain management and economy. In [32], this methodology was considered in engineering field and it gives the good evidences based approach. The four core philosophies of SLR are replicable, exclusive, aggregative and algorithmic. The stages specified in Figure 2 describes how the study was conducted; stage 1-defines what the problem is and its delimitation, stage 2-determines relevant aspects to be included in the study, stage 3-specifies how the information is obtained, stage 4-organises and classifies obtained information in a simplest form, stage 5-discusses the obtained information, and stage 6-compiles the report.

Stage 1: Total Harmonics distortion at the PCC are increasing with the use of non-linear loads and integration of renewable energy generators in the power system. Harmonic source detection is one of the challenges' power utilities and customers are faced with. It is a concern for both parties as no method can be used to give an indication of who is responsible of harmonics when multiple customers are connected at the point of common coupling. Thus most of researchers only focused on a single customer connected at the PCC. Knowing whether the harmonic source is from utility or customer, does not assist the apportioning between the customers connected at PCC. Once a harmonic source is identified to be from the customer side, how can one know which customer is contributing more? Solutions need to be provided to the industry wide problems with respect to the identification of harmonic sources and in dealing with the customer complaints arising from harmonic problems on the network. This review was done to develop the practical solution for the engineers to determine the source of harmonic at PCC. This literature review concentrates only on three categories of the harmonic source detection methods.

Stage 2: The 1st step of this literature review is to give an overview of the important factors when proposing the harmonic source detection methods as indicated in Figure 3. The 2nd step of this literature review is how the harmonic source detection is determined as indicated in Figure 4.

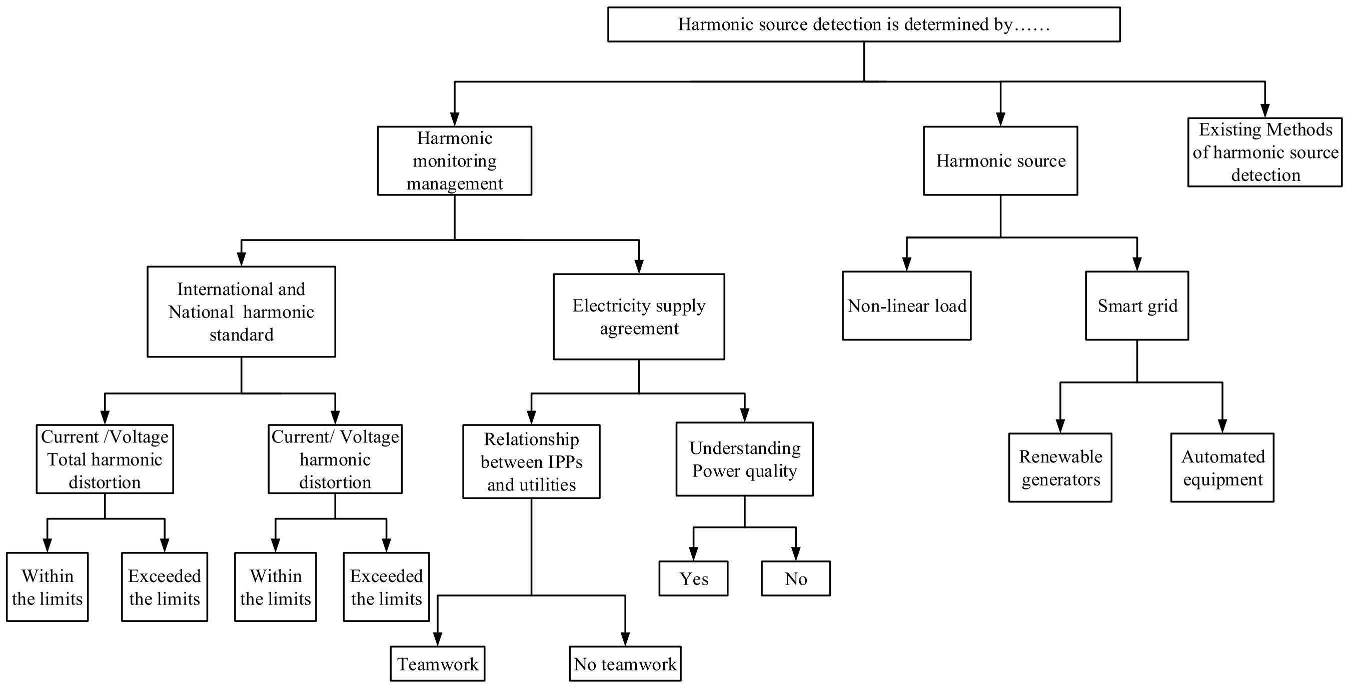

FIGURE 4. Dendrogram deductive research design.

TABLE 1. Keywords used for the search.

Harmonic distortion	Measurement
Power quality, Harmonic distortion, total harmonic distortion, Harmonic source detection, harmonic allocation, sharing harmonic responsibility, direction of active power flow, harmonic monitoring, harmonic management, harmonic limit, Independent Power Producers, Smart grid, Point of Common Coupling, harmonic apportioning, harmonic limit	Single point measurement, Distributed and synchronous measurement

Stage 3: Data/information are collected by using databases as search engines by means of using the keywords. Database of a web of science such as Science Direct, IEEE Xplore and Scopus were considered. Google Scholar was used to search certain journal paper and conduct the citation straight from the web using EndNote X7 and the database of the referencing was exported to Mendeley. The topic of harmonic source detection consists of many literatures with different methodologies/ techniques. The keywords used to search for information are indicated in Table 1.

Stage 4: The collected data which is literature papers on the topic of interest were arranged according to the existing methods. The papers was arranged according to the Prisma 2009 flow diagram [33] as follow:

a) 100 papers are collected through database searching such as IEEE Xplore, Science Direct and Scopus using the keywords in Table 1.
b) 50 additional papers are identified through google scholar search engine.
c) Analysis is done to check the duplicate of the saved papers and only 120 record of papers remains and taken for screening.
d) 38 papers are excluded as it discusses other topic on harmonic distortion, harmonic filters, and power quality which are not the main focus of this research which is harmonic source detection.
e) 82 papers were assessed for eligibility criteria (harmonic source detection method) and 18 papers are excluded with the reason of not reaching the criteria.
f) 64 papers are included in this paper for qualitative synthesis and only 40 papers are included for quantitative synthesis as the criteria is set for only the papers from 2005 – May 2019 will be used (It is indicated in the results section as per Table 4).

Stage 5: The selection of the research papers is based on the inclusion and exclusion criteria to enhance the search as well as recover the most relevant literature on the topic. The inclusion criteria was based on the latest review that is conducted in [28], where only published journal articles and conference proceedings is used. This search excludes the following: (a) the paper with the developed method out of the estimation and far from the three categorized methods based on the direction of active power flow, reactive power and voltage – current ratio; (b) the unpublished work; and (c) text books and web page. The period of the paper used was from 2005 until May 2019. The old papers are neglected as they are cited in the newer papers.

Stage 6: The findings are documented.

