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Methods for the Classification of Harmonic Distortion Sources for Nonlinear Power System Loads: A Critical Review

Elang Kumaran Suppiah and **Herman Wahid**[*]

School of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia.

[*]Corresponding author: herman@utm.my, Tel: 607-5557169, Fax: 607-5566262

Abstract: This paper demonstrates the method available for estimating the impacts of multiple nonlinear loads on current harmonics and voltage harmonics in the electrical network. In the power distribution system, there are standards such as IEEE519 which provide the guidelines for controlling the harmonic levels that give an isolated indicator between utility segment and customer. To ensure the utility voltage distortion at the point of common coupling (PCC), the customer needs to maintain the TDD percentage so that it does not impact the utility distribution system. Nevertheless, there is a possibility for a dispute between utilities and customers regarding who contributes the harmonic distortion to the PCC. This research will address the direction of harmonic source based on the proposed method and verify the output percentage of THD and TDD with reference to IEEE519 standards. There are two modelling schemes introduced in this review which are load modelling and source modelling using the neural network technique. The load modelling is a scheme to predict the current distortion. The source modelling is a scheme to predict the voltage distortion at the PCC. These two methods will operate at customer side as an automatic standalone tool without disrupting the operation of customer's system. Customers will easily monitor the predicted current distortion in the system by the proposed method which internally runs the neural network algorithm. The utility company can penalize the customer based on the load modelling scheme. The proposed load and source modelling will give some idea on the harmonic filtering method.

Keywords: Harmonic, Load modeling, Source modeling, TDD, THD.

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1. INTRODUCTION

Power electronic applications have made many technological advances and brought enormous economic benefits over the years, especially the advancement of technology as a whole. The change in power system technology has also increased the complexity of power system studies. As a result of challenging environment constraints, liberalization of the energy markets, and privatization of the power supply industry, power systems are being operated at their maximum performance levels to maximize asset utilization. For a reliable power system to function effectively with various aspects of power system operation, the system must be secure and reliable operation must be maintained.

Due to the importance of the quality of the electrical power supplied by the utility company and/or by injected current by the customer, it has become increasingly necessary to discover, evaluate, and above all to forecast system behavior. Distribution networks can be able to forecast power quality problems before they occur in their network system by using power electronic loads extensively.

Typically, a power distribution system is designed to operate with pure sinusoidal waves and electric utilities strive to comply with the requirement. In contrast, the presence of harmonics in the power systems is a threat to sensitive equipment such as variable speed drives, power electronics loads, super-computer, inverters, etc. [1]. During normal operation, this equipment induces distortion in the steady-state current and voltage. Because of these

Circumstances, it has become necessary to pay considerable attention to the quality of electrical power which includes addressing the issue of voltage and current harmonic distortions [2][3]. Attempts to establish steady-state harmonic limits in the form of standards for electrical systems containing power electronics or other nonlinear loads have emerged as a viable idea. As a result of standards requirement, harmonic currents are restricted, which in turn influences the voltage waveform within the system.

Harmonics is an important metric for evaluating the parameter of power quality. The economic aspects of harmonics [4] and deregulation [5] have all created a need for extensive monitoring in the power system harmonics. The customers who have sensitive equipment use harmonic current monitoring to locate the source problems relating to harmonics. In addition, utilities try to meet the needs of their customers, which is why they monitor the supply voltage to demonstrate proof that the quality of the power supplied meets pre-specified standards and to gather the necessary information to solve the problems [6][7]. Utilities companies reserve the right to reassess and revise its estimates at any time. It is usually necessary to make these measurements in order to verify and to understand the harmonic level on the customer's side. Lastly, deregulation poses the challenge of constantly monitoring all the measuring parameters.

2. OVERVIEW OF TDD AND THD PREDICTION METHOD

Total Harmonic Distortion (THD) can be used to characterize the current distortion, but it can be misleading. Even a small current can have a high THD value but doesn't have a significant impact on the system. In many adjustable speed drives, the input current THD is high during operation at a low load. Since the harmonic current magnitude is low even though the current distortion level is high, and this is not a significant concern.

