



Improvement of Power Quality Index in Distributed Power System Networks

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Abstract:

This project proposed the new distortion power quality index to replace the previously proposed index. Its computation was carried out based on the load composition rate (LCR) and Euclidean norm of total harmonic distortions (THDs) of the measured voltage and current waveforms at the point of common coupling (PCC). Based on the proposed PQI, the harmonic pollution ranking, which indicates how much negative effect each nonlinear load has on the point of common coupling (PCC) with respect to distortion power, is determined. Time-domain simulations are carried out to prove the effectiveness of the proposed PQI under the other conditions with different nonlinear loads.

Keywords—Distortion power; distribution power system; Euclidean norm; harmonic pollution ranking; power quality index; reduced multivariate polynomial (RMP) model

I. INTRODUCTION

The power quality (PQ) in modern power systems has become a significant issue for both power suppliers and consumers. The proper PQ solutions will be necessary at each physical location where ownership is transferred. Therefore, it is important to develop the appropriate power quality index (PQI) as well as identify the sources and disturbances deteriorating the PQ. This project deals with the Euclidean norm based new power quality index (PQI), which is directly related to the distortion power generated from nonlinear loads, to apply for a practical distribution power network by improving the performance of the previous PQI. The proposed PQI is formed as a combination of two factors, which are the electrical load composition rate (LCR) and the Euclidean norm

of total harmonic distortions (THDs) in measured voltage and current waveforms.

To overcome Power quality problem and achieve its reliable and consistent performance without regard to any given conditions, this project proposes the new distortion power quality index consisting of the electrical load composition rate (LCR) estimated by the reduced multivariate polynomial (RMP) model and the Euclidean norm of THDs of the measured voltage and current waveforms. The proposed provides the relative harmonic pollution ranking (HPR) of each nonlinear load in the existence of distorted voltage at PCC. The HPR can be practically used as an important factor that determines how much effect each load has on the PCC with the relative ranking for distortion power generation. Moreover, the only uses the load currents and the voltage at the PCC from instrument readings without calculating apparent, fundamental active power and fundamental reactive power directly. This paper is organized as follows: Chapter 2 covers the proposed power quality index method. Chapter 3 describes analysis of distortion power to validate the proposed DPQI^{new}. Chapter 4 covers the implementation of the DPQI^{new}. Chapter 5 describes the simulation results for the proposed system. Final section covers the conclusion.

II. NEW DISTORTION POWER QUALITY INDEX

Fig.1 shows a typical distribution power network with the DG.

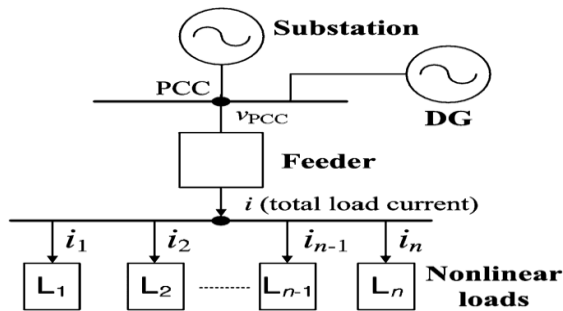


Fig. 1. One-line diagram of a typical distribution power network with the DG.

The injected currents flowing to each load has undesired harmonic components when the nonlinear loads are supplied from a sinusoidal voltage in a substation. They cause harmonic voltage drops through a feeder in supply network and therefore distort the voltage at the PCC. Also, the inverter based grid-connected DG can generate the distorted voltage with the THD less than of 5%. Moreover, by the distorted PCC voltage all linear loads connected to the PCC will have harmonic currents injected into them under this circumstance. Such currents can be referred to as harmonic sources generating distortion power in a power system. Then, the effect of each load relevant to distortion power must be evaluated by the appropriate index or function in an effective manner. As mention before, the DPQI providing the relative HPR of each load has been proposed, where the following three factors need to be considered.

- The relative quantity of the injected currents flowing from the PCC to each nonlinear load,
- The degree of distortion in the current waveforms with high-frequency harmonic components, and the degree of distortion in the voltage waveforms at the PCC with high-frequency harmonic components.

The first factor can be estimated by the LCR of each nonlinear load based on the RMP model. The second and third factors can be obtained by the THDs of the load currents ($i_1, \dots, i_n$) and PCC voltage (V_{pcc}) in Fig. 1, respectively. The DPQI, which is denoted as the $DPQI^{old}$ for the remainder of this project to compare with the proposed DPQI, has been obtained by the inner product of the LCR and the THD of the load current as given in (1).

$$DPQI^{old}(n) = LCR(i_n) \cdot THD(i_n) \quad (1)$$

where n is the load number. And, i_n and $i_n^{\hat{}}$ are the measured and estimated load currents, respectively. That is, the $THD(i_n^{\hat{}})$ in (1) is calculated with the estimated load currents instead of using the measured currents directly under the assumption that a pure sinusoidal voltage is supplied to the PCC. In other words, the third factor seems ignored in (1). As mentioned before, the PCC voltage is mostly distorted in practice due to the harmonics generated from nonlinear loads and the inverter based DGs if they are connected to the grid. To handle this problem, two different procedures were implemented in for the nonlinear load harmonic estimation. One is the training step to predict the optimal admittance weights of the RMP model in the existence of distorted supply voltage at the PCC. The other is the testing step to estimate the load current in (1) with the obtained admittance weights when a pure sinusoidal voltage is applied.

