Modelling and prediction of current harmonics generated by power converters in distribution networks

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Abstract
Predicting current harmonics in distribution networks is essential to find harmonic losses and power quality indices. In order to predict the current harmonics, the effect of grid impedance and voltage distortions on grid-connected power converters need to be considered. The effects of these parameters on current harmonics can be nonlinear, which complicates the system analysis. Consequently, this paper investigates the impacts of background voltage harmonics, grid impedance, and multi-parallel grid-connected converters on current harmonics at a point of common coupling. Moreover, a novel method called combined least squares and kriging (CLSK) is proposed to predict the current harmonics after evaluating the level of system nonlinearity. In the proposed CLSK method, the prediction model is developed by measured voltage and current harmonics at the point of common coupling to identify and predict the current harmonics. This analysis shows that using the proposed CLSK method, the accuracy of the current harmonic prediction is increased compared to the existing methods. The accuracy and the efficiency of the proposed CLSK method are verified by lab experimental results and field measurement data.

1 INTRODUCTION
The proliferation of power electronic loads has brought new challenges into distribution systems, such as increasing the level of current harmonics. These power electronic loads, which are connected throughout the network, use power electronic switching devices as shown in Figure 1 [1, 2]. Predicting current harmonics injected by these power electronic switching devices is an essential factor to calculate power quality indices and harmonics losses [3]. The predicted current harmonics can be also applied to estimate the available capacity and the lifetime of grid cables and transformers [4]. On the other hand, predicting current harmonics in a distribution system is a challenging task, as different power converters and nonlinear loads interact with each other [5, 6]. To investigate current harmonics prediction in Figure 1, two converters connected to the Point of Common Coupling (PCC) are considered. In this figure, \( v_p \) and \( v_g \) are the PCC and grid voltages, and \( i_g \) is the current injected to the grid. To find current harmonics at the PCC generated by highlighted converters in Figure 1, their equivalent phasor representation at harmonic order \( h \) is shown in Figure 2. These converters are modelled by independent current sources for estimating the current harmonics of network in literature [7]. However, they are modelled by dependant current sources \( (I_{c1,h} \angle \theta_{c1,h} \text{ and } I_{c2,h} \angle \theta_{c2,h}) \) in parallel with their impedances \( (Z_{c1,h} \text{ and } Z_{c2,h}) \) in Figure 2. The reason for using dependant current sources is that grid parameters affect the current harmonics generated by converters. In this figure, \( I_{g,h} \angle \theta_{g,h} \text{ and } V_{g,h} \angle \theta_{g,h} \) represent the grid current and grid voltage harmonics, respectively. Moreover, \( Z_{g,h} \angle \theta_{g,h} \) is the grid harmonic impedance, which includes grid inductance \( L_g \) and resistance \( R_g \).

It has been explained in [8, 9] that \( I_{g,h} \) can be affected by the \( I_{c1,h} \), \( I_{c2,h} \), and \( V_{g,h} \). As a result, predicting \( I_{g,h} \) is difficult even with the assumption that the values of \( I_{c1,h} \) and \( I_{c2,h} \), and the parallel impedances \( Z_{c1,h} \) and \( Z_{c2,h} \) are known. Furthermore, estimating \( I_{g,h} \) based on the amplitudes of \( I_{c1,h} \) and \( I_{c2,h} \) is not straightforward, as \( I_{g,h} \) can be affected by \( \theta_{c1,h} \) and \( \theta_{c2,h} \) [10-12]. Similarly, authors in [6] have mentioned that predicting
I\textsubscript{g,h} becomes more complicated when distribution network components such as transformers and loads are nonlinear. Moreover, system loads with power converter technologies, such as electric vehicle battery charger, can also be nonlinear, which add to the system complexity [3]. Notably, I\textsubscript{c1,h} and I\textsubscript{c2,h} depend on the topology of converters as well as grid parameters as mentioned earlier. Authors in [13] have found that applying 12- and 18-pulse configurations compared to 6-pulse 3-phase rectifiers could significantly reduce I\textsubscript{c1,h} and I\textsubscript{c2,h}. The results show that current harmonics at 5th and 7th orders are reduced up to 90% when applying the 12-pulse configuration instead of 6-pulse topology.

Another challenging issue to predict I\textsubscript{g,h} is that I\textsubscript{c1,h} and I\textsubscript{c2,h} may be also affected by voltage harmonics V\textsubscript{p,h}, depending on the power converter topology and control. As a result, considering I\textsubscript{c1,h} and I\textsubscript{c2,h} as independent sources may contribute to additional error in the current harmonic calculation and estimation [14, 15]. Authors in [16] have estimated i\textsubscript{g} based on one-week measurement. In that paper, i\textsubscript{g} has been modelled by Discrete Fourier Transform and a noise function. This noise function has been utilized to model i\textsubscript{g} variations due to relatively low magnitude current harmonics. However, in this method, the required modifications due to the grid and harmonic sources with unexpected variations have not been addressed. In [17], I\textsubscript{g,h} has been predicted based on neural networks. However, the distribution network was assumed to be a radial feeder in those papers, where the impact of other current or voltage harmonic sources was neglected. Authors in [18] have proposed an estimation method for the current harmonics at PCC based on the adoptive neural network approach. In this method, the measured values of voltage and current in both offline and online conditions are used for training the estimation model. In [19], a nonlinear auto-regressive method has been used for estimating the current harmonics passing through the network. Additionally, the wavelet transform has been used for estimating the voltage waveform when voltage measurement device is not available at PCC. The estimated voltage and measured current waveforms are then employed for finding the weighted values in the regressor model. In the above-mentioned methods, however, all the voltage harmonics have been considered as the inputs of the predicting model without neglecting the insignificant harmonics. This increases the calculation time and could create error in the model, as the voltage harmonics magnitudes might be affected by noise. In [20, 21], Kalman filter and state-space model have been employed for estimating the current harmonics in an unbalanced grid using the measured voltage and current values in the time domain. Although these methods estimate the current harmonics in unbalanced condition, the impact of other conditions, such as weak grid, has not been investigated. In [22], least squares, Kalman filter, maximum likelihood estimation, and Goertzel algorithms for harmonic estimation have been compared in terms of estimation error and the computational complexity. It has been found that the estimation error of these algorithms significantly increases at some conditions, such as when a fault occurs. Authors in [23] have developed an estimation method based on trigonometric orthogonal for the current harmonics at PCC. On the other hand, a predicting method based on least squares has been introduced for these current harmonics in [24]. However, the impact of V\textsubscript{g,h} on the current harmonics generated by converters has not been considered in these methods.