Some analysts have attempted to avoid this difficulty by referring to total harmonic distortion by the phrase Total Demand Distortion (TDD) as defined by IEEE 519 Standards-2014 which is a new recommendation made by this organization for optimizing the harmonic distortion in power system [8-14]. Without each customer staying within the specific limits, it will be difficult or impossible for the utility to meet the voltage requirements. If the TDD percentage increases, this will be indirectly impacting the customer power factor, and the voltage distortion will be produced at the utility distribution side. By eliminating or minimizing the TDD percentage, this could help the customer in preventing power sources from the effect of inadequate power factor. TDD value needs to be monitored by the customer to meet the utility standards. However, at this moment the customer needs to measure load current and key in the value separately to capture the TDD distortion in the offline mode.

Besides, it is difficult to distinguish the point sources of the harmonic distortion (i.e., in THD or TDD form) whether it is coming from the customer's side or utility side due to the interconnection of power-line networks. This situation is considered a nonlinear case, and in practice, the investigation should be carried out online (i.e., without turning off the electricity supply) to avoid disruption of customer's operation. Hence, the determination of the noise contributor is a vital process and whether the harmonic distortion level has exceeded the standard limitation level or not. In the literature, several approaches can be used to deal with this harmonic problem by using hardware and statistical configuration. Those methods will be summarized thoroughly in this proposal. In this work, an artificial neural network (ANN) algorithm will be introduced in characterizing the harmonics distortion point sources and their level in nonlinear power load networks.

3. IMPACT OF HARMONIC DISTORTION IN POWER SYSTEM

A harmonic source can cause equipment failure at both in networks and users' installations that are subject to the voltage and currents source. Exposition usually does not produce visible effects [10], however, it can result in serious consequences in the long and medium-term. Below will be the frequent encountered harmonic problem faced by the utility industries:

- Voltage distortion
- Increased RMS currents, heating, and line losses
- Need a higher K-factor transformer due to overheating on the power transformer.
- Derating on equipment performance
- Overloading at neutral and phase conductors
- Tripping due to voltage harmonic sensitivity, fuse blowing of power factor
- Failure of the control system and reduce system stability.

The distribution feeders inject harmonic currents into the utility network from harmonic-producing load such as nonlinear load. As a result, other electrical and electronic equipment connected to the distribution feeder, including the harmonic producing loads. In the transmission and distribution systems, it's become increasingly difficult to discern the direction of harmonic flow. As a result, even small harmonic sources can cause high levels of harmonic current levels between customers and utilities.

The voltage source is affected by the second harmonic effect. As the half-cycle is higher than the following cycle, such an effect can be accentuated in the harmonic flow. There will be three main harmonic order which gives higher impact such as 3rd, 5th, and 7th order of harmonic. The 3rd harmonic is mainly zero direction. Mostly its raises the potential of the neutral. This impact this much greater than that of the 5th and 7th order of harmonics, since additional losses will be created in neutral current paths, regardless of if the load is balanced or unbalanced. The 5th harmonic stills a predominant component-mix that is observed on the voltage level [11]. 5th harmonic travel in negative sequence in another term will be reverse rotation. Once create 5th harmonic, this will cause motor overheating and failure.

To resolve or minimize the harmonic-related problems, IEEE 519 recommended standards enforce by the utility industries. The IEEE standard 519 specifies a maximum level of the Harmonic Distortion (THD) and as Total Demand Distortion (TDD) in terms of voltage and current impact. For IEEE 519 compliance, the Total Demand Distortion is often the most important parameter, as without each customer staying within limits, it will be difficult or impossible for the utility to meet the voltage requirements [15].

4. EXISTING METHODS FOR DETERMINING SOURCE OF HARMONIC DISTORTION

The most important details are that the utility companies need that harmonic direction. Two approaches are being proposed in the industry to control this. The first scheme focuses on the limit on the number of harmonic currents and voltages generated by customers and utilities [16],[17],[18]. The next scheme, inspired by the power factor management practice. This will be charged to the consumer if their harmonic pollution level exceeds the limit. This work area was described by A. McEachern [19] and David Stenberg [20].