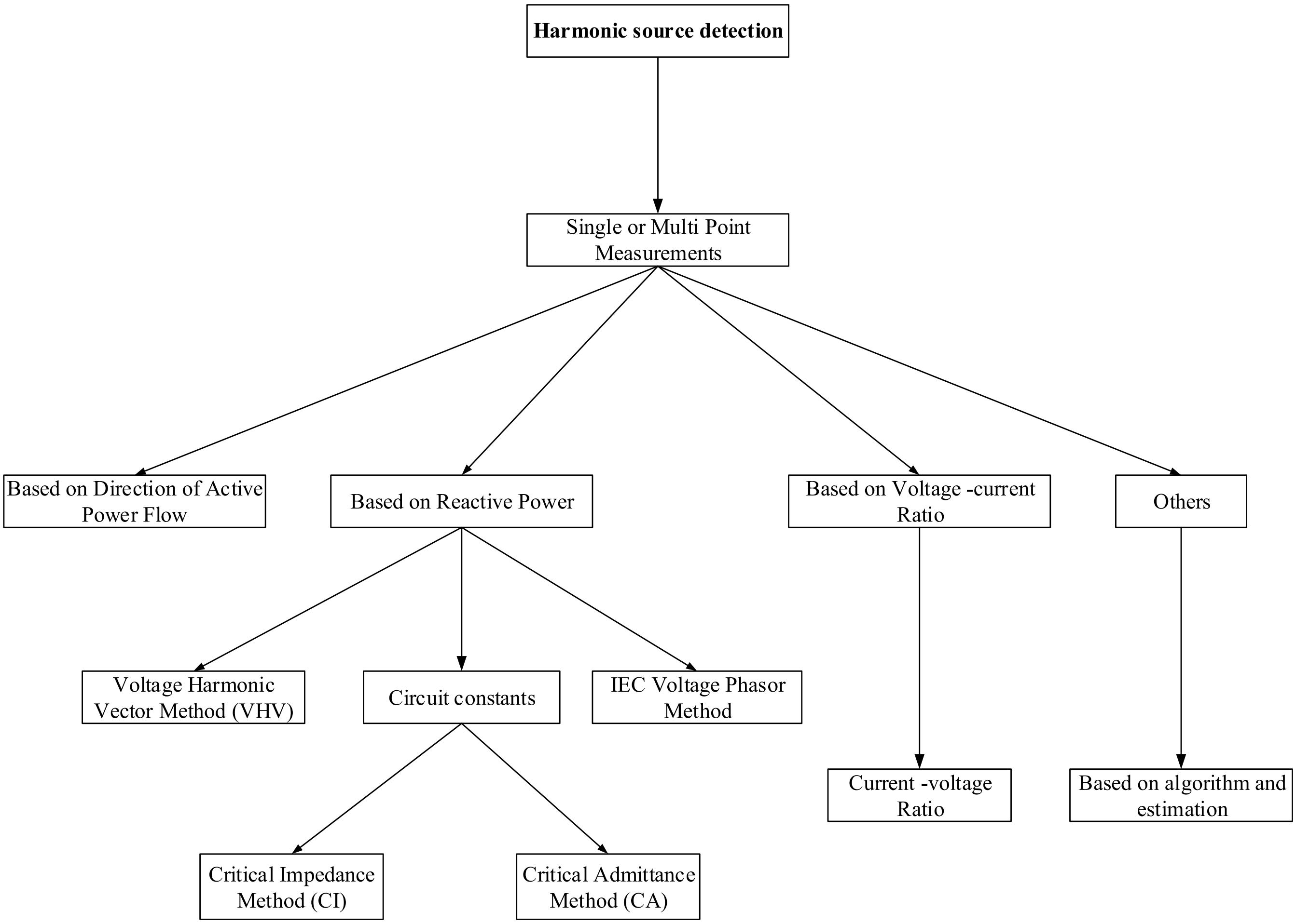

FIGURE 5. Harmonic source detection method block diagram.

III. RESULTS

A. CATEGORIES OF EXISTING METHODS

The harmonic sources detection proposed approaches depends on two groups: distributed and synchronous (multi-point) measurement method and single point measurement method [11], [17], [34]–[36]. Reference [24] highlighted that the distributed and synchronous measurement method gives an accuracy information on the state of power system harmonic. However, it is difficult to be implemented and managed since its measurement instrument hardware and software parts are complex and expensive. On the contrary single point measurement method is less expensive and its implementation is simple, although in some cases it does not provide accuracy information regarding the state of power system harmonic. In medium and low voltage distribution systems, single point measurements are still preferable, even though it is difficult or almost impossible to know the exact network impedance values. The literature shows that extensive research is conducted since 1998 by bodies such as IEC, Cigré, IEEE, etc. to find an accurate method to detect location of harmonic emitting sources.

Harmonic source detections are categorized in three methods as follows [28];

a) Direction of active power flow
b) Reactive power
c) Voltage - current ratio

The authors of this paper conducted analysis and synthesis process. The existing methods based on the three categories are pointed out and analyzed as per Figure 5. The shortcomings of each category are discussed in details. The results are analyzed according to the paper reviewed.

Among these methods, none of them is identified to be accurate due to the shortcomings that other researchers pointed out. Each method and technique has advantages and disadvantages, thus some of the common disadvantages are; the difficulty and high cost of implementation. This literature review is concentrating on the following: methods, shortcoming, and software used. There are several review papers based on harmonic source detection in general, although, as far as the authors know, there is no review paper focusing on the practical method and easy to use in the industry. Thus, in order to fill this research gap, a literature review based on

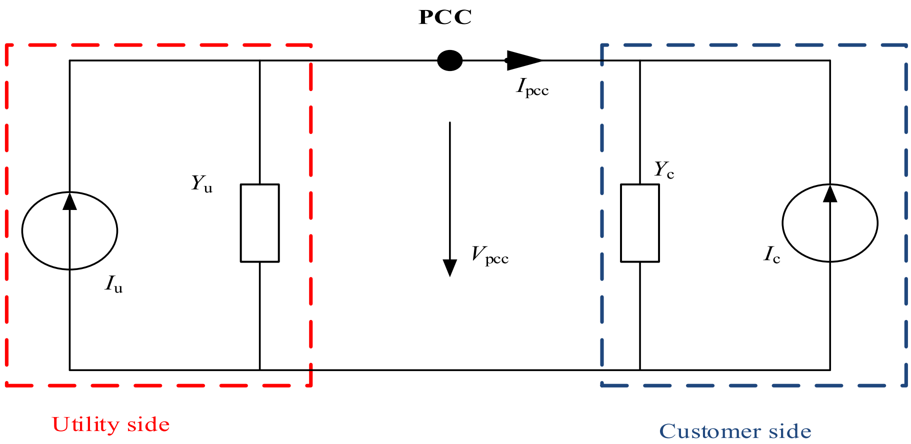

FIGURE 6. Norton equivalent circuit.

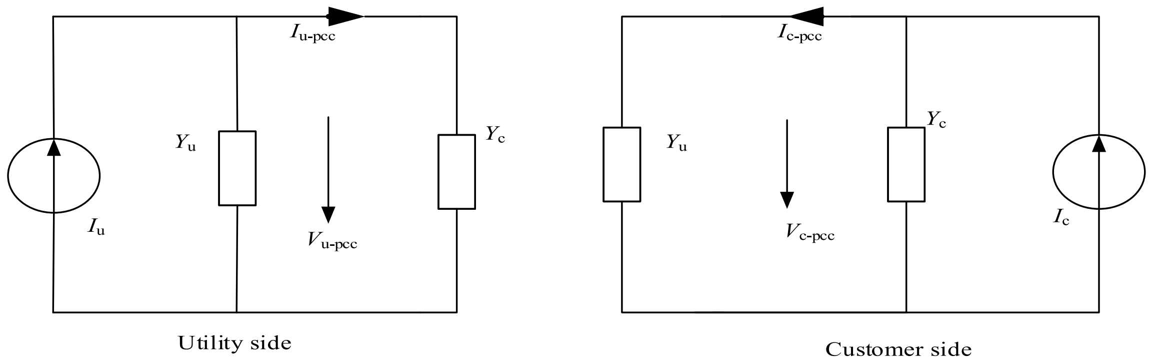

FIGURE 7. Norton equivalent circuit for harmonic voltage sources of two sides.

pointing out the uncertainty regarding the impracticality of the published methods is required.