To analyse and estimate the current harmonics of a nonlinear load, authors in [25–27] have suggested black-box modelling using time-invariant preservation system theory. Besides, deep learning together with the convolutional neural network have been used to model the current harmonics of the system by [28]. However, the impacts of other loads and distribution network on the predicted currents have not been considered in these works. Another method to predict a nonlinear system is the kriging method, which has been introduced in [29]. In this method, a function based on Gaussian process is applied to model non-linearities in a system. As explained in [30–32], the Gaussian function in kriging method helps to estimate systems with high
degree of nonlinearity, such as when several nonlinear loads are connected to the network.

As explained above, the nonlinear impact of network parameters on the current harmonics generated by power converters have not been thoroughly considered in the literature. Although ignoring these interactions reduces the complexity of calculations, it could increase the estimation error of current harmonics. This error is significant and needs to be reduced, as usually there are more than one nonlinear load connected to the PCC. Thus, this paper intends to investigate different grid conditions in terms of current harmonic prediction at the PCC. Moreover, a predicting method is proposed, which can be applied to predict \( I_{g,h} \) in both linear and nonlinear grid conditions. Notably, the main aim of this paper is to consider nonlinear interactions between power converters and distribution network for predicting current harmonics at the PCC. Consequently, the current harmonics injected from PCC into the distribution network can be predicted by applying the proposed method. The contributions of this article are categorized as follows:

- Analysing the nonlinear impact of grid parameters on the current harmonics generated by converters using equations and laboratory tests.
- Proposing a predicting method called combined least square and kriging (CLSK) to estimate the current harmonics at PCC in multi-converter condition. In this prediction method, the current harmonics are modelled using the voltage and current harmonics measurements at PCC.
- Evaluating the impact of nonlinear interactions between grid and converters on the current harmonics at PCC. By doing this, an efficient set of effective voltage harmonics is selected as input variables for estimating the current harmonics.

The paper is organized as follows: In the next section, challenges to predict current harmonics in distribution networks are explained. Then, these challenges are described further using field data in Section 3. Next, the difficulties to consider nonlinear and their impacts on the system are investigated in Section 4. Afterwards, Section 5 presents the proposed method for current harmonic identification and prediction. Indices to select effective PCC voltage harmonics for predicting current harmonic are then introduced in Section 6. In the next step, CLSK method based on least squares and kriging methods is proposed in Section 7. In this CLSK method, the inverter side of PCC is modelled based on sampled data points. After that, to evaluate the proposed predicting method, the predicted current harmonics values are compared with experimental results in Section 8. Finally, Section 9 presents the research conclusions.

2 PREDICTING CURRENT HARMONICS IN AN ACTIVE DISTRIBUTION NETWORK

As discussed above, predicting \( I_{g,h} \) in distribution networks is complex since \( I_{c1,h} \) and \( I_{c2,h} \) values may depend on system parameters, such as \( V_{g,h} \) and \( Z_{g,h} \). These challenges are discussed in this section using equations and equivalent circuits. In order to find \( I_{g,h} \) in Figure 2, KCL can be written for the PCC as given in (1).

\[
I_{g,h} \angle \theta_{g,h} = I_{c1,h} \angle \theta_{c1,h} + I_{c2,h} \angle \theta_{c2,h} - \frac{V_{p,h} \angle \theta_{p,h}}{Z_{c1,h}} - \frac{V_{p,h} \angle \theta_{p,h}}{Z_{c2,h}}
\]  

(1)

As it can be concluded from (1), \( I_{g,h} \angle \theta_{g,h} \) is calculated simply using the values of \( I_{c1,h} \) and \( I_{c2,h} \). However, as the grid parameters affect \( I_{c1,h} \) and \( I_{c2,h} \), \( V_{p,h} \) might nonlinearly affect \( I_{c1,h} \) and \( I_{c2,h} \), it is assumed that these current harmonics are affected by \( V_{p,h} \) linearly according to (2).

\[
I_{c1,h} \angle \theta_{c1,h} = \alpha_{c1,h} \cdot (V_{p,h} \angle \theta_{p,h}) + \beta_{c1,h}
\]

(2)

where \( \alpha_{c1,h} \) is a constant representing the impact of \( V_{p,h} \) on \( I_{c1,h} \), which can be calculated based on converter’s topology. Also, \( \beta_{c1,h} \) is equal to the current injected by the converter when \( V_{p,h} \) is zero. Notably, the equation for \( I_{c2,h} \) is obtained similar to \( I_{c1,h} \) as given by (2). It can be inferred from (2) that for estimating \( I_{g,h} \), \( V_{p,h} \) needs to be determined. Therefore, the value of \( V_{p,h} \) is found using KCL at the PCC as given in (3). It is noted that converter 2 is assumed disconnected for simplifying the analysis, so \( I_{c2,h} \) and \( Z_{c2,h} \) are not considered in (3). However, this simplification does not change the conclusions.

\[
V_{p,h} \angle \theta_{p,h} = \left( \frac{Z_{c1,h}}{-\alpha_{c1,h} Z_{gh} \angle \theta_{c1,h} + Z_{gh} + Z_{c1,h}} \right) \times (V_{g,h} \angle \theta_{g,h} + Z_{gh} \angle \theta_{g,h})
\]

(3)

This equation shows that as \( V_{p,h} \) relates to \( V_{g,h} \), \( Z_{gh} \), and \( Z_{c1,h} \), \( I_{c1,h} \) depends on the values of these parameters as well. It can be understood from (2) and (3) that when \( V_{g,h} \) is relatively low, \( V_{p,h} \) might be reduced and its impact on \( I_{c1,h} \) can be neglected. On the other hand, (3) shows that a relatively high \( V_{g,h} \) can increase \( V_{p,h} \) which affects \( I_{c1,h} \) according to (2). Although the effect of \( V_{p,h} \) on \( I_{c1,h} \) is estimated by a linear function in (2), calculating \( I_{c1,h} \) still depends on system parameters since \( \alpha_{c1,h} \) needs to be found based on the converter topology. On the other hand, \( V_{p,h} \) depends on \( \alpha_{c1,h}, Z_{gh}, \) and \( \beta_{c1,h} \) in addition to \( V_{g,h} \) as can be seen in (3). Consequently, it is realised that predicting current harmonics is difficult, as the impact of several grid parameters on the current harmonics needs to be evaluated.