4.1 Harmonic Power Flow Direction Method

The harmonic power flow direction is a common method for checking the power direction. As the point that generates harmonic power, it is mainly considered to contain the dominant harmonic source or have a larger contribution of harmonic distortion of the measurement point. The entire details of this method have been reported by Yuayun, Sun, and W.Xu in [21]-[24].

Figure 1 shows the harmonic Norton equivalent circuit to analyze the power direction method at the utility customer interface.

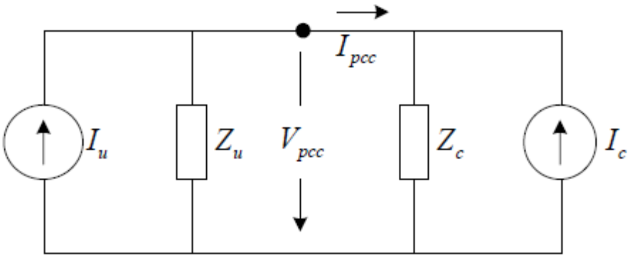

Figure 1. Norton equivalent circuit

The circuit is applied to different levels of harmonic frequencies. Ic represent the harmonic current of the customers and Iu represents the harmonic current of utilities. Zc and Zu are the harmonic impedances of the customer and utility segments, respectively. The main task for this circuit to determine which direction contributes more harmonic to the PCC point. A power direction method utilizes to measures voltage and current to determine direction at the harmonic order h.

$$P= \mathcal{K}(V_{pcc}I_{pcc}) \quad (1)$$

where Vpcc and Ipcc are harmonic current and voltage which focus on PCC for a harmonic order. The direction of the P flows from utility side (U) to customer side (C) it shows positive. Below explain the power direction method conclusions:

If P> 0, the U side causes more harmonic distortion.
If P<0, the C side causes more harmonic distortion.

4.2 Load Impedance Variation method

The method explains the relationship between distorted voltage waveform, distorted current waveform, and waveform-related links. Abhishek et.al proposed this unique method in [25-27]. In this method, the load parameter of R&L value variations under the harmonic influence will be monitored. Harmonics plays a major role in determining the source of harmonic distortion and assessing the nonlinearity of the load. The load of R&L increases linearly with the harmonic disturbance.

In this load impedance variation method, a sinusoidal voltage is applied to the linear load to compensate for the sinusoidal current. A distorted current waveform would result if a sinusoidal voltage is applied to a nonlinear load. This step will be repeated when the system effect in reverse.

When a sinusoidal current is injected through a nonlinear impedance, the voltage across that element will be distorted. According to the result, the nonlinear loads indicate distorted voltages or currents waveform, but the reverse is not true. The load with a distorted current or voltage is not necessarily nonlinear in this method. By considering the distorted current and voltage waveforms, it is impossible to determine the source of harmonics. The very first step is to find a simple way to monitor the load pattern under the harmonic influence.

4.3 Online Impedance Measurement method

An analysis of the harmonic propagation within a power system cannot be accurately simulated or predicted without knowing the network impedance value. The current injection method for online impedance measurement has been proposed by G.Moreau, et al [28]. This method extended to the extra higher voltage (EHV) transmission networks by Zanotto et al. [29]-[31].

Two direct-injection methods have been used by the researcher, one of which entails injecting a small sinusoidal current signal at every harmonic frequency of interest. Depending on the phase and amplitude of voltage and current measured at the injection point, the impedance can be determined at each frequency.

The Second method involves injecting a narrow current spike to the network proposed by Hamid Reza Baghaee et, al [32],[33]. The injected current and voltage transient are recorded, and the point of injection is calculated. A frequency-domain analysis will be carried out as follows,

$$z(f) = \frac{\mathbb{F}(V(t))}{\mathbb{F}(I(t))} \quad (2)$$

In this case, $\mathbb{F}$ is the Fourier transform.

This method has the disadvantage that we need the power electronic converters to inject the current pulse. During online measurements, the power electronic converters introduce their nonlinearity into the signal, which affects the overall system.