B. DOMINANT HARMONIC SOURCES CALCULATIONS

Most studies concentrated on the dominant harmonic source. This dominant harmonic source depends on two scenarios, which are Thevenin (larger equivalent harmonic voltage) and Norton (larger equivalent harmonic current) equivalent circuits. When the equivalent circuit is not indicated in the study this can cause confusion in the results as the equivalent circuit has different meanings. Reference [28] demonstrated clearly the confusion by giving an overview of the magnitude of the equivalent circuit of the harmonic voltage and/or current source. Reference [28] concluded that where there is a larger magnitude current is also where there is a larger magnitude of voltage or vice versa. The following sections explains the difference between harmonic current source and harmonic voltage source in detail:

1) HARMONIC CURRENT SOURCE

The Norton equivalent circuit shown in Figure 6, which is used to investigate the harmonic current source. The circuit indicated in Figure 6 is simplified according to the superposition principle as indicate in Figure 7.

To determine the voltage at the point of common coupling of the customer and utility, the following equations are used based on Figure 7:

$$V_{pcc} = V_{u-pcc} + V_{c-pcc} \tag{1}$$

$$V_{u-pcc} = \frac{I_u}{Y_u + Y_c} \tag{2}$$

$$V_{c-pcc} = \frac{-I_c}{Y_u + Y_c} \tag{3}$$

Combining (2) and (3) to obtain the following;

$$\frac{I_u}{I_c} = \frac{V_{u-pcc}}{V_{c-pcc}} \tag{4}$$

Therefore, Equation (4) indicates that the larger the magnitude of harmonic current refers to the higher harmonic voltage contribution at the PCC. Thus, if it is known that the larger magnitude of harmonic current is on the side where harmonic is dominant, then that side also has the high harmonic voltage contribution at the PCC. Table 2 gives the required current source input data and indicators for the different categories of harmonic source detection methods.

To define the indicators for the methods mentioned in Table 2 mathematically, the following formulae where used according to [28];

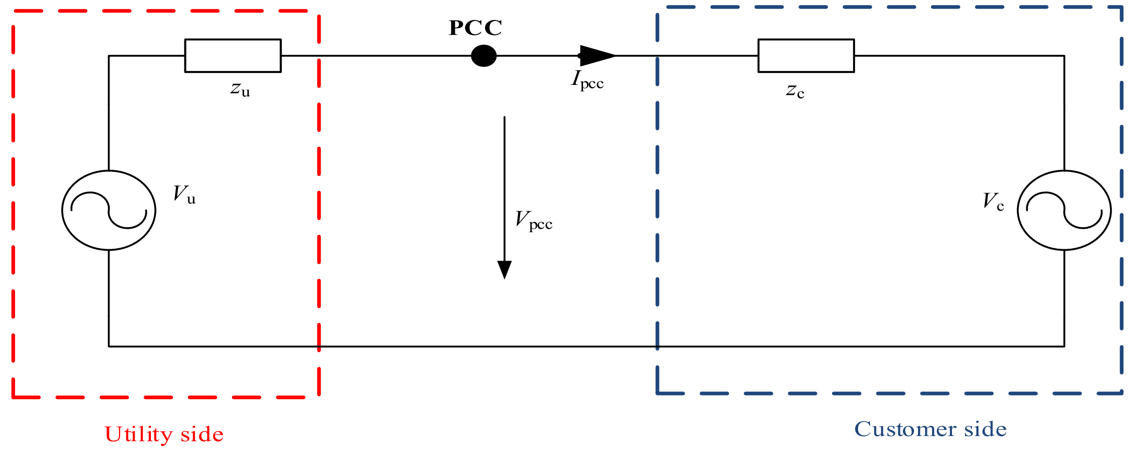

FIGURE 8. Thevenin equivalent circuit.

TABLE 2. Current source input data and indicators for the different categories of harmonic source detection methods.

Method	Input Data	Indicator
Direction of active power flow	V_{pcc} , I_{pcc}	Sign of P_{pcc}
Reactive Power (Critical Admittance)	V_{pcc} , I_{pcc}, Y_c , Y_u	Sign of $Q_{t,u,i}$ $\|CA\|$
Current-voltage ratio	V_{pcc} , I_{pcc}, Y_c , Y_u	$G_{i,v}$

a: DIRECTION OF ACTIVE POWER FLOW METHOD

$$P_{pcc} = Re\left\{V_{pcc}I^*_{pcc}\right\} \tag{5}$$

A harmonic active power at the PCC which is negative ($P_{pcc} < 0$) utility is a dominant harmonic current source, whereas a positive harmonic active power at PCC ($P_{pcc} > 0$), a customer is a dominant harmonic current source.

b: REACTIVE POWER METHOD

According to Figure 6 the equivalent harmonic current source for the utility side is;

$$I_u = I_{pcc} - Y_u V_{pcc} \tag{6}$$

Equivalent harmonic admittance

$$Y_{tot} = Y_u + Y_c \tag{7}$$

Transformation angle

$$\alpha = \arctan\left(\frac{\mathrm{Re}\{Y_{tot}\}}{\mathrm{Im}\{Y_{tot}\}}\right) \tag{8}$$

$$Q_{t,u,i} = \begin{cases} -[-\sin\alpha \;\; \cos\alpha]\begin{bmatrix}\mathrm{Re}\left\{V_{pcc}I^*_u\right\}\\ \mathrm{Im}\left\{V_{pcc}I^*_u\right\}\end{bmatrix} & \mathrm{Im}\{Y_{tot}\}\geq 0,\\ +[-\sin\alpha \;\; \cos\alpha]\begin{bmatrix}\mathrm{Re}\left\{V_{pcc}I^*_u\right\}\\ \mathrm{Im}\left\{V_{pcc}I^*_u\right\}\end{bmatrix} & \mathrm{Im}\{Y_{tot}\}< 0.\end{cases} \tag{9}$$

$$CA = 2\frac{Q_{t,u,i}}{V^2_{pcc}} \tag{10}$$

If $|CA| > Y_{tot.}$, utility side is dominant for the equivalent harmonic current source $\left(\frac{I_u}{I_c} > 1\right)$;

If $|CA| < Y_{tot.}$, is the same as $Q_{t,u,i} > 0$ customer side is dominant for the equivalent harmonic current source $\left(\frac{I_u}{I_c} < 1\right)$.

c: CURRENT -VOLTAGE RATIO METHOD

$$G_{iv} = \frac{I_{pcc}}{V_{pcc}} \tag{11}$$

If $|G_{iv} + Y_c| > |G_{iv} + Y_u|$ the equivalent harmonic current source of the customer side is dominant $\left(\frac{I_u}{I_c} < 1\right)$; If $|G_{iv} + Y_c| < |G_{iv} + Y_u|$ equivalent harmonic current source of the utility side is dominant $\left(\frac{I_u}{I_c} > 1\right)$.

2) HARMONIC VOLTAGE SOURCE

The Thevenin equivalent circuit shown in Figure 8, which is used to investigate the harmonic voltage source. The circuit indicated in Figure 8 is simplified according to the superposition principle as indicate in Figure 9.