As \( I_{c1,h} \) and \( I_{c2,h} \) are affected by \( V_{g,h} \) and \( Z_{g,h} \), the interactions between converters and grid need to be considered to predict \( I_{g,h} \) in the case of having multi-converters. Also, the current harmonic cancellation between the two converters is another important parameter, which can make the analysis nonlinear. This indicates that modelling the current harmonics is complex
due to dependence on several parameters whose values are generally unknown and change nonlinearly in the distribution network.

The challenges to predict current harmonics in distribution networks were explained in the previous sections using equivalent circuits and equations. In order to verify the above-mentioned challenges, laboratory tests have been performed, which are described in the next section.

3 VERIFICATION OF THE IMPACT OF GRID PARAMETERS ON THE CURRENT HARMONICS

As discussed above, the impact of $V_{g,h}$, $Z_{g,h}$, and multi-converter condition can make predicting current harmonics difficult. In this section, experimental measurements are used to investigate the impact of $V_{g,h}$, $Z_{g,h}$, and multi-converter condition on $I_{g,h}$. For that purpose, the setup shown in Figure 3 was constructed according to the equivalent circuit of Figure 2 and laboratory tests were performed. In the laboratory tests, a three-phase programmable grid simulator, Chroma 61511, was used to model distribution network $V_{g,h}$. Also, two power electronics converters based on adjustable speed drives (ASD) with similar power rating 7.5 kW were connected to two induction motors with a controller to change the output power. The switching frequencies of converters 1 and 2 were set at 3 and 6.6 kHz, respectively. Furthermore, a DC motor (operating in generator mode) with adjustable output power up to 4.8 kW was coupled to the induction motor of converter 1, whereas the induction motor of converter 2 was operating at no-load. Grid inductance $l_g$ was set to 0.2 and 1.2 mH for a stiff and weak grid, respectively, using a combination of series inductors in Figure 3. A commercial power quality measurement device was used to measure voltage and current harmonics at the PCC.

The lab measurements are investigated in the following sections to evaluate the impact of $V_{g,h}$, $Z_{g,h}$ and multi-converter condition in predicting current harmonics at the PCC. Although the grid impedance in these laboratory tests has been assumed purely inductive, this analysis can be also used for distribution grids with resistive-inductive impedance.

3.1 Impact of $V_{g,h}$ on $I_{g,h}$ - active and passive grids

To investigate the impact of $V_{g,h}$ on $I_{g,h}$ in single converter condition, only converter 1 was connected to the PCC in this case. Also, grid impedance was set to the stiff grid with $r_g = 0$, $l_g = 0.2$ mH, and $V_{g,r} = 240$ V. On the other hand, the converter’s load was increased by 20% per minute from no-load to full-load (4.8 kW). Then, $I_{g,5}$ was measured at $V_{g,5} = 0\%$ and $6\%$ while increasing the converter’s load as shown in Figure 4. As can be seen in Figure 4, at the converter no-load condition, $I_{g,5}$ is slightly affected by $V_{g,5}$. However, when converter load increases, $I_{g,5}$ is significantly affected by $V_{g,5}$. Consequently,
comparing to $I_{g,5}$ at $V_{g,5} = 0\%$, $I_{g,5}$ is reduced by 0.27 A in $V_{g,5} = 6\%$ at 20% loading level (60–120 s), whereas it drops by 0.75 A at full-load condition. This experiment shows that the converter current harmonic depends on $V_{g,5}$ and the interaction between $V_{g,5}$ and $I_{g,5}$ can be nonlinear.

3.2 Impact of $Z_{g,h}$ on $I_{g,h}$ - active and passive grids

To investigate the impact of $Z_{g,h}$ on $I_{g,h}$, the test conditions were kept the same as the previous section except for $V_{g,h}$ and $I_{g}$. These tests were performed for two cases of weak grid ($I_{g} = 1.2$ mH) and stiff grid ($I_{g} = 0.2$ mH) at $V_{g,h} = 0\%$. The measurements of $I_{g,7}$ from converter no-load to full-load conditions for these two cases are shown in Figure 5. This figure shows that the variation of $I_{g,7}$ at $I_{g} = 0.2$ mH is totally different from $I_{g} = 1.2$ mH. At converter no-load condition (0–60 s), the difference between $I_{g,7}$ at the weak and stiff grids is quite small, whereas it is increased to 0.3 A at 20% load, and 0.8 A at full-load conditions. These tests reveal that $I_{g,7}$ can be significantly affected by the variation of $Z_{g,h}$. Thus, it is important to consider the impact of $Z_{g,h}$ on current harmonics. However, since $I_{g,h}$ can be affected by $Z_{g,h}$ in a nonlinear manner, considering $Z_{g,h}$ impact in the calculations is difficult.

3.3 Impact of multi-converter on predicting $I_{g,h}$

To investigate the effect of multi-converter condition, converter 2 was connected to the PCC in addition to converter 1. In these tests, $V_{g,h} = 0\%$ and $I_{g} = 0.2$ mH with converter 2 operating at no-load condition. The converter 1 load was also increased from no-load to full-load with 20% load increments. Then, $I_{g,11}$ was measured at multi-converter condition and is compared with $I_{g,11}$ at single-converter condition in Figure 6.

As can be seen in Figure 6, the value of measured $I_{g,11}$ at the first minute is only 0.1 A greater for the multi-converter case, whereas it is decreased and reaches to a minimum at the second minute by increasing converter 1 load to 20%. Although $I_{g,11}$ reaches to a minimum and then increases gradually at two-converter case, $I_{g,11}$ increases steadily from converter 1 no-load to full-load when only one converter is connected to the PCC. These results show the current harmonic cancellation effect, which makes the $I_{g,11}$ characteristic unpredictable and nonlinear.