Even though the RMP model has the one-shot training property, which is the more powerful advantage over other neural networks (NNs). Moreover, the $DPQI^{old}$ in (1) cannot be used in practice if the admittance weights of the RMP model are tested in a completely different condition at which it was not sufficiently trained, because it might lose its robustness and reliability. For example, such case may happen when the nonlinear load currents are severely distorted with a high THD by their high-frequency harmonics or when there are phase differences between the load currents and the PCC voltage (therefore, depending on applications they have different power factors).

To overcome the above disadvantage of the, the $DPQI^{old}$ is proposed as given in (2).

$$DPQI^{new}(n) = LCR(i_n) \cdot \sqrt{THD(V_{pcc})^2 + THD(i_n)^2} \quad (2)$$

Basically, the $DPQI^{new}$ is composed of two parts as given in (2). The first part, LCR is the same as that of the $DPQI^{old}$ in (1). The second part represents the distortion of corresponding loads as the form of Euclidean norm of THDs computed from the measured voltage and current waveforms. That is, the Euclidean

norm of THDs is formulated as a kind of vector magnitude with the two THDs when they are assumed to have orthogonal characteristics. Even though it is difficult to describe its exact physical meaning, the Euclidean norm of THDs can be considered as the quantity of mixed distortion reflecting nonlinearity between the measured voltage and currents. Also, the direct use of measured waveforms to calculate their THDs avoids taking the second testing step, which was required for the load current estimation in (1) for the DPQI^{old}. Therefore, the DPQI^{new} can reduce the computational efforts dramatically when compared to the DPQI^{old}.

Moreover, the can provide the relative HPR for each nonlinear load with the powerful robustness under any conditions, where they cannot achieve its desirable performance, since it considers the effect of the distorted voltage at the PCC itself. More detailed explanations about how to implements they are given in the following sections with the theoretical analysis based on the simulation and experimental verifications.

III ANALYSIS OF DISTORTION POWER TO VALIDATE THE PROPOSED DPQI^{NEW}

A. Distortion Power

To validate the proposed DPQI^{new}, the theoretical analysis for distortion power is required based on the mathematical derivation. The fundamental active power (P_1), apparent power (S_a), distortion power (D) and fundamental reactive power (Q_1), for the each load are computed as given in (3). Therefore, it is reasonably acceptable that the dominant components, (Q_1) and (P_1) are used to represent the reactive and active powers, respectively, as proposed in this project. Then, all harmonic powers are considered in distortion terms

$$\begin{aligned} S_a &= \sqrt{\frac{1}{M} \sum_{m=0}^{M-1} v(m)^2} \cdot \sqrt{\frac{1}{M} \sum_{m=0}^{M-1} i(m)^2} \\ P_1 &= V_1 \cdot I_1 \cdot \cos(\theta_1 - \varphi_1) \\ Q_1 &= V_1 \cdot I_1 \cdot \sin(\theta_1 - \varphi_1) \\ D &= \sqrt{S_a^2 - P_1^2 - Q_1^2} \end{aligned} \quad (3)$$

Where M is the number of samples obtained during one period T. And, the subscript, 1 of voltage and current denotes the fundamental component. Again,

the (S_a) can be rewritten as given in (4) by assuming that inter-harmonics are negligible.

$$S_a = \sqrt{V_{DC}^2 + \sum_{k=1}^{N-1} V_k^2} \cdot \sqrt{I_{DC}^2 + \sum_{k=1}^{N-1} I_k^2} \quad (4)$$

Where N is the maximum number of harmonics from obtained samples during one period T. And, the subscript k of voltage and current denotes the order of high-frequency harmonics.