To determine the current at the point of common coupling of the customer and utility, the following equations are used based on Figure 9:

$$I_{pcc} = -I_{c-pcc} + I_{u-pcc} \tag{12}$$

$$I_{u-pcc} = \frac{V_u}{Z_u + Z_c} \tag{13}$$

$$I_{c-pcc} = \frac{V_c}{Z_u + Z_c} \tag{14}$$

Combining (13) and (14) to obtain the following;

$$\frac{V_u}{V_c} = \frac{I_{u-pcc}}{I_{c-pcc}} \tag{15}$$

Therefore, Equation (15) indicates that the larger the magnitude of harmonic voltage refers to the higher harmonic current contribution at the PCC. Thus, if it is known that the larger magnitude of harmonic voltage is on the side where harmonic is dominant, then that side also has high harmonic current

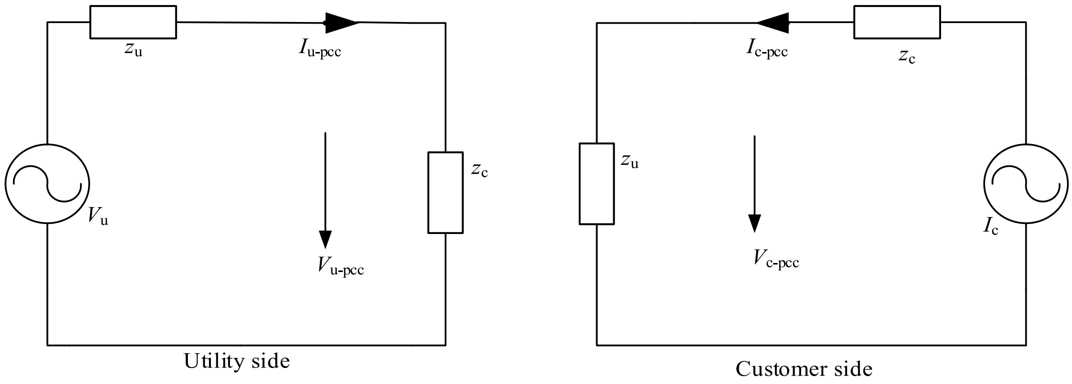

FIGURE 9. Thevenin equivalent circuit for harmonic current sources of the two sides.

TABLE 3. Voltage source input data and indicators for the categories of harmonic source detection methods.

Method	Input Data	Indicator
Direction of active power flow	V_{pcc} , I_{pcc}	Sign of P_{pcc}
Reactive Power (Critical Impedance)	V_{pcc} , I_{pcc}, Z_c , Z_u	Sign of $Q_{t,uv}$ $\|CI\|$
Current-voltage ratio	V_{pcc} , I_{pcc}, Z_c , Z_u	$R_{v,i}$

contribution at the PCC. Table 3 gives the required voltage source input data and indicators for the different categories of harmonic source detection methods.

To define the indicators for the methods mentioned in Table 3 mathematically, the following formulae where used according to [28]

a: DIRECTION OF ACTIVE POWER FLOW

Equation 5 is used in the harmonic current source is applicable to be used for a harmonic voltage source. Therefore, a harmonic active power at the PCC which is negative ($P_{pcc} < 0$) utility is a dominant harmonic voltage source, whereas a positive harmonic active power at PCC ($P_{pcc} > 0$), a customer is a dominant harmonic voltage source.

b: REACTIVE POWER

According to Figure 8 equivalent harmonic voltage source for the utility side is;

$$V_u = V_{pcc} - Z_u I_{pcc} \tag{16}$$

Equivalent harmonic impedance

$$Z_{tot} = Z_u + Z_c \tag{17}$$

Transformation angle

$$\beta = \arctan\left(\frac{\mathrm{Re}\{Z_{tot}\}}{\mathrm{Im}\{Z_{tot}\}}\right) \tag{18}$$

$$Q_{t,u,v} = \begin{cases} +[\sin\beta \ \ \cos\beta]\begin{bmatrix}\mathrm{Re}\{V_u I^*_{pcc}\}\\ \mathrm{Im}\{V_u I^*_{pcc}\}\end{bmatrix} & \mathrm{Im}\{Z_{tot}\} \geq 0, \\ -[\sin\beta \ \ \cos\beta]\begin{bmatrix}\mathrm{Re}\{V_u I^*_{pcc}\}\\ \mathrm{Im}\{V_u I^*_{pcc}\}\end{bmatrix} & \mathrm{Im}\{Z_{tot}\} < 0. \end{cases} \tag{19}$$

$$CI = 2\frac{Q_{t,u,v}}{I^2_{pcc}} \tag{20}$$

If $|CI| > Z_{tot.}$, utility side is dominant for the equivalent harmonic voltage source $\left(\frac{V_u}{V_c} > 1\right)$;

If If $|CI| < Z_{tot.}$, is the same as $Q_{t,u,v} > 0$ customer side is dominant for the equivalent harmonic voltage source $\left(\frac{V_u}{V_c} < 1\right)$.

c: CURRENT -VOLTAGE RATIO

$$R_{vi} = \frac{V_{pcc}}{I_{pcc}} \tag{21}$$

If $|R_{vi} + Z_c| > |R_{vi} + Z_u|$ equivalent harmonic voltage source of the customer side is dominant $\left(\frac{V_u}{V_c} < 1\right)$; If $|R_{vi} + Z_c| < |R_{vi} + Z_u|$ equivalent harmonic voltage source of the utility side is dominant $\left(\frac{V_u}{V_c} > 1\right)$.

C. DESCRIPTION OF HARMONIC SOURCE DETECTION METHODS

1) DIRECTION OF ACTIVE POWER FLOW METHOD

In early years the researchers focused on locating the source that is producing the harmonics as in [11], [36], [37]. To identify the dominant side between the utility and the customer, the direction of active power flow at the PCC was used. Reference [13] stated that the method based on the active power direction is widely used as it gives the practical application in engineering, and that method is independent of harmonic impedance of any party. Thus the calculation of the harmonic impedance is possible but it is not practical because harmonic impedance depends on the loading of the networks. Reference [8] proposed a revised method with certain restrictions for the direction of active power. The restrictions were developed based on the current and voltage measurements at the PCC and the impedance properties of the two sides. The determination of the dominant current harmonic source can be through the Norton equivalent circuit as shown in Figure 6, whereas for voltage harmonic sources it can be through Thevenin equivalent circuit as shown in Figure 8. These equivalent circuit is only accurate when there is only one customer connected at PCC, but as the distribution network is becoming more complex, there are multiple customers connected at the PCC. Therefore, it is not possible to represent these customers as one customer due to different load conditions as well as operation scenarios.

The active Power at the PCC is calculated as [8]

$$P = \mathrm{Re}\left(V_{\mathrm{pcc}} I_{pcc}^{*}\right) = V_{\mathrm{pcc}} I_{\mathrm{pcc}} cos\varphi \tag{22}$$

where, V_{pcc} is the harmonic voltage measured at the PCC, the term I_{pcc}^{*} is the complex conjugate of the harmonic current measured at the PCC I_{pcc}, and φ is the angle between V_{pcc} and I_{pcc}.

Reference [8] did not explain the order of harmonic voltage and harmonic current used in Equation (22). It was as well concluded that $P > 0$, the dominant harmonic source is the utility side and $P < 0$, the dominant harmonic source is the customer side.

Reference [8] proved this method to be unreliable, and proposed the impedance properties of the two parties (customer and utility) and based on the actual measurement of voltage and current at the PCC. The accuracy of customer and utility harmonic impedance's phase angle is not a requirement for this method.

References [38], [39] found a concrete proof that power direction method is inaccurate and cannot be used for harmonic source detection, although it is the most commonly used method accepted by the industry, because it is easy to implement and less expensive. The concept of superposition is contradicted by the direction of active power flow as the flow of harmonic power can be at either directions once the phase angle is greater than 180°. Since the current phase angle between utility and customer(s) has no guarantee to remain in a certain range, one can conclude that the method based direction of active power flow is not suitable for harmonic source detection [38].

In addition reference [40] indicated that there are quantitative and qualitative methods that can be used for determination of harmonic contribution at the PCC. The quantitative method depends on the harmonic impedance measurements and calculation using the superposition principle method. Qualitative methods are known as power direction methods (active power, reactive power and non- active power methods). Since the phase angle between a harmonic source of both upstream and downstream the PCC varies between 0° to 360°, when it is high, the method based power direction cannot work effectively. Figure 10 indicates the direction of electrical power flow in a power system at different phase.

