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Improvement of Distortion Power Quality Index in Distributed Power Grids

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Abstract— **This paper presents 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 proposed by the authors. 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.**

The reduced multivariate polynomial (RMP) model with the one-shot training property is applied to estimate the LCR. 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. Its effectiveness and validity are verified by the experimental results from its prototype's implementation in a laboratory with a single-phase 3 kW photovoltaic(PV) grid-connected inverter, which contributes to a small distortion in voltage at the PCC, and practical nonlinear loads. Then, the harmonic current injection model based time-domain simulations are carried out to prove the effectiveness of the proposed PQI under the other conditions with different nonlinear loads.

Index Terms— **Distortion power, distribution power system, Euclidean norm, harmonic pollution ranking, power quality index, reduced multivariate polynomial (RMP) model.**

I. INTRODUCTION

Generation of harmonics and the existence of waveform pollution in power system networks are important problems facing the power utilities. Due to the widespread proliferation of many nonlinear harmonic loads, by various power-electronic-based equipment on a consumer side, serious power quality problems can be caused by distorted currents from those nonlinear loads. In addition, the increase in nonlinear loads might even distort the grid voltage. As a result, a distributed power system can be placed in an undesired situation by these power quality problems. For example, it is known that a power outage may occur as a result of serious voltage distortion. To tackle these problems, the limits on the amount of harmonic currents and voltages generated by customers and/or utilities have been the waveform is distorted with high frequency harmonic components. The THD regulates the harmonic pollution of each load. However, it is insufficient for analyzing the effects of polluted loads on an overall power system with the only THD factor. Therefore, a new index is necessary to deal with this issue. GENERATION of harmonics and the existence of waveform pollution in power system networks are important problems facing the power utilities. Due to the widespread proliferation of many nonlinear harmonic loads by various power electronic- based equipment on a consumer side, serious power quality problems can be caused by distorted currents from those nonlinear loads.

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In addition, the increase in nonlinear loads might even distort the grid voltage. As a result, a distributed power system can be placed in an undesired situation by these power quality problems. For example, it is known that a power outage may occur as a result of serious voltage distortion. To tackle these problems, the limits on the amount of harmonic currents and voltages generated by customers and/or utilities have been established in IEEE Standard 519 [1] and IEC-61000-3 Standard [2]. However, these limits are based on conventional power quality indexes (PQIs), such as total harmonic distortion (THD), which determines how much the waveform is distorted with high-frequency harmonic components. The THD regulates the harmonic pollution of each load. However, it is insufficient for analyzing the effects of polluted loads on an overall power system with the only THD factor. Therefore, a new PQI is necessary to deal with this issue. In addition, several PQIs and measurement methods [3], [4] have been reported with the analysis of distorted current and voltage waveforms. However, in the authors' opinion, no research has investigated the use of the PQI, which focuses on the direct relationship between distortion power and harmonic problem. This paper introduces the new PQI to monitor the effect of each nonlinear load on a point of common coupling (PCC) of a distribution power system by using the concept of distortion power generated from each load.To overcome this problem and achieve its reliable and consistent performance without regard to any given conditions, this paper 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. Why is power quality a concern, and when did the concern begin? Since the discovery of electricity 400 years ago, the generation, distribution, and use of electricity have steadily evolved. New and innovative means to generate and use electricity fueled the industrial revolution, and since then scientists, engineers, and hobbyists have contributed to its continuing evolution. In the beginning, electrical machines and devices were crude at best but nonetheless very utilitarian. They consumed large amounts of electricity and performed quite well. The machines were conservatively designed with cost concerns only secondary to performance considerations.

II. DISTORTION POWER QUALITY INDEX (DPQI)

Fig.1 shows a typical distribution power network. When the nonlinear loads are supplied from a sinusoidal voltage source, its injected harmonic current is referred to as contributions from the load. Harmonic currents cause harmonic voltage drops in the supply network and therefore distort the voltage at the PCC.
Any loads, even linear loads, connected to the PCC will Have harmonic currents injected into them by the distorted PCC voltage. Such currents are referred to as contributions from the power system or supply harmonics [3]. In this circumstance, a distortion power generation from each load depends mainly on two factors.

1) How much current is injected from the PCC in Fig.1 to each nonlinear load?
2) To what extent current waveforms are distorted with high frequency harmonic components? The preceding two questions can be solved by computation of the electric LCR for each nonlinear load and THD of the load currents (i1, . . . , in), respectively.