Assume that the dc components of voltage and current are zero. Then, with the THD defined as (5), the (S_a) and D in (4) and (3) can be approximated as (6) and (7), respectively. This transformation is reasonably acceptable in a practical power system because the dc component of voltage and current are mostly close to zero in practice even when there exists some distortion in their waveforms. Moreover, in the case of dc injection into connection point by the DG in Fig. 1, it is limited to within 0.5% of its full rated output according to the IEEE standard 1547. Therefore, it can be negligible. From (6) to (7), it is observed that the distortion power, D is related to the THDs of voltage and current fundamental components.

$$THD_V = \sqrt{\frac{\sum_{k=2}^{N-1} V_k^2}{V_1^2}}, \quad THD_I = \sqrt{\frac{\sum_{k=2}^{N-1} I_k^2}{I_1^2}} \quad (5)$$

$$S_a \approx V_1 \cdot I_1 \sqrt{(1 + THD_V^2) \cdot (1 + THD_I^2)} \quad (6)$$

$$D \approx V_1 \cdot I_1 \sqrt{THD_V^2 + THD_I^2 + (THD_V \cdot THD_I)^2} \quad (7)$$

With the detailed analysis for the following section, the proposed DPQI^{new} is proved to be valid for providing the information with respect to distortion power without its direct measurement, therefore determining the relative HPR of nonlinear loads.

B. Parseval's Theorem on THD Calculation

The Parseval's theorem states that the average power in a periodic signal equals the sum of the average powers in all of its harmonic components. And, its mathematical description is given in (8).

$$P_x = \frac{1}{M} \sum_{m=0}^{M-1} f(m)^2 = \sum_{k=0}^{N-1} F_k^2 \quad (8)$$

With the relation of (8), the THDs of voltage and current in (5) can be represented as given in (9).

$$\begin{aligned} \text{THD}_V &= \sqrt{\frac{\frac{1}{M} \sum_{m=0}^{M-1} v(m)^2 - V_{DC}^2 - V_1^2}{V_1^2}} \\ \text{THD}_I &= \sqrt{\frac{\frac{1}{M} \sum_{m=0}^{M-1} i(m)^2 - I_{DC}^2 - I_1^2}{I_1^2}} \end{aligned} \quad (9)$$

When there are no inter-harmonics, the values of THD in (5) and (9) become same. In this paper, the proposed is DPQI^{new} developed to measure the power quality in a stationary condition representing all loads in a steady-state condition, where the effect of inter-harmonics is trivial.

Then, it is required to describe the application of (9) in exceptional situation, where inter-harmonics from unexpected disturbances exist. Actually, the use of THD defined as (9) to implement the D and DPQI^{new} is more preferable to that defined as (5) since it can reflect the effect of all inter-harmonics into the signal power, which is calculated in implementation procedure. On the other hand, the definition of THD as given in (5) cannot consider inter-harmonics. Therefore, the losses in calculation caused by domain change are ignored. For this reason, the equation (9) can help the proposed index to measure the exact level of power quality in practice.

IV. IMPLEMENTATION OF THE DPQI^{new}

A. Derivation of the DPQI^{new} and LCR Estimation

The DPQI^{new} in (2) is now derived from D in (7). Firstly, the term, $(\text{THD}_V, \text{THD}_I)^2$ in right-hand side of (7) can be ignored because its value is much smaller than the value of $(\text{THD}_V^2 + \text{THD}_I^2)$. Their rate is defined as the square of multiplication ratio (SMR) in (10).

$$\text{SMR} = \frac{\text{THD}_V^2 \cdot \text{THD}_I^2}{\text{THD}_V^2 + \text{THD}_I^2} < 0.0025 \quad (10)$$

Then, the distortion power D, for the individual nonlinear n load, in Fig. 1 is approximated as follows. Note that $V_{1,\text{PCC}}$ and $I_1(n)$ in (11) are fundamental

components of each PCC voltage V_{PCC} and load current I_n , respectively.

$$D(n) \approx V_{1,\text{PCC}} \cdot I_1(n) \sqrt{\text{THD}(v_{\text{PCC}})^2 + \text{THD}(i_n)^2} \quad (11)$$

The approximated distortion power in (11) has the same form of Euclidean norm of THDs as the DPQI^{new} . Thereafter, the analysis of the relation between $V_{1,\text{PCC}}$, $I_1(n)$ in (11) and $\text{LCR}(i_n)$ gives the final solution to derive DPQI^{new} from D. First of all, every load has the same fundamental component of V_{PCC} , as shown in Fig. 2.1. Therefore, it can be treated as a constant for all loads in the distribution power system.

For formulation of the LCR estimation, the relation between the total electric current $i(t)$, and the load currents $i_1, i_2, \dots, i_n$, is modelled as (12) with their normalized values, which are denoted by the superscript, norm. The normalization is achieved by making each fundamental component of measured currents to be unity in its magnitude.

$$i^{\text{norm}}(t) = k_1 i_1^{\text{norm}}(t) + k_2 i_2^{\text{norm}}(t) + \dots + k_n i_n^{\text{norm}}(t) \quad (12)$$

Where k_1 , k_2 , and k_n are the unknown coefficients, without any calculation of powers, they provide the actual rate of the composition of each load current with respect to total current. Also, without regard to measurement scales used with different current Transformer (CT) ratios the estimation scheme through the normalization is always valid. This LCR can give a standard for current injection limits from each load with the benefit of being an effective evaluation tool for the effects of individual load types. Each load current $i_n(t)$, is formed by the superposition of all harmonic components including its fundamental, which is higher than the other harmonic components. Then, the LCR is proportional to the rate of its fundamental components; therefore, $V_{1,\text{PCC}}$, $I_1(n)$ and $\text{LCR}(i_n)$ also have the proportional relationship. Finally, the relative HPR provided by the DPQI^{new} represents the original ranking for the associated of nonlinear loads.