According Figure 10, when the direction of the active power is being supplied from the utility through the metering point to the load this means that the power is delivered and it has a positive sign. When the direction of active power flow is from the load which has a distributed energy source such as rooftop Photovoltaic system through a metering point to the source the power is received and it has a negative sign. Active power does not fall on any of the quadrants only exist on the x-axis it is referred as delivered or received not lead or lag as the current and voltage.

In traditional power system, the active power direction flow at the fundamental frequency (f_1) (50Hz) is normally flowing from the utility source to the load and it has the positive sign, as there were no disturbances that causing the power quality issues. In modern smart grids it consists of distributed energy sources and non-linear loads that inject harmonic current. The power system consists of harmonic frequencies (f_{h}).

2) REACTIVE POWER METHOD

References [41], [42] agreed that to detect the harmonic source, an existing techniques have been applied to determine the harmonic contributions of the customer and the utility. Harmonic vector method has been proposed to determine harmonic contributions of the utility and customer at the PCC based on the reference impedance. This method made it possible without determining customer impedance to calculate the harmonic contributions and in resonance conditions it evaluates the results better. In recent literature [16], [19], [26] the Independent Component Analysis (ICA) methods were used, which requires the impedance at the customer's side to be higher than the one at the utility side. This is impractical when the network has filters or capacitors installed at the customer side. Reference [16] improved this method whereby some assumptions were removed.

References [16], [43]–[45] did qualitative analysis on determining the dominant harmonic source using the reactive power direction when the sum of reactive power is negative. The direction of reactive power flow gives a better similarity with the source magnitudes.

According Figure 10 when the direction of the reactive power is being supplied from the source through the metering point to the load, this is referred as delivered reactive power and it has a positive sign. When the reactive power flow from the load through a metering point to the source, this is referred as received reactive power and it has a negative sign. Reactive power does not fall on any of the quadrants only exist on the y-axis as it is referred either as delivered or received not lead or lag as the current and voltage.

Reference [39] concluded that the direction of power flow is influenced by the polarity or phase angle difference between the two harmonic sources than the differences in magnitudes. References [38], [39], [46] proposed techniques to quantify the harmonic sources with a set of superposition-based indices. Reference [18] presented a methodology which utilizes marginal number of connections and anticipates minimal computation duration for operation using the design of Cascade Correlation Network (CCN).

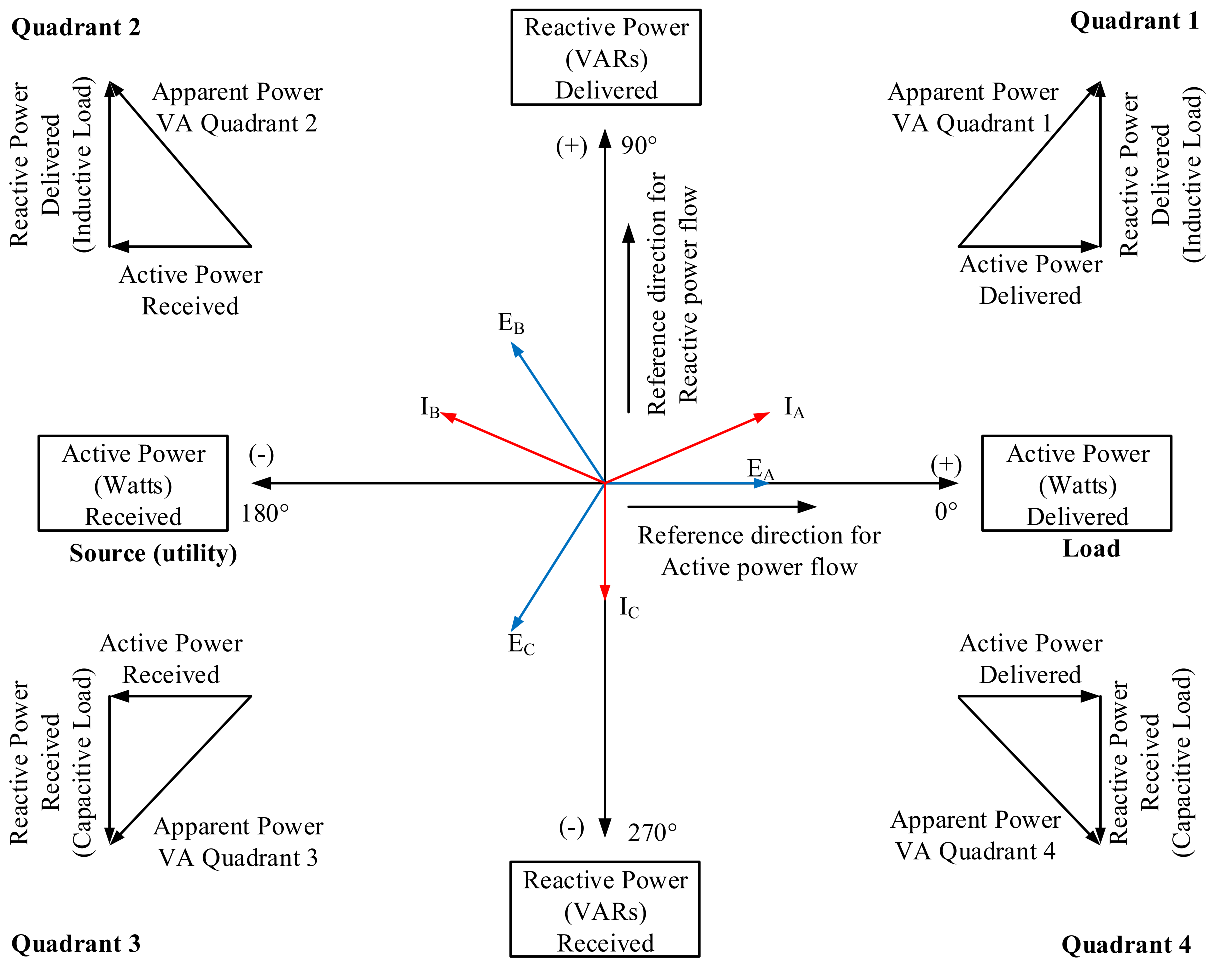

FIGURE 10. Direction of electrical power flow.

Reference [44] used a harmonic reactive power direction and critical impedance methods to evaluate a harmonic contribution and measurement at PCC. It is difficult to detect harmonic source in a power system with unbalanced supply conditions, due to the current and voltage affected by negative sequence components. Critical impedance methods are used by means of calculating harmonic reactive power generated by the utility and the equivalent impedance or admittance that consumes the reactive power. Dominant harmonic source can be estimated by comparing the utility and customer(s) merged impedances. Critical impedance methods and reactive power direction methods has similarity in theory for calculating the utility and customer side voltages. When these methods indicate that the voltage at the customer side is greater than at the utility side this would mean that the customer side have higher harmonic contribution at PCC [39].

A novel method was presented by reference [47] to split the harmonic contribution of customers and utilities at the PCC, it uses reference impedance and converts impedance changes into equivalent current source changes. These methods can be validated by field measurements. Power system harmonics are classified as a supply or load harmonics depend on the origin. The harmonic impedance flowing in the power system depends on the source impedance. Hence, little modification in the impedance source is reflected in the current harmonic spectrum. Reference [48] proposed a new method using the artificial neural networks to separate and assess the influence of the source impedance change without interference with the load operation by using actual field data. This method requires voltages and currents waveforms of single and/or three phase loads to be measured at the PCC. Reference [48] stated that to determine a true harmonic current of the customers, the supply voltage at the PCC has to be sinusoidal. It may be unfeasible to establish a pure sinusoidal voltage at the PCC since it requires performing switching of a customer to reduce the system impedance closer to zero to obtain a sinusoidal supply voltage.