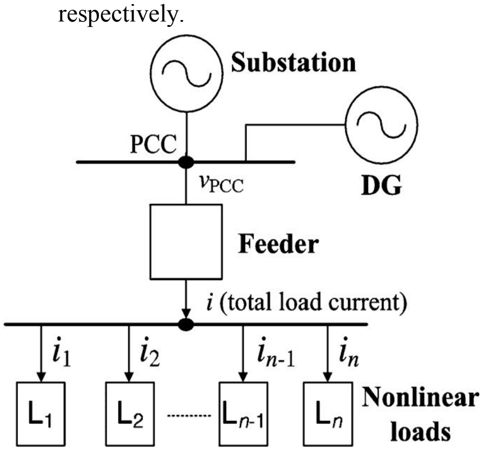


Fig1.One line diagram of a typical distribution power network.

DPQI is relevant to the distortion power of a certain electric load and can be obtained by inner product of the LCR and the THD, as given in (1). The waveform of each load current in (1) can be represented by

$$DPQI(n) = LCR(in).THD(in) \quad (1)$$
$$i_n(t)_T = i_{n,1}(t)_T + \sum_{h=2}^{\infty} i_{n,h}(t)_T \quad (2)$$

Where T is the period of the measured current i, and h is the number of high-frequency harmonic components. For all electric loads connected to the PCC in Fig.1, the DPQI provides important information of how much effect each load has on PCC with the relative ranking for harmonic pollution of distortion power generation.
In this study, the RMP model [1], [4] ,which is summarized in the next section, is applied to estimate the LCR and the Nonlinear load harmonics required to obtain the proper THD of each load current. This optimization technique is a kind of training algorithm to search the weight parameters for the nonlinear input–output mapping, such as the neural networks (NNs). The main advantage of the RMP model over the NNs is that it has the one-shot training property [1]. In other words, it does NOT require iteration procedures during the process of obtaining a solution weight vector.

Multivariate Polynomial (MP) Model

The general MP model can be expressed as

$$g(\alpha, \mathbf{x}) = \sum_{i}^{K} \alpha_i x_1^{n1} x_2^{n2}, \ldots, x_l^{nl} \quad (3)$$

where the summation is taken over all nonnegative integers n1, n2, . .. , nl for which n1 + n2 +**…** + nl ≤ r, with r being the order of approximation. The vector α = [α1, . . . , αK] is the parameter vector to be estimated, and x denotes the regressor vector as [x1, . . . , xl]T containing inputs. K is the total number of terms in g(α, x).
The general MP model in (3) can be replaced with

$$g(\alpha, \mathbf{x}) = \alpha^T p(\mathbf{x}) \quad (4)$$

by using the parameter vector α and the function p(x), which is composed of variables of the regressor vector. Given m_{data} points with m>K and using the least-squares error minimization objective given by

$$s(\alpha, \mathbf{x}) = \sum_{i=1}^{m} [y_i - g(\alpha, \mathbf{x}_i)]^2 = [\mathbf{y} - \mathbf{P}\alpha]^T [\mathbf{y} - \mathbf{P}\alpha] \quad (5)$$

the parameter vector α can be estimated as

$$\alpha = (\mathbf{P}^T \mathbf{P})^{-1} \mathbf{P}^T \mathbf{y} \quad (6)$$

where P ∈ Rm×K denotes the Jacobian matrix of p(x), and y = [y1, . . . , ym]T .

Note that (6) involves computing the inverse of a matrix. Therefore, the problem of multi collinearity may arise if some linear dependences among the elements of x are present. A simple approach to improve numerical stability is to perform a weight decay regularization using the following error objective:

$$s(\alpha, \mathbf{x}) = \sum_{i=1}^{m} [y_i - g(\alpha, \mathbf{x}_i)]^2 + b\|\alpha\|_2^2$$
$$= [\mathbf{y} - \mathbf{P}\alpha]^T [\mathbf{y} - \mathbf{P}\alpha] + b\alpha^T \alpha \quad (7)$$

where b is a regularization constant.
Minimizing the new objective function (7) results in

$$\alpha = (\mathbf{P}^T \mathbf{P} + b\mathbf{I})^{-1} \mathbf{P}^T \mathbf{y} \quad (8)$$

where P ∈ Rm×K, y ∈ Rm×1, and I is the K × K identity matrix. The approximation capability of polynomials is well known from the Weier strass approximation theorem [10], which states that every continuous function defined on an interval can be approximated as closely as desired by a polynomial function.