4.4 Probabilistic Methods

The probabilistic modeling of power system harmonic current injection and propagation proposed by Baghzouz and Tan [34]-[36]. Using this method, harmonic loads are modeled based on their time-varying and probabilistic characteristics of harmonic loads. Figure 2 represents the main connection exiting among the value assumed by the final quantity of voltage harmonic (V_h), the value of quantities of direct influence of current harmonic (I_h), the harmonic impedance supply Z_h and back to the ground supply voltage which is V_{BG}^{h}.

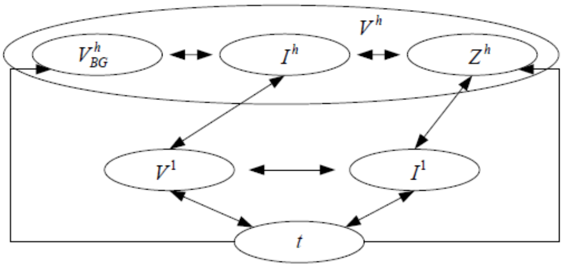

Figure 2. The relationship between different quantities in a power system

For this method, the researcher used three different modeling approaches for evaluating the final quantity of harmonic voltage V_h ;

- Model without impedance variability
- Model without the actual correlation effect between currents and impedances

- The model includes the actual behavior of currents and impedance.

For the system analysis, the impedance and current are assumed uniformly distributed between a range of minimum and maximum values.

$$Z^h_{min} = 0,\ Z^h_{max} = 1p.u,\ I^h_{min} = 0,\ I^h_{max} = 1p.u \qquad (3)$$

There are four reference conditions for probability distribution function and cumulative function to calculate harmonic voltage V_h:

Condition 1. Constant value for the impedance.

$$Z^h_{max} = Z^h = 1 \qquad (4)$$

Condition 2. Independence, which means the different value of Z_h and I_h

$$P(Z^h|I^h) = P(Z^h)\ and\ P(I^h|Z^h) = P(I^h) \qquad (5)$$

Condition 3. Direct dependence, which means distance from a minimum value of harmonic impedance Z_h proportional to the distance of current harmonic I_h minimum value.

$$P(Z^h|I^h) = 1\ if\ \frac{Z^h - Z^h_{min}}{Z^h_{max} - Z^h_{min}} = \frac{I^h - I^h_{min}}{I^h_{max} - I^h_{min}}$$

$$Otherwise = 0 \qquad (6)$$

Condition 4. Cross dependence, which means distance from minimum value of harmonic impedance Z_h proportional to the distance of current harmonic I_h maximum value.

$$P(Z^h|I^h) = 1\ if\ \frac{Z^h - Z^h_{min}}{Z^h_{max} - Z^h_{min}} = \frac{I^h_{max} - I^h}{I^h_{max} - I^h_{min}},$$

$$Otherwise = 0 \qquad (7)$$

The variation of the load impedance makes this method the most accurate in predicting the corresponding nodal harmonic voltage, but it is unable to distinguish between the load harmonics and the source harmonics.

4.5 Neural Networks Based Methods

Recently, Artificial Intelligent (AI) technology, and in particularly neural networks had an impact on the power system and power electronic segment. The Neural network is dealing with the nonlinear relationship between load and source parameters. Venayagamoorthy [37], Bose [38], and Pioneers like Harley [39] are the forefront author, among the others who create the effort to promote the application of neural network in power systems, power electronics, and machines in the year 2001 onwards.

In the power system application, N.K Nguyen et.al [40] apply the active filtering power system which is using neural network algorithm in 2013. They used the high precision selective harmonic compensation scheme for an active filter. The total harmonic distortion is identified and tracked on-line by using novel Adaline- based architecture which works in different frames and this resulting in power decompositions. This method allows the compensation schemes are well adopted for on-line approaches.

Marek Rogoz and Zbigniew Hanzelka [41] has applied the neural network method to estimate the harmonic level in the power system. He introduces a filtering method to reduce the total harmonic distortion in the power system. The researcher has presented the neural network-based algorithm that can identify magnitude and phase harmonies losses. This all depends on the losses caused by Total Harmonic Distortion generates by real harmonics or injected from the load. After that, he modified the neural network algorithm to take into account total harmonic distortion and created the filtering to meet the IEEE 519 requirement.