To estimate the LCR the RMP model is applied. This optimization technique is a kind of training algorithm to search the weight parameters for the nonlinear input/output mapping such as NN. The

main advantage of the RMP model over NNs is that it has the on e-shot training property.

the relative HPR provided by the $DPQI^{new}$ represents the original ranking for the associated of nonlinear loads.

In other words, it does NOT require iteration procedures during the process to find a solution weight vector. The brief descriptions for the RMP model are summarized in below.

B. Reduced Multivariate Polynomial Model

The general multivariate polynomial (MP) model can be expressed as:

$$g(\alpha, \mathbf{x}) = \sum_i^K \alpha_i x_1^{n_{i1}} x_2^{n_{i2}} \cdots x_l^{n_{il}} \quad (13)$$

where the summation is taken over all nonnegative integers $n_1, n_2, \dots, n_l$ for which $n_1 + n_2 + \dots + n_l \leq r$ with r being the order of approximation. $\mathbf{x}$ denotes the regressor vector as $[x_1, \dots, x_l]^T$ containing inputs and the vector $\alpha = [\alpha_1, \dots, \alpha_K]$ is the parameter vector to be estimated. K is the total number of terms in $g(\alpha, \mathbf{x})$.

The general MP model in (13) can be replaced with (14) by using the parameter vector, α and the function $\mathbf{p}(\mathbf{x})$, which is composed of variables of the regressor vector.

$$g(\alpha, \mathbf{x}) = \alpha^T \mathbf{p}(\mathbf{x}) \quad (14)$$

Given m data points with $m > K$ and using the least-squares error minimization error objective given by

$$\begin{aligned} s(\alpha, \mathbf{x}) &= \sum_{i=1}^m [y_i - g(\alpha, \mathbf{x})]^2 + b \|\alpha\|_2^2 \\ &= [\mathbf{y} - \mathbf{P}\alpha]^T [\mathbf{y} - \mathbf{P}\alpha] + b\alpha^T \alpha \end{aligned} \quad (15)$$

where b is a regularization constant and $\|\alpha\|_2^2$ denotes the Euclidean norm, objective function (15) after minimizing the error result in

$$\alpha = (\mathbf{P}^T \mathbf{P} + b\mathbf{I})^{-1} \mathbf{P}^T \mathbf{y} \quad (16)$$

Where $\mathbf{P} \in \mathbb{R}^{m \times K}$ denotes the Jacobian matrix $\mathbf{p}(\mathbf{x})$ of, and $\mathbf{y} = [y_1, \dots, y_m]^T$, and $\mathbf{I}$ is the $K \times K$ identity matrix. Weierstrass approximation theorem includes that every continuous function defined on an interval can be approximated as closely as desired by a polynomial function. However, the number of independent adjustable parameters would grow as l^r for the r^{th} -

order model with input dimension. Thus, the MP model would need a huge quantity of training data to ensure that the parameters are well determined. The RMP model is considered to significantly reduce the huge number of terms in the MP model,

$$\begin{aligned} \hat{f}_{RMP}(\alpha, \mathbf{x}) &= \alpha_0 + \sum_{k=1}^r \sum_{j=1}^l \alpha_{kj} x_j^k \\ &+ \sum_{j=1}^r \alpha_{r+l+j} (x_1 + x_2 + \cdots + x_l)^j \\ &+ \sum_{j=2}^r (\alpha_j^T \cdot \mathbf{x}) (x_1 + x_2 + \cdots + x_l)^{j-1}, \\ &l, r \geq 2 \end{aligned} \quad (17)$$

The number of terms in this model can be expressed as $K = 1 + r + l(2r - 1)$. It is shown that when compared to the MP model, the RMP model, in which the number of weight parameters increases linearly, is a much more efficient algorithm in a complicated polynomial system with the higher-order, in which the number of parameters increases exponentially with respect to the order of polynomials.