3.4 Impact of voltage harmonics phase-angle

In distribution networks, the penetration of motor drives designed based on IEC 61000-3-12 is significant [33]. These motor drives are based on conventional three-phase diode rectifier front-end as shown in Figure 7. Therefore, this section investigates the impact of grid distortion on the current harmonic emission of this significant part of loads. As shown in Figure 7, the distorted grid is represented by voltage harmonics connected to the PCC. Thus, the input voltage at phase “a” under the presence of voltage harmonics can be as given in (4).

$$v_{an} = V_m \sin (\omega_0 t) + \sum_{b=2}^{\infty} V_h \sin (b\omega_0 t + \theta_h) \quad (4)$$

Where $V_m$ and $\omega_0$ are the peak magnitude and the angular frequency of the fundamental voltage, and $V_h$ and $\theta_h$ are the peak and phase-angle of the voltage harmonic order $b$. The
rectified voltage “\(v_{\text{rec}}\)” can then be calculated based on Fourier series as given in (5).

\[
v_{\text{rec}} = A_0 + \sum_{n = 1}^{\infty} \left( A_n \cos (6n\omega_0 t) + B_n \sin (6n\omega_0 t) \right)
\]

Where \(A_0, A_n, \) and \(B_n\) are Fourier coefficients. To calculate the impact of voltage harmonics on the input currents, the inductor current (\(i_L\)) needs to be calculated at first. The inductor current can be calculated by dividing the rectified voltage by the impedance (\(Z_n\)) seen from the rectifier output at each harmonic frequency. Thus, \(Z_n\) and \(i_L\) can be calculated as given in (6) and (7).

\[
Z_n = j6n\omega_0 L_{\text{dc}} + \frac{Z_{\text{inv,a}}}{1 + j6n\omega_0 C_{\text{dc}} Z_{\text{inv,a}}}
\]

\[
i_L = \frac{A_0}{[Z_0]} + \sum_{n = 1}^{\infty} \frac{A_n}{[Z_n]} \cos (6n\omega_0 t - \theta_{Z_n}) + B_n \sin (6n\omega_0 t - \theta_{Z_n})
\]

Where \(Z_{\text{inv,a}}\) is the inverter impedance, which can be determined as the power consumed by the inverter. The input current at phase “a” of the grid side (\(i_a\)) is a representation of the inductor current modulated by 120° conductivity in that phase. For that purpose, a switching function (“\(s_{da}\)” for the diode conductivity needs to be obtained as shown in Figure 8. The switching function of the diode rectifier at phase “a” can be calculated based on its Fourier series as given in (8). Then, the phase “a” input current can be obtained by multiplying the inductor current with the switching function as given in (9).

\[
s_{da} = \frac{4}{\pi} \sum_{k = 1,3,5...}^{\infty} \frac{\cos (k\pi/6)}{k} \sin (k\omega_0 t)
\]

\[
i_a = i_L \times s_{da}
\]

It should be highlighted that both phase-angle and magnitude of the voltage harmonic could impact the input current harmonics. However, the main current harmonics (5th and 7th) are slightly affected by the variation in the phase angle of the background voltage harmonics. The reason for this is that these current harmonics are mainly generated due to the rectifier switching function. In order to study the impact of the phase angle of background voltage harmonics on the current harmonics further, two different cases of grid voltage harmonics have been defined: case 1 with the presence of 2% of 5th, 7th, and 11th voltage harmonics all with 0° phase-angle, and case 2 with the same harmonics’ magnitudes but with a phase-angle of 30°. The current harmonics of phase “a” for cases 1 and 2 are compared in Table 1. As can be seen, the impact of voltage harmonics phase-angle on the current harmonics generated by power converter is not significant.

As described in these case studies, the interactions between \(V_{g,h}\) and \(I_{g,h}\) can be nonlinear, which makes the analysis difficult. These difficulties are elaborated in the next section.

### 4 | CONSIDERING NONLINEAR PARAMETERS AND IMPACTS ON THE CALCULATIONS

As explained in Sections 2 and 3, a distribution network is nonlinear when it is connected to a nonlinear load [6, 17, 34]. As a result, assuming the system as linear and using (1) cannot accurately estimate \(I_{g,h}\). However, approximating a nonlinear system as a linear system reduces the complexity of analysis as discussed below. In order to explain the difference between linear and nonlinear circuits, Figure 9 compares the relationships between voltage and current harmonics in a linear system with a nonlinear system. It can be seen in Figure 9(a) that any current harmonic is only related to the voltage harmonic with the same order in a linear system. By considering nonlinearities, however, a current harmonic can also be related to other voltage harmonics with different orders as shown in Figure 9(b) [27]. Therefore, in Figure 2, once \(V_{g,h}\) is relatively high or \(Z_{g,h}\) is nonlinear, \(I_{g,h}\) may be affected by any voltage harmonics. To calculate \(I_{g,h}\) in these conditions, conventional methods such as Superposition theorem cannot be used since they are valid for linear circuits. Consequently, to solve this problem, a prediction method based on least squares and kriging methods is proposed in the next sections.

### 5 | HARMONIC IDENTIFICATION AND MODELLING IN A DISTRIBUTION NETWORK

As described in the previous section, developing equations to predict current harmonics at the PCC becomes complicated if

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**TABLE 1** Phase “a” current harmonic of the motor drive under the presence of PCC voltage harmonics

| Case | \(I_{a,bd}\) (%) | \(I_{a,b7}\) (%) | \(I_{a,b11}\) (%) | \(I_{a,b13}\) (%) |
|------|----------------|----------------|----------------|----------------|
| 1    | 32.0           | 21.1           | 8.6            | 7.4            |
| 2    | 32.7           | 22.4           | 8.4            | 8.0            |
the nonlinearity of the distribution system is considered. Consequently, a predicting method valid in a network with linear and nonlinear conditions needs to be developed. To address this issue, CLSK method is proposed based on least squares and kriging methods in the following sections.