III. IMPLEMENTATION OF DPQI

As mentioned before, it is necessary to compute the values of the LCR and THD for the harmonic load currents to implement the DPQI in (1). The RMP model is now applied to estimate the two aforementioned factors. Overall Procedure to Calculate the DPQI by Using the RMP Model The overall procedure to calculate the DPQI is shown in Fig. 2. The left flow of Fig. 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 in (1) 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. B. Estimation of Electric Load Composition (LCR) by Using the RMP Model For the formulation of load composition, the total electric current i(t) in Fig. 1 is modeled by with several electric load classes connected to the distribution power system, where k1, k2, . . . , kn−1, and kn are the unknown coefficients, which provide the actual rate of the composition of each load current with respect to the total current. This rate is called the LCR. The explanation about how to apply the RMP model is described as follows: Because (14) has the form of the firstorder polynomial function, the RMP model with the firstorder (r = 1) in (12) may simply be applied. Its associated equation is given in (15). By comparing the relation between the coefficient vector α = [α1, α2, α3, α4, α5]t and the LCR vector k = [k1, k2, k3, k4]t, the unknowns in which are k1, k2, k3, and k4, can be obtained.

In a physical application in the existence of noise and/or complex correlations among the nonlinear harmonic loads, the relatively high-order RMP model might preferably be used to enhance the estimation accuracy. However, the very high order RMP model requires extensive computation and memory in real-time operation. Therefore, it is important to determine the optimal number of order r in (12) of the RMP model, depending on its application. After carrying out several tests, the sixth order (r = 1) RMP model is used to estimate the LCR. More detailed explanation is given in [7] with the full description of how to select the proper order of the RMP model applied to estimate the LCR.

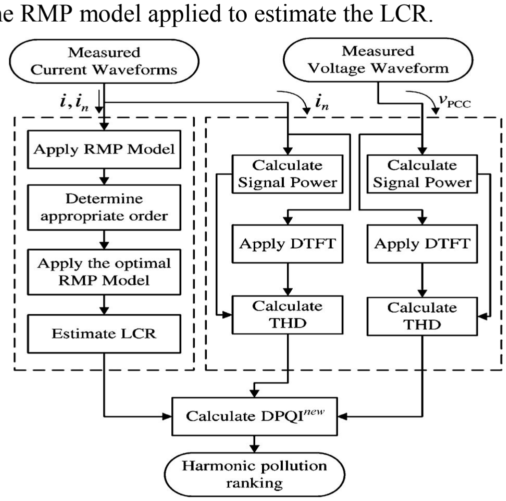


Fig. 2. Overall procedure to implement the DPQI^{new}.

After estimating the LCR for the given loads with the RMP model, the real power P, apparent power Sa, fundamental reactive power QB, and distortion power D for the each load can be computed by where N is the number of samples obtained during the one period T. The subscript n denotes the each load class, which corresponds to the LCR for the total electric current i(t) at the PCC. This LCR can provide a standard for harmonic current injection limits from each load with the benefit as an effective evaluation tool on the effects of individual load types.

In addition, the electric utility company may use the LCR to quantify the contribution of individual customers on a power distribution network for power quality degradation. For the formulation of load composition, the total electric Current i(t) in Fig. 1 is modeled by

$$i(t) = k_1 i_1(t) + k_2 i_2(t) + \cdots + k_{n-1} i_{n-1}(t) + k_n i_n(t) \quad (9)$$

with several electric load classes connected to the distribution power system, where k1, k2, . . . , kn−1, and kn are the unknown coefficients, which provide the actual rate of the composition of each load current with respect to the total current. This rate is called the LCR. As mentioned before, harmonic currents at nonlinear loads might have the distorted PCC voltage VPCC in Fig. 1. Then, the nonlinear correlation between the distorted VPCC and load current harmonics occurs. This relationship is complex and therefore difficult to analyze.

The estimation of LCR in (1) can be carried out without considering whether a pure sinusoidal or a distorted voltage is supplied to several loads. The reason is that it deals with the only portion of each load current over the total current at the PCC. However, when the THD is calculated, the additional consideration for nonlinear load harmonics is necessary in the existence of distorted VPCC in Fig.1. This problem even exists When a single load is connected to the PCC. If the true harmonic current injections from the load were known, then a utility could penalize the offending consumer in some appropriate way, including, for example, a special tariff, or insist on corrective action by the consumer. Simply measuring the harmonic currents at each individual load is not sufficiently accurate since these harmonic currents may be caused by not only the nonlinear load but also a nonsinusoidal PCC voltage. This is not a new issue, and researchers have proposed tools based on traditional power system analysis methods to solve this problem. The harmonic active power method [5], [6] and critical impedance measurement method [7] yield results to a certain degree of accuracy.

IV. SIMULATION RESULTS

In this Section, the case study related to a numerical simulation of a simple test circuit with different nonlinear loads is carried out to more clearly show the potential of the proposed DPQI^{new}.