The preceding MP regression provides an effective way to describe complex nonlinear input-output relationships. However, for the r^{th} -order model with input dimension l , the number of independent adjustable parameters would grow with Lr . Thus, the MP model would need a huge quantity of training data to ensure that the parameters are well determined. To significantly reduce the huge number of terms in the MP model, the following model in (3) is considered:

$$\hat{f}_{MN}(\alpha, \mathbf{x}) = \alpha_0 + \sum_{j=1}^r (\alpha_{j1} x_1 + \alpha_{j2} x_2 + \cdots + \alpha_{jl} x_l)^j \quad (3)$$

It is noted that this gives rise to a nonlinear estimation model where the weight parameters may not be estimated in a straightforward manner. Although an iterative search can be formulated to obtain some solutions, there is no guarantee that these solutions are global. The following RMP model can be written as

$$\begin{aligned} \hat{f}_{RMP}(\alpha, \mathbf{x}) &= \alpha_0 + \sum_{j=1}^l \alpha_j x_j + \sum_{j=1}^r \alpha_{l+j} (x_1 + \\ &x_2 + \cdots + x_l)^j + \sum_{j=2}^r (\alpha_j^T \cdot \mathbf{x}) (x_1 + x_2 + \cdots + \\ &x_l)^{j-1}, \quad l \geq 2 \end{aligned} \quad (4)$$



The RMP model is a much more efficient algorithm in a complicated polynomial system with higher order, in which the number of weight parameters linearly increases, compared with the MP model, in which the number of parameters exponentially increases with respect to the order of polynomials.

As mentioned before, it is necessary to compute the values of the LCR and THD for the harmonic load currents to implement the DPQI. The RMP model is now applied to estimate the two aforementioned factors.

The overall procedure to calculate the DPQI is shown in Fig. 2.2 The left flow of Fig. 2.2 shows how to estimate the LCR by applying the RMP model. Meanwhile, the right flow of Fig. 2 shows how to calculate the THD for the nonlinear load harmonics predicted by the RMP model when the voltage at the PCC in Fig. 1 is not a purely sinusoidal waveform. Generally, it has slight harmonics in practice. Note that the proposed DPQI exploits distortion in the only current waveform without considering that in voltage for both the LCR and THD. To take into account the case in existence of a distorted voltage, the nonlinear load harmonics are predicted by the same RMP model to calculate the proper THD.

C. Evaluation of Performance

To evaluate the performance of the RMP model applied to the estimation problems, the RMSE and mean-absolute-percentage error (MAPE) in where y_m and $\hat{y}_m$ are the actual and estimated values, respectively, and n represents the number of data samples, are computed with the measurement of the actual current waveforms.

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{m=0}^{n-1} (y_m - \hat{y}_m)^2}, \quad \text{MAPE} = \frac{1}{n} \sum_{m=0}^{n-1} \left| \frac{y_m - \hat{y}_m}{y_m} \right| \quad (13)$$

The RMSE uses the absolute deviation between the estimated and actual quantities. Due to squaring, the RMSE gives more weight to larger errors than smaller ones. The MAPE is, on the other hand, dimensionless and can thus be used to compare the accuracy of the model on different series.

D. Overall Procedure

The overall procedure to implement the is shown in Fig. 2.2 There are two parts, one is to simply to

calculate their THDs of the measured current and voltage and the other is estimate the LCR by using the RMP model, based on the Parseval's theorem. It is important to determine the proper order when the RMP model is applied to estimate the LCR. In a physical application in the existence of noise and/or complex correlations among the many nonlinear harmonic loads, the relatively high-order of RMP model might be preferably used to enhance estimation accuracy. However, the estimation process by very high-order RMP models requires extensive computations and memory in real-time operation. Also, its weight-solution vector mapping to high dimension is hard to analyze. Moreover, it is not true that the high-order RMP model always outperforms the relatively low-order RMP model. There is no firm solution for selecting its optimal order. By several tests, the sixth-order RMP model is optimally selected to estimate the LCR in this project. Meanwhile, the estimation of nonlinear load harmonics, which was required to implement the DPQI^{old}, is not necessary here for calculating the THD of waveforms. Therefore, it avoids applying another RMP model. This makes the implementation of DPQI^{new} more efficient and effective for use in practice.

The overall procedure will be as shown in figure. From the overall procedure we can conclude that the DPQI^{new} tool for improvement of distortion power in distributed power grids. On improvement of distortion power quality index in distributed power grids can be done by DPQI^{new}. The estimation process by very high-order RMP models requires extensive computations and memory. The estimation of nonlinear load harmonics is not necessary here for calculating the THD of waveforms. Harmonic pollution ranking can be done by the above procedure.