Methods based on reactive power depend on the calculations of the customer(s) and utility harmonic impedance to determine the dominant contribution, this is mathematically possible by assuming the harmonic impedance being constant although in actual power system the harmonic impedance of

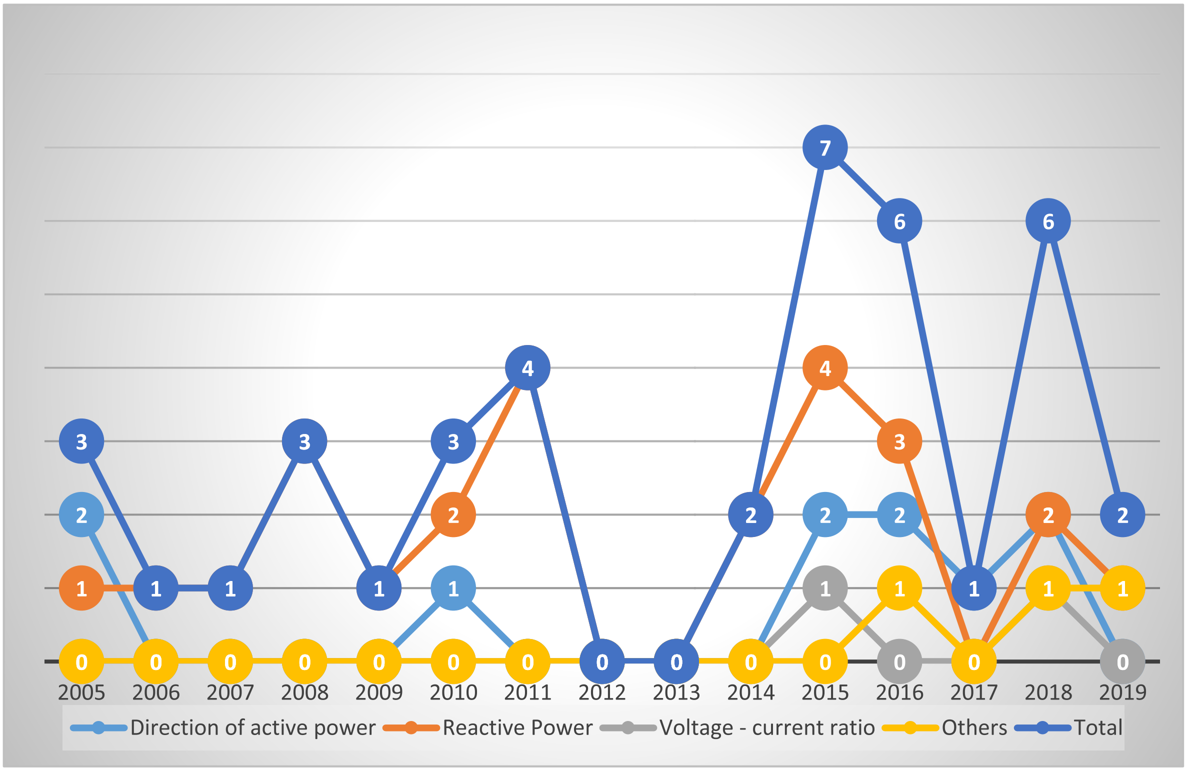

FIGURE 11. Aggregate number of papers used to review the three categories of harmonic source detection methods.

the utility fluctuates. It affects the calculation of the dominant harmonic contribution. The harmonic impedance information needs to be accurate in order to have accurate information regarding the dominant harmonic source

3) VOLTAGE-CURRENT RATIO METHOD

A newly developed was introduced using the voltage -current ratio for harmonic source detection at the PCC [10]. This method requires the measured voltage and current at the PCC as well as the utility and custome's equivalent impedance values. Reference [10] concluded that this does not only detect the harmonic source, but it also determines the contribution between the parties. Reference [28] developed a current-voltage ratio for harmonic current source detection. This method requires harmonic impedance of the utility and the customer, which is a challenging process.

D. SOFTWARE

There are many different software packages that power utilities are using to conduct harmonic studies. On top of those tools is Matlab/Simulink as used in references such as [14], [16]–[19], [24], [49], and PSCAD as in [9]. Other general computation software is used such as MathCAD as in [35]. Monte Carlo mathematical method was used in [50] to model the probabilistic behavior of the harmonic. It was found that there is no simulation done using the DIgSILENT Power factory package for harmonic source detection yet. Various research validates the simulation results with the measurement and the instrument that is mostly used is MAVOWatt 70 Power quality analyzers. There are Unipower, Vectograph and Impedograph power quality analyzers that can be used to validate the simulated results as well. Matlab that is widely used to validate the results of harmonic source detection is uncommon used by most Southern Africa power utilities.

In this study the reviewed articles are given in Table 4 as per date of publication. As per Table 4 publications of each method are used to derive the graph for the period of analysis since 2005, as specified in Figure 11.

According to Figures 11, the harmonic source detection is still an active research point in the power system field and number of publication about this topic has grown considerably in the period from 2005 - 2019. Among the 40 papers reviewed, there are more papers (25 papers) based on reactive power or non-active power compared to the other methods. Within this systematic literature review it is noticed that there is still no accurate method that is approved by international bodies such as IEEE, CIGRE, IEC to be used to give the practical and commercial results needed by the power utilities.

IV. DISSCUSSION, GAPS AND FUTURE RESEARCH WORKS

This section addresses the research gaps identified in the reviewed literature, the challenges for future research work, and proposes a framework for developing a more accurate and practical harmonic detection method.

TABLE 4. Fundamental aspects from the reviewed papers.

Harmonic source detection methods	Reference	Fundamental aspect to be identified
Direction of active power flow	[8], [13], [20], [21], [40], [46], [51]–[54]	• The input data required are the measured power or current and voltage at the PCC. • The sign of the Power at the PCC gives an indication of the contributor of the harmonic distortion. • The method is easy to implement and commercially viable. • Most of the existing instruments used for measurement in the industry give the total power and show the direction. • The methodology used is simple and does not require any switching of the load. • No assumption needed. • Inaccuracy of the measurement output due to the incorrect set up of the measuring instruments.
Reactive Power	[5], [6], [24]–[26], [41]–[43], [48], [49], [55], [56], [7], [57]–[61], [9], [14], [16]–[19], [23]	• Assumption of customers and utility admittance and impedance cause it to be ineffective. • Inaccuracy of the measurement output. • Difficult to implement with multiple customers connected at PCC. • To conduct the measurement of impedance other customers' needs to be disconnected. • It is a theoretically viable but not practical.
Voltage – current ratio	[10], [28]	• Assumption of customers and utility admittance and impedance cause it to be ineffective. • Inaccuracy of the measurement output. • Difficult to implement with multiple customers connected at PCC. • To conduct the measurement of impedance other customers' needs to be disconnected. • It is theoretically viable but not practical.
Others	[62]–[64]	• Theoretically viable but not practical.

A. METHODS

Active power flow method is found theoretically inaccurate and unreliable to determine the source of harmonics in cases when both upstream and downstream the metering point there is a source of harmonics [8]. In this method, the authors focused on the phase angle (δ) difference between the two harmonic sources as the main factor influencing the active power direction, with paying less attention to the magnitudes of voltage and current, which are important in a harmonic source detection problem. The characteristic of the circuit affects the direction of the power flow. This implies that the position or the point of measurement also influence the harmonic source detection. Unlike the active power that depends on the phase shift angle, the reactive power depends on the magnitudes of the voltage sources, and this technique could be used as an indication of the dominant harmonic source. The direction of active or reactive power is affected by the harmonic source size and customer(s) impedances. Therefore, it is concluded that the power-direction-based methods is concluded to be unreliable.