5. INTELLIGENT OPTIMIZATION TECHNIQUES USING NEURAL NETWORK PREDICTION

5.1 Neural Network Learning

A neural network requires a learning algorithm to identify or approximate a process. It includes the three basic learning process which is supervised, unsupervised, and reinforcement learning. Supervised learning regroups different techniques which all sharing the same principles. The process starts with training data from the process which represents of desired model behavior. The training data will be used to train the ANN such that the ANN approximates fit the training data. When the ANN is trained and then receives an input sequence, it should generate an output that resembles the actual output of the original system. The mean-squared error is commonly used to minimize the average error between the ANN output and the target value. This will be minimizing the cost function using the gradient descent method which called Multi-layer perceptron's [42].

On the other hand, unsupervised learning does not use output data. Most of the time unsupervised learning algorithms are used to pre-process the data, during the exploratory analysis or pre-train data. The main objective of unsupervised learning is to discover patterns or features in the input data with no help from a teaching algorithm. In this learning system, it uses some data x, the cost function to be minimized which can be any function of the data x, and the ANN output g(x) [43].

Reinforcement learning will find the best ways to earn the greatest rewards. Moreover, it's not presented the expected answer but only indicates if the computed output is correct or incorrect. The information provided helps the network in its learning process. In this research, unsupervised and reinforcement learning is not considered as it would be inappropriate for the intended application.

5.2 Harmonic Current Prediction Using LMI Method

The load model identifier (LMI) is designed to predict the true harmonic current distortion a customer can be attributed to, without affecting the operation. This method will overcome many problems discussed in Section 2. A new concept is shown in Figure 3.0 that combines a utility equivalent circuit, customer load, and the neural network-based Load Model Identifier (LMI).

This design circuit consists of a three-phase supply network with a sinusoidal voltage source Vs, network impedance Ls, Rs, and several other loads, which can be linear or nonlinear. LMI consist of two individual neural network blocks. The first block addresses identification neural networks (ANN1) and estimating neural network (ANN2). At first, the nonlinear load injects distorted line voltage Vabc into the network together with its previous data, z-1. By training ANN1, it learns how the load behaves nonlinearly, otherwise known as its admittance. In the estimation phase, the weight is transferred to the ANN2 after the ANN1 training. This sine wave data is then used to estimate $\hat{\imath}$ abc-distorted output using ANN2. Any distortion of the current waveform $\hat{\imath}$abc-distorted can now be attributed to the nonlinearity of the load admittance. This entire process is known as load modeling.

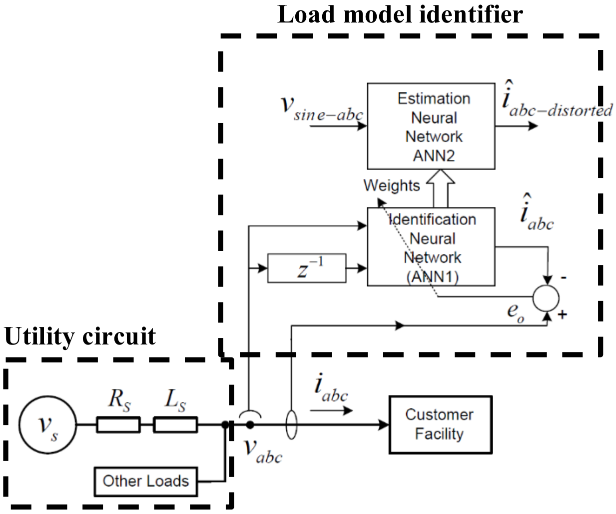

Figure 3. Load modeling identifier method

5.3 Voltage Distortion Prediction Using SMI Method

Any nonlinear load affects the voltage at the point common coupling (PCC), and thereby all loads are connected to the same PCC. In the presence of several nonlinear loads attached to the PCC point, it's difficult to predict mathematically how much the nonlinear load affecting the voltage distortion level at PCC. For the current situation, a customer with nonlinear loads must use and apply the harmonic filter to clean up their current and avoid utility penalties. A customer who performs a repair will be interested in and will pay attention to the level of voltage distortion level at the PCC point of connection as one of the important parameters.