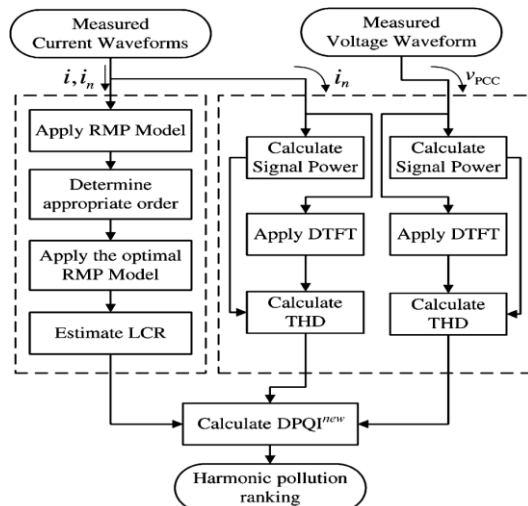


Fig.2 Overall procedure to implement the DPQI.

V. SIMULATION RESULTS

The single- phase 3 kW photovoltaic (PV) grid-connected inverter system and its schematic circuit is shown in Fig 3

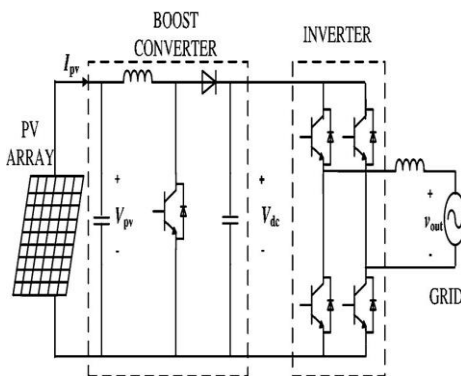


Fig 3 Schematic circuit of the inverter system.

It consists of a dc-dc boost converter, a dc-link capacitor, and a dc-ac inverter. The dc-dc boost converter steps up the PV voltage, which has a wide range corresponding to solar irradiance, to an acceptable level of the dc-link capacitor voltage V_d , by controlling the gate signal. The dc-ac inverter outputs the rated voltage of 220 V with 60 Hz. It operates with the maximum power point tracking (MPPT) control, which extracts the maximum possible power from the PV array, and the current control for power factor correction. The output voltage qualified with the THD within 5% according to IEEE standard 1547.

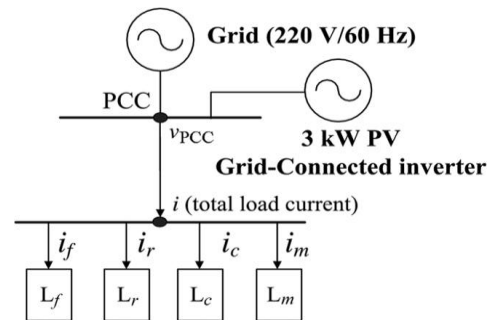
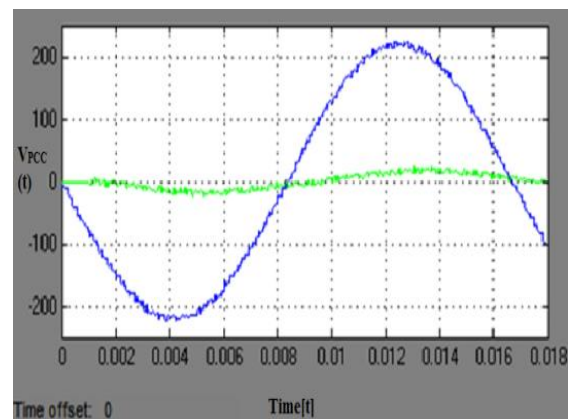
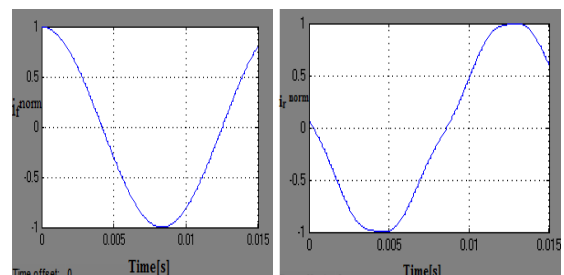


Fig 4 One-line diagram of proposed system for data acquisition

Fig.4 shows the one -line diagram of the experimental implementation used to obtain the associated sampling data. The grid -connected inverter system plays the role in distorting the PCC voltage with the low THD within 5%. Then, the four nonlinear loads are connected to the PCC. These are the fluorescent lighting, radiator, computer, and motor, which are denoted by the subscripts f , r , c , and m , respectively. Without losing the generality, the other experimental set-up can be similarly implemented, for example, as a small distribution system extended in power-scale with a 50 kW-scale PV based DG and typical loads such as commercial buildings, factories, and water treatment facilities, etc.

Fig 5.the voltage $V_{PCC}(t)$, and the total electric load current $i(t)$, at the PCC during one period of the fundamental.

The voltage $V_{PCC}(t)$, and the total electric load current $i(t)$, at the PCC in Fig.5 are measured simultaneously during one period T of the fundamental. It is shown from Fig. 6 that is lagging and that both are slightly distorted.