5.1 Least squares approach

Least Squares method is a standard method to estimate variables of a system by minimizing the square error of the system equations [35]. To estimate current harmonics using least squares method, the measured values of voltage are considered as given by (10).

\[
X_v T Y = \begin{bmatrix} V(t_1) & V(t_2) & \ldots & V(t_n) \end{bmatrix} \tag{10}
\]

Where \( t_n \) represents the time when \( n \)th data point is recorded. Also, \( V \) is defined as a set of voltage harmonics up to order \( k \) as given in (11).

\[
V = \{ V_{p,1}, V_{p,2}, \ldots, V_{p,h}, \ldots, V_{p,k} \} \tag{11}
\]

where \( k \) is equal to the greatest harmonic order of the measured voltage signal. On the other hand, the values of \( I_{g,h} \) at \( t_n \) are measured as given by (12).

\[
Y_I T I = \begin{bmatrix} I_{g,h}(t_1) & I_{g,h}(t_2) & \ldots & I_{g,h}(t_n) \end{bmatrix} \tag{12}
\]

Then, matrices \( Y_I \) and \( X_v \) are used for developing the prediction model as given by (13).

\[
Y_I = X_v \lambda + \epsilon \tag{13}
\]

where \( \epsilon \) is the error matrix, and matrix \( \lambda \) includes constant values that minimise \( \epsilon \). From (13), square error \( (\epsilon^2) \) can be found as given in (14).

\[
\epsilon^2 = (Y_I - X_v \lambda)^T \cdot (Y_I - X_v \lambda) \tag{14}
\]

After some manipulations, (14) can be simplified to (15).

\[
\epsilon^2 = Y_I^T Y_I - 2Y_I^T X_v \lambda + \lambda^T X_v^T X_v \lambda \tag{15}
\]

To minimize the square error, the derivative of (15) with respect to \( \lambda \) needs to be equal to zero as shown in (16).

\[
d \epsilon^2 / d \lambda = -2Y_I^T X_v \lambda + 2 \lambda^T X_v^T X_v \lambda = 0 \tag{16}
\]

Solving (10) results in a value of \( \lambda \) as given in (17).

\[
\lambda = \left( X_v^T X_v \right)^{-1} X_v^T Y_I \tag{17}
\]

By applying the value of \( \lambda \) from (17) in (13), \( I_{g,h} \) is predicted based on voltage harmonics \( V \). As explained in [35], Least Squares method may have some error in predicting
nonlinear systems; however, with some modifications such as using Weighted Least Squares [36], the error can be reduced. In this paper, kriging method is employed in addition to Least Squares method to increase the accuracy, which is explained as follows.

5.2 | Kriging method

Kriging method is a method of estimating variables of a system based on a set of sampled data points [21]. This method can be applied to model nonlinear interactions. Using the kriging method, a prediction model is created by measured voltage and current harmonics data points. This model is then used to predict current harmonics based on voltage harmonics data. In order to apply Kriging method, \( V_{ph} \) and \( I_{gh} \) are considered as input and output variables similar to Least Squares method. Next, current harmonics can be estimated as given in (18) [31].

\[
Y_j = X_j \lambda + G(V) \quad (18)
\]

Where \( \lambda \) and \( X_j \) are the same as (13). Function \( G \) can be also found based on Gaussian function and an optimisation as explained in [29, 32]. This optimisation controls the range of influence of input data, so a relatively smooth model is obtained in the end [29]. Consequently, \( X_j \lambda \) of (18) represents the linear regression of data, and \( G(V) \) is applied to modify the response surface of linear regression [29]. By applying this method, the equivalent circuit of Figure 1 is changed to the one shown in Figure 10.

In this analysis, the set of voltage harmonics in (10) is defined as the input variables. Since a number of voltage harmonics in (10) have small magnitudes, they can be neglected. In the next section, the procedure to modify the set of voltage harmonics in (10) is described.

6 | SELECTING PCC VOLTAGE HARMONICS AS THE MODEL INPUTS

As stated in the previous section, voltage harmonics with small magnitudes do not have much impact on the current harmonics. Also, these voltage harmonics can be significantly affected by background noises that may insert error in the calculations. Consequently, if voltage harmonics with small magnitudes are removed from (11), both time and accuracy of the calculation are expected to be improved. In order to modify (11), voltage harmonics based on 95 percentile values are considered for the estimation method. Moreover, the effective voltage harmonics are selected based on the correlation between voltage and current harmonics as explained in the following sections.

6.1 | 95 percentile values

In distribution systems, unless there is a significant source of voltage harmonics in high frequencies, voltage harmonics with orders greater than 13 typically have small magnitudes. Also, some voltage harmonics such as even order voltage harmonics under 13th have small magnitudes and can be ignored from the analysis. To select the most significant voltage harmonics, Percentile 95 index, which indicates the value of \( V_{ph} \) that is greater than 95% of \( V_{ph} \) measured values, is applied as given by (19) [37].

\[
\text{Percentile } 95, (V_{ph}) > C, h = 1, 2, \ldots, k \quad (19)
\]

where the threshold level \( C \) is defined as a percentage of fundamental voltage (for instance, 1%). The value of \( C \) may need to be modified based on the grid conditions considering the levels of both noise sources and voltage harmonics. Consequently, by applying (19), a group of \( V_{ph} \) with percentile 95 greater than \( C \) are selected for the data set (10).

6.2 | Correlation between voltage and current harmonics

In three-phase converters, triplen voltage harmonics are automatically removed based on the electrical circuit. Thus, triplen voltage harmonics, such as \( V_{p3}, V_{p6}, \) and \( V_{p9} \), can be removed from the set \( V \) in (11) to reduce the amount of data. After removing a number of voltage harmonics based on the percentile 95 and converter electrical circuit, the voltage harmonics with the highest impact on current harmonics are selected here. For that purpose, the correlation analysis, which is explained in [38], is performed between \( V_{ph} \) and \( I_{gh} \). Predicting variable \( V_{ph} \) is then selected as a voltage harmonic that has significant correlation with \( I_{gh} \). Another predicting variable \( V_{pn} \) is also selected as a voltage harmonic with the same order as \( I_{gh} \).

By finding an efficient set of inputs, least squares and kriging methods can be applied to predict \( I_{gh} \) using the measured data. The process of applying these methods for \( I_{gh} \) prediction is explained in the next section.