It is also unknown of how to use these methods when multiple customers are connected at the PCC as well as when multiple customers are Independent Power Producers (IPPs) using distributed generation sources. This case is not also included in the surveyed literature. The contributions of the IPPs to the harmonic contents needs to be determined. The active power flow formula used in Equation (22) needs to be well defined as follow:

$$P_T = P_1 + P_{\text{h}} \tag{23}$$

where, P_1 is the power at the fundamental frequency andP_h is the total power for all the harmonic order part of the network. $P_{\text{h}} = P_2+P_3+P_5+P_{nth}+\ldots$ the sign of the harmonic power to be taken into consideration and the meaning to be understood. It is unknown how to determine whether the dominant will be determined per harmonic order or per network, as it is possible to have a different harmonic source as per harmonic order and/or per even/odd or triplen harmonics.

A negative sign of total power ($P_T = P_1 + P_h$) means the harmonic source is from the utility side, while a positive sign of the total power means the harmonic source is from the customer's side, however, it does not indicate which customer is it. It was concluded that the total power of each customer needs to be determined either by means of calculation or to be obtained from a software simulation. Thus, once the total power for each customer is determined this will give a better indication of which customer is a main contributor of harmonics. It was concluded that the customer with a higher total power is contributing more harmonic at the PCC.

References [16], [19], [25] indicated that the value of the impedance at the customer side is far larger than the utility, when only one customer is connected at the PCC, therefore the reactive power method is not possible with multiple customers connected at the PCC and all of the loads are harmonic source. This method depends either on the current, voltage and harmonic impedance or the admittance of the utility and the customer as the input data. The harmonic impedance of the utility and the customers are challenges it varies depending on the load condition and any other operation scenarios. The inaccuracies of harmonic impedance should always be taken into consideration, therefore this method based on reactive power cannot be used for practical and commercial purposes.

In the voltage-current ratio method, the time variation of harmonics has to be taken into consideration. It is highlighted in the literature that to determine and evaluate the contribution of the dominant harmonic source, this depends on

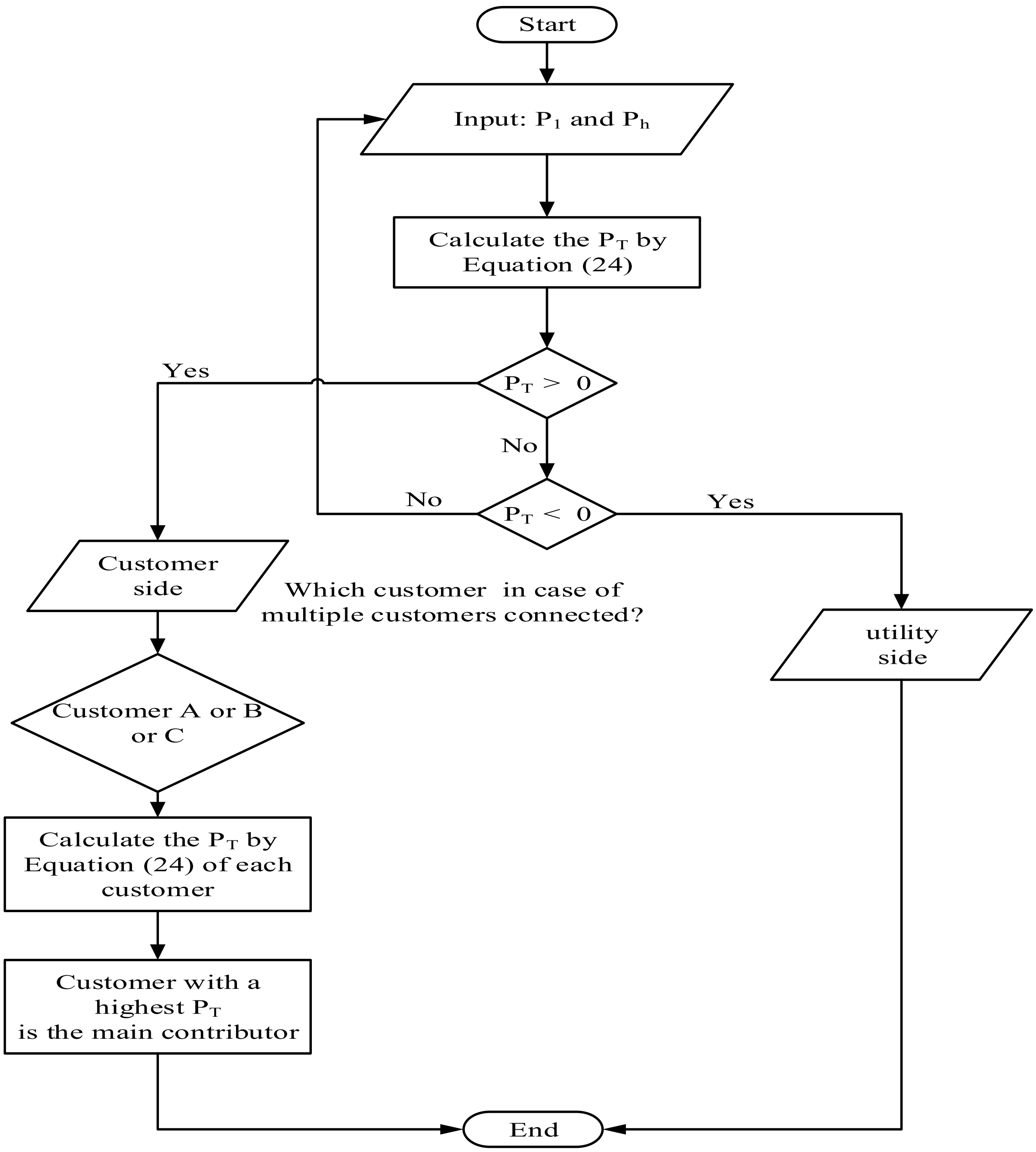

FIGURE 12. Flowchart of the method based on a direction of active power flow for identifying the harmonic source.

computing the utility and the customer (s) impedance from the measured harmonic voltage and current at a PCC. In some cases, it is assumed that the background harmonic voltage is stable. These cases are not practical as the impedance of the distribution network varies depending on the instrument transformers (voltage and current transformers) accuracies, whether they are programmed and calibrated correctly, and the load conditions.

Most of the reviewed harmonic detection methods are mathematically correct. However, in order for those methods to be implemented, certain strategic plan needs to be in place as the network of supply might require some profiling or switching off certain sections in order to verify the network parameters. Assessment of resonance conditions is not part of most of the reviewed methods, whereas, this scenario is of high importance because during the resonance condition the harmonic distortion rises. In a practical situation, voltage and current harmonics can be a combination of positive, negative and zero sequences, this needs to be achieved in simulation as well.

This systematic literature review enabled the authors to select and propose a modified harmonic detection method based on the direction of active power flow, where shortcomings of previous detection strategies need to be considered.