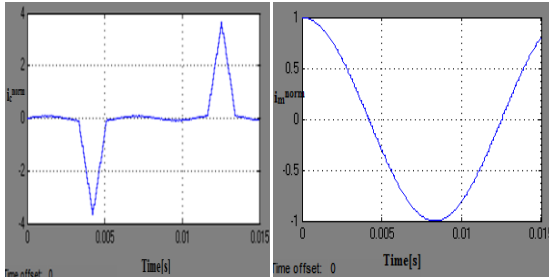


Fig. 6 Normalized load currents of i_m during one period of the fundamental.

All load currents i_f , i_r , i_c and i_m are measured, and their normalized waveforms with respect to their own fundamental components are shown in above figures.

Again, all load currents the degree of their distortion is more severe than $i(t)$ lagging $V_{PCC}(t)$. Each load current waveform (normalized) and the harmonics of $V_{PCC}(t)$ are calculated by using discrete-time-Fourier transform (DTFT).

The sampling frequency of all obtained waveforms is 500,000 Hz in this Fourier analysis, which is high enough to satisfy the Nyquist theorem with respect to the other high-frequency (up to 20th-order) components as well as the fundamental.

With the data in above figures THDs of the PCC voltage and load currents are calculated, according to the definition of THD

It is observed that the PCC voltage is distorted with the small THD of 3.78%, which is reasonably acceptable, from the results in Table I.

All nonlinear loads are affected by the distortion from and therefore have more harmonic currents than those generated due to their own nonlinearity. Also, note that the load current, injected into the computer is most severely distorted with the highest THD of 145.36%.

THDs of PCC voltage and load currents are tabulated. the tabular column gives the total harmonic distortion of voltage and current'

TABLE I
THDs of PCC voltage and load currents

Load type	Fluorescent	Radiator	Computer	Motor
THD(V_{PCC}) [%]	3.78			
THD(i) [%]	11.7	4	145.4	5.33

A. Calculation of the $DPQI^{new}$

It is now ready to calculate the according to the procedure in Fig. 2. Firstly, the sixth-order ($r=6$) RMP model, which provides the best performance after testing several RMP models with the other orders, is applied to find the LCR. Then, its solution vector,

$$L=[k_1, k_2, k_3, k_4]^t=[LCR(i_f), LCR(i_r), LCR(i_c), LCR(i_m)]^t \\ = [0.062, 0.7961, 0.0181, 0.1237]^t$$

is obtained. With this LCR, the result of estimating the total load current $i(t)$, is given in Fig.7, which shows very good estimation performance.

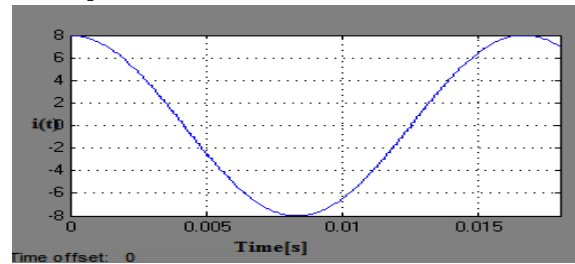


Fig. 7 Estimation of the total current $i(t)$, by the RMP model.

TABLE II

LCR OF APPARENT POWERS AND L

Load type	Fluorescent	Radiator	Computer	motor
S_a [VA]	245	3134	126	487
$LCR(S_a)$	0.0614	0.7853	0.0315	0.122
L	0.0614	0.7853	0.0315	0.122

Also, when it is compared with the actual LCR of apparent powers, $LCR(S_a)$, its performance is shown in Table II. Even though the distortion of computer is severe, the values of $LCR(S_a)$ and L are acceptably matched. Thereafter, the $DPQI^{new}$ in (2) is finally computed with the previously obtained THDs of voltage and current waveforms. Its values are [0.7312, 4.3853, 2.6363, and 0.8090] for the given nonlinear loads, which are fluorescent, radiator, computer, and motor, respectively.

B. Determination of the HPR

By dividing the $DPQI^{new}$ by the sum of its each value, the normalized relative ratio of the index ($DPQI_R^{new}$) is obtained as [0.0854, 0.5122, 0.3079, 0.0945].

Then, the relative HPR is determined by the order of magnitude of the $DPQI^{NEW}$, and the result is given in Table III.

Each factor of $DPQI_R^{NEW}$ indicates how much each load takes the portion of distortion power, D generated from each load with respect to the PCC in an overall system. It can be observed from Table III that the 'radiator' has the worst effect on the system by aggravating power quality problem with the highest HPR even though its current has the lowest THD among the four load currents.

On the other hand, the distortion power D , for each load is computed by (3) as $D=[29.20, 192.54, 104.11, 33.33]$. Similarly to the calculation of $DPQI_R^{NEW}$, its normalized relative ratio (D_R) is obtained as $[0.0813, 0.5361, 0.2899, 0.0928]$, and is shown in Table III.