7 | PREDICTION OF CURRENT HARMONICS BASED ON THE PROPOSED CLSK METHOD

In the previous sections, least squares and kriging methods were introduced for predicting current harmonics in linear and nonlinear conditions. Also, indices to find an efficient set of inputs for the prediction model of current harmonics were explained. In this section, the process of applying those methods to predict...
FIGURE 11  The process of applying CLSK method in order to model the current harmonics of converters

\[ r_h = \frac{\text{cov}(I_{g,h}, V_{g,h})}{\sigma_{I_{g,h}} \sigma_{V_{g,h}}} \]  

(20)

where \( \text{cov}(I_{g,h}, V_{p,h}) \) is the covariance between \( I_{g,h} \) and \( V_{p,h} \). Also, \( \sigma_{I_{g,h}} \) and \( \sigma_{V_{p,h}} \) are standard deviations of \( I_{g,h} \) and \( V_{p,h} \), respectively. When the value of \( r_h \) is 1, there is a linear relationship between \( I_{g,h} \) and \( V_{p,h} \). Otherwise, the relationship is nonlinear. In order to clarify the CLSK method, the process of applying this method is illustrated in Figure 11. This figure shows that after reducing the voltage harmonics, \( r_h \) is calculated based on sampled data points for \( I_{g,h} \) and \( V_{p,h} \). If \( r_h \) is almost equal to 1, least squares method can be employed. Otherwise, the kriging method is applied. In the next section, the field test data of linear and nonlinear cases are used to validate the prediction method.

8 | COMPARING PREDICTED CURRENT HARMONICS WITH EXPERIMENTAL RESULTS

In this section, the proposed prediction method is examined under several conditions similar to real scenarios. To examine the CLSK method, the lab setup shown in Figure 3 was set at passive and active conditions. In the passive condition, the grid voltage total harmonic distortion (THD) was set at 0% as shown in Table 2, whereas the grid voltage THD was increased from 1% to 12% according to Table 2 in active condition. Also, weak and stiff grid conditions were modelled by \( L_g = 1.2 \) mH and \( L_g = 0.2 \) mH using different combinations of series inductors as explained in Section 3. In the next step, the measured current and voltage harmonics at the above-mentioned grid conditions were applied to develop a prediction model for current harmonics in multi-converter condition. It is worth mentioning that the above-mentioned network conditions and the THD levels were set in laboratory to examine the predicting method. However, the concept of this paper analysis and the predicting method can be used to predict current harmonics at other network conditions in real scenarios. In this study, sensitivity analysis software optiSLang is employed for calculating correlations and modelling [39]. Also, modelling and prediction of current harmonic \( I_{g,7} \) at weak grid condition are investigated here. However, these investigations and the concept can be applied to model other current harmonic orders at different grid conditions.

Predicting \( I_{g,7} \) in multi-converter condition could be more complicated than single-converter condition, as the current harmonics of converters can cancel each other out. In order to verify the proposed prediction method in this condition, both converters 1 and 2 were connected to the setup. Then, the voltage and current harmonics at the PCC were measured at different levels of THD according to Table 2. Afterwards, based on these measured voltage and current harmonics, predicting \( I_{g,h} \) at both \( V_{g,h} = 0% \) and \( V_{g,h} \neq 0% \) is investigated in the following sections.

| THD (%) | \( V_{g,5} \) (%) | \( V_{g,7} \) (%) | \( V_{g,11} \) (%) | \( V_{g,13} \) (%) |
|---------|-----------------|-----------------|-----------------|-----------------|
| 0       | 0               | 0               | 0               | 0               |
| 1       | 1               | 0               | 1               | 0               |
| 2       | 1               | 1               | 1               | 1               |
| 4       | 2               | 2               | 2               | 2               |
| 6       | 3               | 3               | 3               | 3               |
| 8       | 4               | 4               | 4               | 4               |
| 12      | 6               | 6               | 6               | 6               |
8.1 Predicting $I_{g,h}$ in distribution networks without $V_{g,h}$ (a passive grid)

To analyse the relationship between $I_{g,h}$ and $V_{g,h}$ at multi-converter condition in a passive grid, the measured $I_{g,h}$ and $V_{g,h}$ at THD = 0% are shown in Figure 12. As it can be seen in this figure, the relationship between $V_{p,h}$ and $I_{g,h}$ is linear since $V_{p,h}$ versus $I_{g,h}$ can be approximated by a line with constant slope. To verify the linear relationship between $V_{p,h}$ and $I_{g,h}$, $r_7$ is also calculated 0.99, which indicates that $I_{g,h}$ is affected by $V_{p,h}$ in a linear manner. As a result, $I_{g,h}$ can be predicted based on (13) since interactions between $V_{p,h}$ and $I_{g,h}$ can be approximated by a line according to Figure 9.

As explained in Section 3, a network parameter that can make network nonlinear is $V_{g,h}$. Therefore, the effect of $V_{g,h}$ on predicting $I_{g,h}$ at the multi-converter condition is investigated in the following section.

8.2 Predicting $I_{g,h}$ in distribution networks with $V_{g,h}$ (an active grid)

Predicting $I_{g,h}$ in an active grid with multiple converters connected to the PCC needs to be investigated using experimental results. To investigate predicting $I_{g,h}$ in an active grid at multi-converter condition, the measured values of $V_{p,h}$ and $I_{g,h}$ at THDs from 1% to 12% of Table 2 are shown in Figure 13. As this figure shows, $I_{g,h}$ is nonlinearly affected by $V_{p,h}$ since the relationship between measured $V_{p,h}$ and $I_{g,h}$ cannot be modelled by a line and $r_7 = 0.5$. As a result, the proposed kriging method needs to be applied to predict $I_{g,h}$ based on CLSK method in Figure 11. Therefore, $V_{p,1}$ and $V_{p,7}$ are selected as prediction variables after applying the reduction indices. Next, the values of these variables and $I_{g,h}$ at the THD states of Table 2 are used to develop the prediction model of $I_{g,h}$ in Figure 14. This figure shows that the prediction model accurately predicts the measured data points, which are represented by black spheres.

The measured and predicted values of $I_{g,h}$ at grid voltage THD = 12% are compared in Table 3 at four randomly selected points. Besides, the predicted values of $I_{g,h}$, which are estimated by both methods presented in [7] and [28] at this condition, are provided in Table 3. In [7], which presents a conventional method, the load current harmonics have been modelled using independent current sources. In [28], the background voltage harmonics have been considered for estimating the current harmonics. Besides, the estimation model has been developed using the regression of measured current and voltage harmonics.

As can be seen in Table 3, the maximum prediction error of the proposed model at grid voltage with a 12% THD is 2.1%. This error is 2.5% less than the maximum error of [28], and it is 34% less than the maximum prediction error of method in [7]. The reason for the relatively high error of the conventional method in [7] compared with the proposed CLSK method and the method in [28] is that the effect of $V_{g,h}$ has not been considered. Additionally, the interactions between background voltage harmonics and the current harmonics have not been accurately modelled in [28], so the error of this method increases to 4.6%.