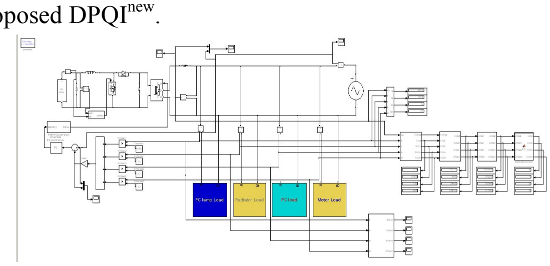
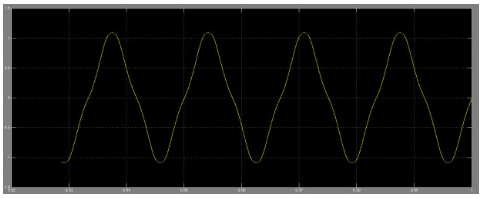


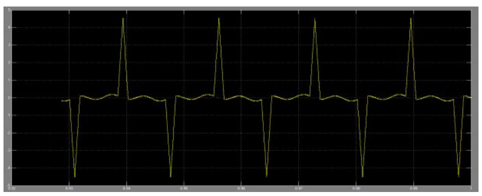
Fig.3. Simulink model of proposed system.

A. Harmonic Current Injection Model

For the harmonic load modeling, several methods such as a constant current source (CCS), crossed frequency admittance matrix (CFAM), Norton model, and harmonic current injection model have been commonly used [25]. These can be selected by considering the trade-off between simplicity and sensitivity. In this paper, the harmonic current injection model is properly chosen on the purpose of simulation. In this method, any loads are represented by aggregating each effect of individual loads at a distribution level.



(a)



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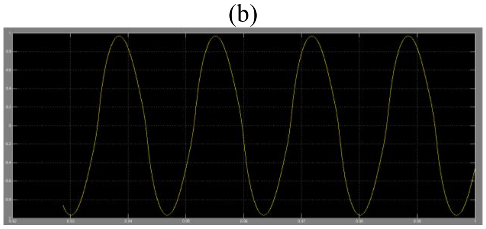

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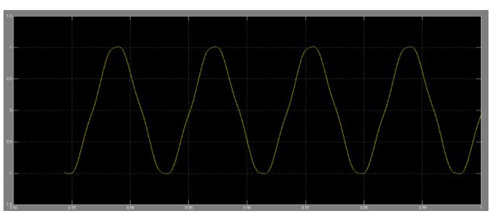

(d)

Fig. 4. Normalized load currents of i_f,i_c,i_r ,i_m and during one period T of the fundamental.

Then, the aggregate harmonic load is represented by a harmonic current source in parallel with some linear impedances [25]. The one-line diagram of system used in the simulation is shown in Fig.1 with the representation of harmonic loads. Each nonlinear load in Fig.1 consists of a constant power load and a harmonic current injection source, which can generate up to 19th-order high-frequency harmonic. To reflect various conditions close to the practical situation, all related parameters such as power, harmonic injections, and power factor, etc to represent the nonlinear loads are randomly generated in every single simulation by uniform probability distribution defined in a certain range, which includes the severe conditions where voltage distortion is almost close to its harmonic limits defined in [6] and [7]. Then, the total number of 10000 simulations is carried out.

B. Tests in Three-Phase Balanced System

The clear definition of distortion power is necessary to evaluate and verity the . Although many theories have been developed for the single-phase case, their extension to the three-phase system is also important. Therefore, the proposed index is now applied to a three-phase balanced system in Fig.1.It shows the one-line diagram of the prototype's experimental

implementation used to obtain the associated sampling data.As mentioned before, the grid-connected inverter system plays the role in distorting the PCC voltage with the low THD within 5%. Then, the four nonlinear loads, which are selected by the load classification guide in [7], are connected to the PCC. i_f,i_c,i_r ,i_m 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. The voltage, and the total electric load current,at the PCC in Fig.1 are measured simultaneously during one period of the fundamental. that is lagging and that both are slightly distorted. Also, all load currents and are measured, and their normalized waveforms with respect to their own fundamental components are shown in Fig.4.

CONCLUSIONS

This paper proposed the new distortion power quality index ($DPQI^{new}$) to replace the previously proposed index($DPQI^{OLD}$). 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 $DPQI^{new}$ could avoid applying another RMP model, which is required in the implementation of $DPQI^{OLD}$ to estimate the nonlinear load harmonics. This advantage of $DPQI^{new}$ allows for more effective and preferable use in practice. Also, the experimental results showed that $DPQI^{new}$ 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 $DPQI^{OLD}$ 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. Moreover, the good estimation performance of the proposed $DPQI^{new}$ and its applicability in practice was verified by the simulation results based on the harmonic current injection model.

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