TABLE III

Load type	Fluorescent	Radiator	Computer	Motor
THD(i)[%]	12.03	0.97	77.52	21.6
$DPQI_R^{old}$	0.7459	0.7716	1.403	2.671
HPR	4	3	2	1

$DPQI^{NEW}$ AND ITS CORRESPONDING HPR

The order in its magnitude is exactly the same as that of. This proves that the HPR represents the exact ranking of the distortion power produced from the nonlinear loads. Also, Table III shows that the values of SMR, which is defined to validate the proposed $DPQI^{NEW}$ for the distortion power, are very small as mentioned earlier.

These experimental results verify that the $DPQI^{NEW}$ can be effectively used as a decision-making index for power quality ranking without requiring the direct measurement of distortion powers of each nonlinear load.

C. Drawback of the $DPQI^{OLD}$

For the same measurement obtained in above, the $DPQI^{OLD}$ in (1) is now calculated. The solution vector L , to estimate the LCR is already given as $L=[0.062, 0.7961, 0.0181, 0.1237]^T$. As mentioned before, the THD(i_n) in (1) is calculated with the estimated (not measured) load currents with the assumption that a pure sinusoidal voltage is supplied to the PCC. Therefore, another RMP model with the eighth-order ($r=8$) is applied to estimate the exact nonlinear load harmonics.

Except for the $i_c(t)$ injected into the radiator, which has the small phase difference with the $V_{PCC}(t)$, the estimation performances for the other currents are poor. Simulink model for finding $DPQI^{OLD}$ is as shown below

The results of $DPQI^{OLD}$ and its corresponding HPR are given in Table IV.

TABLE IV

$DPQI^{old}$ and its corresponding HPR

Load type	Fluorescent	Radiator	Computer	motor
$DPQI^{new}$	0.7312	4.385	2.636	0.809
$DPQI_R^{new}$	0.0854	0.5122	0.3079	0.0945
HPR	4	1	2	3
$D[VA_d]$	29.2	192.5	104.1	33.33
D_R	0.0813	0.5361	0.2899	0.0928
SMR	0.0013	0.0008	0.0014	0.001

It is clearly show that with the incorrect HPR they give totally wrong answers. This proves that when the load current is severely distorted like the $i_c(t)$ the $DPQI^{OLD}$ has the serious drawback and/or with a low power factor it has a large phase difference with the $V_{PCC}(t)$. The good estimation performance of the proposed system and its applicability in practice was verified by the simulation results. The proposed $DPQI$ is expected to provide the important information to a supervisory control and data acquisition system

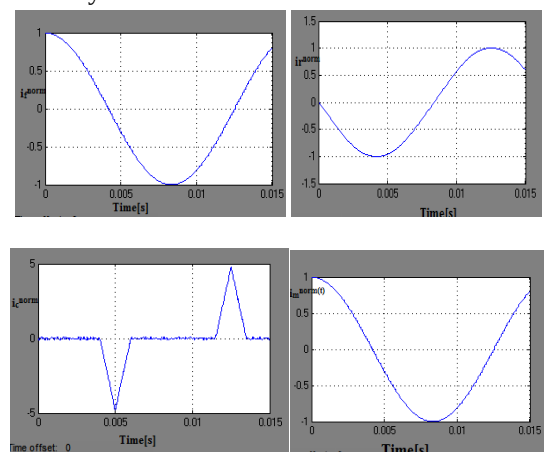


Fig 8 Estimation of load current i_m by the RMP model



VI. CONCLUSIONS

This project proposed the new distortion power quality index to replace the previously proposed index. Its computation was carried out based on the load composition rate (LCR) and Euclidean norm of total harmonic distortions (THDs) of the measured voltage and current waveforms at the point of common coupling (PCC). The reduced multivariate polynomial (RMP) model with the one-shot training property was successfully applied to estimate the LCR. Moreover, the use of could avoid applying another RMP model, which is required in the implementation of to estimate the nonlinear load harmonics. This advantage of allows for more effective and preferable use in practice. Also, the experimental results showed that the can provide the relative harmonic pollution ranking (HPR) of several nonlinear loads with good performance, which is directly related to their distortion powers without the need for direct measurements. In contrast, the results also verified that the has the serious drawback of obtaining wrong answers with an incorrect HPR. This was the case when the load current was severely distorted with the high THD and/or when it had a large phase difference with the PCC voltage with a low power factor.

The good estimation performance of the proposed system and its applicability in practice was verified by the simulation results based on the harmonic current injection model. It is expected to use the proposed as an effective tool for monitoring and regulating the power quality in distribution system as well as in a residence.

The proposed DPQI is expected to provide the important information to a supervisory control and data acquisition system or an advanced metering infrastructure for monitoring and regulating the power quality in a more effective manner.

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