The measured current and voltage harmonics at grid voltage THD = 10% ($V_{g,5}$, $V_{g,7}$, $V_{g,11}$, and $V_{g,13}$ = 5%) were not considered in the prediction model of Figure 14. Consequently, to examine the model accuracy in a new THD level, the predicted $I_{g,h}$ is compared to its measured values at grid voltage THD = 10% in Table 4. Additionally, the accuracy of proposed CLSK method is compared with the method presented in [7] and [28] in this Table. This table reveals that the error of CLSK method in a new THD condition is calculated between
TABLE 3 Comparing the accuracy of the proposed CLSK method with [7] and [28] at THD = 12% as a considered THD level at the multi-converter condition

| Measured $I_{g,7}$ (A) | Proposed CLSK method | Method in [7] | Method in [28] |
|------------------------|----------------------|---------------|---------------|
|                        | Predicted $I_{g,7}$ (A) | Error (%)     | Predicted $I_{g,7}$ (A) | Error (%)     | Predicted $I_{g,7}$ (A) | Error (%)     |
| 0.89                   | 0.88                 | 0.8           | 1.21          | 35.9         | 0.89                 | 0.06          |
| 0.90                   | 0.90                 | 0.2           | 1.23          | 36.6         | 0.93                 | 3.6           |
| 0.91                   | 0.89                 | 2.1           | 1.18          | 30.3         | 0.92                 | 1.23          |
| 0.91                   | 0.90                 | 1.6           | 1.18          | 29.2         | 0.95                 | 4.60          |

TABLE 4 Comparing the accuracy of the proposed CLSK method with [7] and [28] at THD = 10% as a new THD level at the multi-converter condition

| Measured $I_{g,7}$ (A) | Proposed CLSK method | Method in [7] | Method in [28] |
|------------------------|----------------------|---------------|---------------|
|                        | Predicted $I_{g,7}$ (A) | Error (%)     | Predicted $I_{g,7}$ (A) | Error (%)     | Predicted $I_{g,7}$ (A) | Error (%)     |
| 0.76                   | 0.82                 | 8.8           | 0.84          | 9.9          | 1.28                 | 68            |
| 0.77                   | 0.82                 | 7.5           | 0.85          | 10.4         | 1.34                 | 74            |
| 0.95                   | 0.67                 | 29.6          | 1.25          | 30.6         | 1.42                 | 49            |
| 0.96                   | 0.69                 | 26.9          | 1.24          | 30.4         | 1.43                 | 49            |

7.5% and 30% at four randomly selected points. According to Table 4, although the prediction error of the proposed method is increased at a new THD condition, it is still less than [7]. This is because the impact of the grid parameters on the current harmonics is considered in the CLSK method. It must be noted that the error of the method in [28] increases significantly under new background voltage harmonics conditions. The reason for this is that the effect of background voltage harmonics on the current harmonics has not been modelled accurately. Thus, the model does not work when background voltage harmonic has not been considered in the training process. This reveals the advantage of CLSK method for estimating current harmonics, where it models the nonlinear interactions between voltage and current harmonics.

The above-mentioned studies prove that current harmonics at the PCC can be estimated by applying the CLSK method in multi-converter condition. The main advantages of the CLSK method compared to the existing methods for current harmonic estimation can be elaborated as follows:

- Considering the nonlinear impact of background voltage harmonics and other grid parameters to estimate the current harmonics generated by multi converters. In order to consider the effect of background voltage harmonics, laboratory tests were performed. Then, the experimental results were analysed by calculating correlation coefficients between voltage and current harmonics at different conditions.
- Modelling the current harmonics using a set of two voltage harmonics as predicting variables. In order to select these two voltage harmonics, a reduction method based on correlation analysis is proposed. By reducing the voltage harmonics, modelling calculations are decreased and the accuracy of the prediction model is improved.
- Predicting $I_{g,h}$ at passive and active grids in multi-converter condition. The error of CLSK method is always lower than 2.1% at the multi-converter condition. As a result, the current harmonics of converters at the PCC can be accurately estimated using CLSK method. These estimated current harmonics can be then employed in different power quality analysis applications.

9 | CONCLUSION

In this paper, the current harmonics of a distribution network with power electronic loads are investigated at different network conditions. CLSK method is then proposed to predict current harmonics at the PCC. Consequently, equivalent circuits and experimental results are used to investigate the impact of different parameters, such as grid impedance, on distribution network current harmonics. These investigations reveal that at some network conditions, such as when grid background voltage harmonic is relatively high, network can be nonlinear. As a result, CLSK method is developed, which employs least squares and kriging methods to predict current harmonics at PCC. One advantage of this method is that it can be applied to predict current harmonics at both linear and nonlinear conditions of the grid. Moreover, CLSK method only needs measured current and voltage harmonics at the PCC for the current harmonic prediction. In this method, effective voltage harmonics are employed as inputs of model to estimate the current harmonics instead of all the voltage harmonics. To test the performance of the proposed method, laboratory tests are performed at the active and passive grid conditions when single or multi-converter are connected to PCC. These experimental results then are employed to examine the performance of the predicting method. These investigations prove that the predicting method is more accurate than the existing methods, which neglect the impact of grid parameters on the current harmonics.
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REFERENCES

1. Yaghoobi, J., et al.: Analysis of High Frequency Harmonics in Distribution Networks: 9–150 kHz. In: 2019 IEEE International Conference on Industrial Technology, pp. 1229–1234. IEEE, Piscataway, NJ (2019)

2. Molina, J., et al.: LED lamp modelling for harmonic studies in distribution systems. Transmission Distribution IET Generation 11(4), 1063–1071 (2017)

3. Zare, F., et al.: Harmonic emissions of three-phase diode rectifiers in distribution networks. IEEE Access 5, 2819–2833 (2017)

4. Yaghoobi, J., et al.: Power quality issues of distorted and weak distribution networks in mining industry: A review. IEEE Access 7, 162500–162518 (2019)

5. Aldurabbi, A., et al.: A new technology to reduce harmonic emission in distribution networks: Addressing IEC 61000-3-12. In: 2018 Australasian Universities Power Engineering Conference, pp. 1–6. IEEE, Piscataway, NJ (2018)