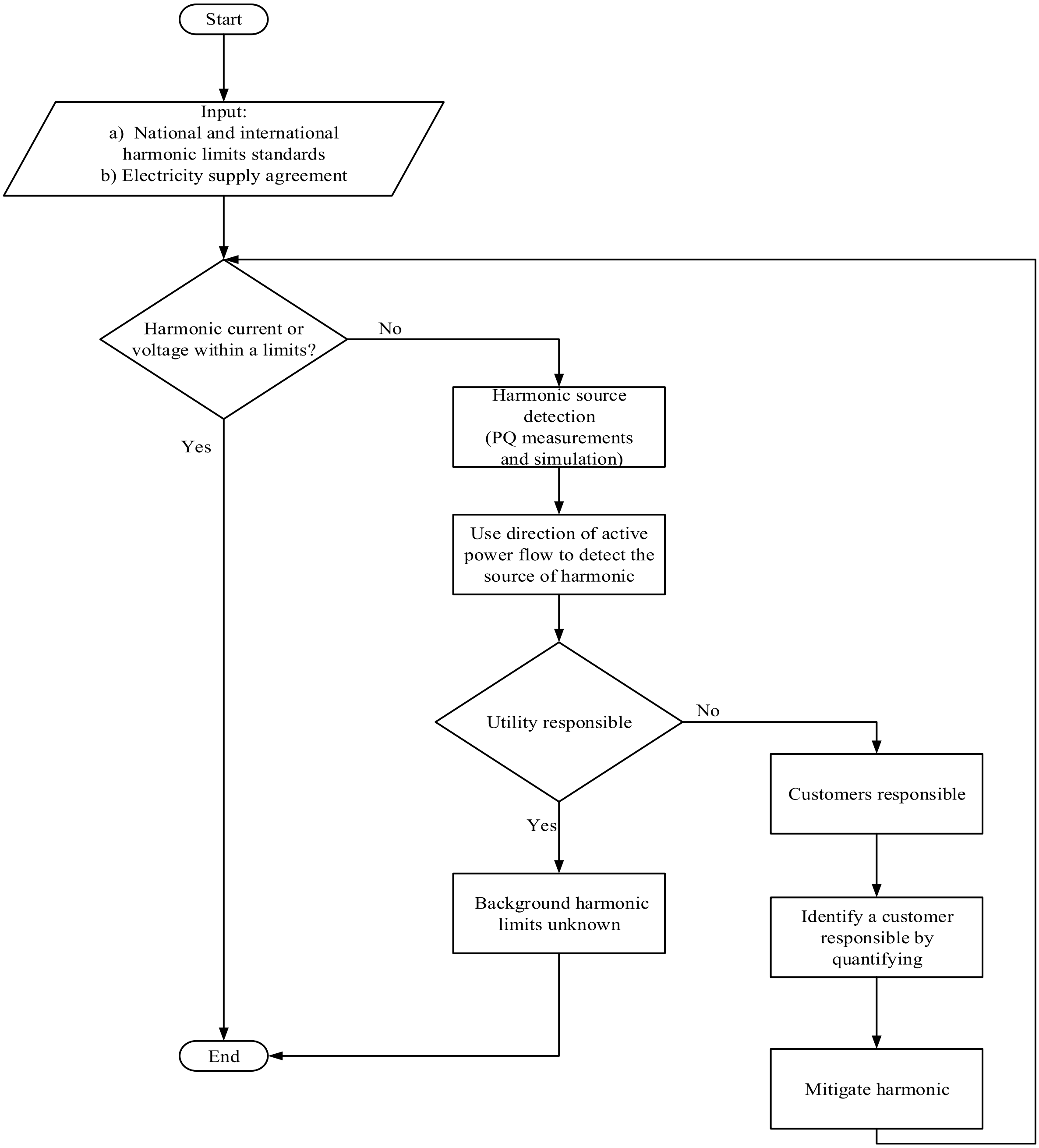

FIGURE 13. Harmonic monitoring management.

According to the synthesis of the literature, the direction of active power flow method is the only method that gives the practical results and without any input data being assumed. A proposed method should be tested using the IEEE PES benchmark test system with renewable energy generators connected at PCC as well as prosumers (energy producers and consumers) with mixed non-linear loads and distributed generators which form a microgrid. The direction of active power flow method helps the engineers solve the practical issues as they arise. However, modifications are needed to cater for the entire challenges that are currently facing the power system multiple customers connected at the PCC.

It is identified that the harmonic source detection is a major concern for most power utilities, thus the future research areas should formulate a strategy plan with different scenarios of the power system to reduce the harmonic content for certain customer(s) at the PCC. The analysis of the power quality indexes which are part of the international standards should be re-evaluated and check whether the limits identified covers the shortcomings of the literature when it comes to harmonic source content. Studies on harmonic source detection should include the resonance condition as well as the unbalance networks which consists of sequence components (positive, negative and zero sequences). It is also required to develop a new adapted Norton or Thevenin equivalent circuits to include the new phenomena that cover the modern practical power system. Determination and discussion in detail of the harmonic mitigation actions is required between the two parties that has harmonic contents higher than the prescribed harmonic limits stated in the international standards. To prevent the cost of purchasing and installation of harmonic filter and design an effective harmonic mitigation, one need a practical solution to detect harmonic sources and thereafter to monitor and well manage the harmonic distortion at the PCC. This is a cost effective methodology for both the utilities and the customers. Important parameters in using a modified harmonic detection method based on the direction of active power flow are the fundamental power (P_1) and the harmonic power (P_h). Figure 12 shows the flowchart presenting the framework for the proposed method to identify the harmonic source at the PCC where multiple customers.

It is worthwhile for the power utilities to invest in limiting the harmonic content of their customers. Utilities do allow the harmonic level as per electricity supply agreement. It is advisable for the utilities to monitor the harmonic levels at the PCC not to exceed the prescribed limits specified in the electricity supply agreement to reduce the harmonic effects to the grid. When the power system is monitored well and harmonic are managed to be within the limits prescribed by the national and international standard, thus the harmonic source detection cannot be a challenge. Figure 13 describe the harmonic monitoring management process.

B. SOFTWARE

Most researchers used mathematical model to calculate the harmonic source content and many algorithms are given on how to determine the harmonic source detection. The method based on the direction of active power flow is the only method that gives the practical overview and it needs modification to fill the gaps identified in this systematic review. Most researchers use the MATLAB/Simulink to validate their mathematical model. This software is uncommonly used by most Southern Africa power utilities. Most Southern Africa power utilities uses DIgSILENT for their harmonic analysis during the planning phase to connect new customers at the PCC. DIgSILENT software indicates the direction of power per harmonic order which can be a good sign for determining the harmonic contribution. Measurements of actual data on harmonic gives a better indication of the harmonic content of the power system compared to the simulation and mathematical model. The authors recommend the use of the measurements of the harmonic content at the PCC where multiple customers are connected using the power quality analyzers such as Unipower and Vectograph and/ or Impedograph. Thereafter, use the DIgSILENT to simulate the network with actual harmonic content of each customer.

Finally, it would be interesting if most research on harmonic source detection can use the same test system such as the IEEE PES given by [9] and test the mathematical model provided in literature as this would give a better understanding of the topic and the results can be compared on the same basis.

V. CONCLUSIONS

The main purpose of this paper was to demonstrate an up-to-date outline of methods used in harmonic source detection at the PCC. The three categories of harmonic source detection methods are: direction of active power flow method, reactive power method and voltage – current ratio method. The shortcoming of the methods was discussed, and indicated the most common software packages used by the researchers for simulation in the field. The mathematical model of different methods was analyzed.

The systematic literature review methodology was used for this analysis, that enabled the authors to discover and categorize the existing literature, analyses and combine data, and develop clear conclusions of what is known and is unknown about the topic by classifying the interdependence between the reviewed papers. In the research areas, the research gaps were identified and future research areas were proposed. The analysis of this paper presented guidelines to the researchers who are new in the study of the harmonic source detection. The research questions raised can present a focus to the experienced researchers and engineers within the studied areas.

In this review paper it was highlighted how the operation of modern power system is changed with the integration of the renewable energy generators. This caused challenges for the power quality, mainly harmonic distortion. Harmonic distortion affects the electrical equipment which forms the power system. A modified harmonic source detection method based on the direction of active power flow was proposed to cater for multiple harmonic customers connected at the PCC. The harmonic monitoring management process were defined. The use of Norton and Thevenin equivalent circuit can no longer combine the customers at PCC as one because of different operation scenarios, thus in this paper it was proposed to adapt these equivalent circuits. In addition, software applications were reviewed, it was noticed that researchers are mostly using Matlab/Simulink software packages and using different test system during simulation, thus in this paper it was proposed to use DIgSILENT powerfactory, as it is widely used by most utilities. It is advised to use the actual measurement data during simulation to obtain accurate results. Additionally, it is beneficial to use of the IEEE PES benchmark test system for harmonic source detection, in order for the researchers to better compare the results of different methods.

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