6. Mazumdar, J., et al.: Neural network based method for predicting nonlinear load harmonics. IEEE Trans. Power Electron. 22(3), 1036–1045 (2007)

7. Esparza, M., et al.: A comprehensive design approach of power electronic-based distributed generation units focused on power-quality improvement. IEEE Trans. Power Delivery 32(2), 942–950 (2017)

8. Aldurabbi, A., et al.: Harmonic mitigation technique using active three-phase converters utilised in commercial or industrial distribution networks. IET Power Electron. 13, 2794-2803, (2020)

9. Wang, X., et al.: Full feedforward of grid voltage for grid-connected inverter with LCL filter to suppress current distortion due to grid voltage harmonics. IEEE Trans. Power Electron. 25(12), 3119–3127 (2010)

10. Mansoor, A., et al.: Predicting the net harmonic currents produced by large numbers of distributed single-phase computer loads. IEEE Trans. Power Delivery 10(4), 2001–2006 (1995)

11. Infield, D.G.: Combined switching harmonics from multiple grid-connected single-phase inverters. Transmission and Distribution IEEE Proceedings - Generation 148(5), 427–430 (2001)

12. Kumar, D., Zare, F.: Harmonic analysis of grid connected power electronic systems in low voltage distribution networks. IEEE Journal of Emerging and Selected Topics in Power Electronics 4(1), 70–79 (2016)

13. Kumar, D., Zare, F.: A comprehensive review of microwave microgrids: System architectures, energy efficiency, power quality, and regulations. IEEE Access 7, 67249–67277 (2019)

14. Li, H., Zhao, J., Yang, X.: Mathematical model of grid-connected inverter system in weak grid. Electron. Lett. 51(23), 1922–1924 (2015)

15. Yaghoobi, J., Aldurabbi, A., Zare, F.: Current harmonic estimation techniques based on voltage measurements in distribution networks. In: 2018 Australasian Universities Power Engineering Conference, pp. 1–6. IEEE, Piscataway, NJ (2018)

16. Miegeville, L., Guerin, P.: Identification of the time-varying pattern of periodic harmonics. IEEE Trans. Power Delivery 21(2), 845–851 (2006)

17. Mazumdar, J., Harley, R.G.: Utilization of echo state networks for differentiating source and nonlinear load harmonics in the utility network. IEEE Trans. Power Electron. 23(6), 2738–2745 (2008)

18. Beltran-Carabajal, F., Tapia-Olvera, R.: An adaptive neural online estimation approach of harmonic components. Electr. Power Syst. Res. 186, 106406 (2020)

19. Rahmani, A., Dehimi, A.: Reduction of harmonic monitors and estimation of voltage harmonics in distribution networks using wavelet analysis and NARX. Electr. Power Syst. Res. 178, 106406 (2020)

20. Molina-Moreno, I., et al.: Enhanced harmonic state estimation in unbalanced three-phase electrical grids based on the Kalman filter and physical scale-down implementation. International Journal of Electrical Power & Energy Syst. 123, 106243 (2020)

21. Chen, D., Xiao, L.: A novel fundamental and harmonics detection method based on state-space model for power electronics systems. IEEE Access 8, 170002–170012 (2020)

22. Labrador Rivas, A.E., da Silva, N., Abrão, T.: Adaptive current harmonic estimation under fault conditions for smart grid systems. Electr. Power Syst. Res. 183, 106276 (2020)

23. Kashif, M., et al.: A fast time-domain current harmonic extraction algorithm for power quality improvement using three-phase active power filter. IEEE Access 8, 103539–103549 (2020)

24. Laniuch, M., et al.: Nonlinear loads model for harmonics flow prediction, using multivariate regression. IEEE Trans. Ind. Electron. 64(6), 4820–4827 (2017)

25. Morti, H., et al.: An artificial neural-net based method for predicting power system voltage harmonics. IEEE Trans. Power Delivery 7(1), 402–409 (1992)

26. Klatt, M., et al.: Generic frequency-domain model for the emission of PWM-based power converters in the frequency range from 2 to 150 kHz. Transmission Distribution IET Generation 13(24), 5478–5486 (2019)

27. Baylis, C., Marks, R.J.: Small perturbation harmonic coupling in nonlinear periodicity preservation circuits. IEEE Trans. Circuits Syst. I Regul. Pap. 59(12), 3034–3045 (2012)

28. Severoglu, N., Salor, O.: Amplitude and phase estimations of power system harmonics using deep learning framework. Transmission Distribution IET Generation 14(19), 4089–4096 (2020)

29. Martin, J.D., Simpson, T.W.: Use of kriging models to approximate deterministic computer models. AIAA J. 43(4), 853–863 (2005)

30. Vignes, M., et al.: Fast and accurate approximation to kriging using common data neighborhoods. Math. Geosci. 49(5), 619–634 (2017)

31. Kleijn, J.P.C.: Kriging metamodeling in simulation: A review. Eur. J. Oper. Res. 192(3), 707–716 (2009)

32. Xia, B., Ren, Z., Koh, C.-S.: Utilizing kriging surrogate models for multi-objective robust optimization of electromagnetic devices. IEEE Trans. Magn. 50(2), 693–696 (2014)

33. IEC 61000–3-12, Electromagnetic compatibility (EMC). Part 3–12: Limits – Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current≯16 A and ≤75 A per phase (2011) https://webstore.iec.ch/publication/4144. Access 1 June 2020

34. Chen, C.-I., Chen, Y.-C.: A neural-network-based data-driven nonlinear model on time- and frequency-domain voltage–current characterization for power-quality study. IEEE Trans. Power Delivery 30(3), 1577–1584 (2015)

35. Molagaram, K., Rao, G.S.: Chapter 12 - Analysis of time series. In: Molagaram, K., Rao, G.S., (eds) Statistical Techniques for Transportation Engineering, pp. 463–489, Butterworth-Heinemann, Oxford (2017)

36. Yoshikawa, G., et al.: Meshless method based on weighted least square minimistic computer models. AIAA J. 43(4), 853–863 (2005)

37. Upton, G., Cook, I.: Percentile, In: A Dictionary of Statistics. Oxford University Press, Oxford (2014)

38. Bewick, V., Cheek, L., Ball, J.: Statistics review 7: Correlation and regression. Crit. Care 7(6), 451–459 (2003)

39. optiSLang, https://www.dynardo.de/en/software/optislang.html, Accessed 5 March 2020

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