Based on the neural network, the second new method proposed to predict the change in voltage distortion levels of the voltage from the PCC if the customer draws only were to draw only fundamental current and filters out its harmonics. This method is called source modeling. Based on a source model approach, we can predict voltage distortion on the customer side of the PCC for both utility and customer. By modeling the source, we could determine what would happen to the THD and TDD of V_{PCC} if the recommended filters at the front end were to suppress harmonics. The diagram in Figure 4 illustrates the implementation of the source modeling approach. This model can be implemented for single-phase and 3-phase systems.

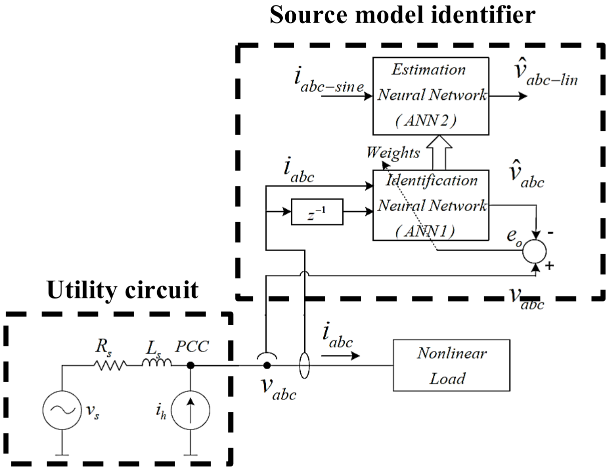

Figure 4. Implementation of the source model identifier method

In the source modeling, I_{abc} injects distorted the current into the network. The input of current I_{abc} is used as the input to the identification neural network (ANN1). ANN1 that presents with the input current will be trained and identify the voltage characteristics at PCC mode. When the ANN1 training has been completed, its weight is transferred to the estimated neural network (ANN2). If the absence of harmonics in the nonlinear loads current, the distortion level of the voltage at the PCC would change if the nonlinear loads drew sinusoidal current waveform. When ANN2 is supplied with a mathematically generated sine wave offline to estimate its output $\hat{v}$ abc-lin. The output of ANN2 gives the same information that could have been obtained if the nonlinear load will have replaced by a similar-sized linear load or it is equipped with front-end filters. The nonlinear load harmonic now can be attributed to the difference in the voltage distortion level at PCC.

6. CONCLUSION

This paper presented the different types of methods to identify the harmonic losses in the power system. As a part of the power distribution system, there are standards such as IEEE519 that establish guidelines for control of harmonic levels that indicate the difference between utility segment and customers. To keep the utility voltage distortion at the PCC, the customer needs to maintain the TDD percentage so that it does not go to impact the utility system. However, a dispute may arise between utilities and the customer regarding who is responsible for the harmonic distortion. In the following research, we will determine the direction of harmonic sources using the proposed method and we will demonstrate the output percentage of THD and TDD using IEEE519 standards.

This study reviews the harmonics of fundamental studies and related issues that were reviewed in Section 2, and a comprehensive literature survey is presented to summarize the state-of-the-art techniques relevant to the methods being proposed. Moreover, the fundamentals of the algorithms used for the NN training and their suitable adaption to the problem at hand were also described.

There are two modelling schemes introduced in this research which are load modelling and source modelling using the neural network technique. The load modelling will be verified on several different types of load. The source modelling is to verified principle on a simulation circuit with two nonlinear loads. The source modelling is a scheme to predict the voltage distortion at the PCC if there is a high TDD percentage at the customer side. If there is any high distortion in the source voltage, the clean sine wave current is induced to recover the TDD percentage in the system via the thyristor drive circuit. To verify the source modelling scheme, it is expected to compare the voltage distortion at the PCC predicted by the neural network with a clean sine wave current input and the voltage measured at PCC by replacing the clean current source.

These two methods will operate on the customer side as an automatic standalone tool without disrupting the operation of the customer system. Customers will easily monitor the predicted current distortion in the system by the proposed method which internally running the neural network algorithm. The utility company can penalize the customer based on the load modelling scheme. The proposed load and source modelling will give some idea on the harmonic filtering method. Active filter control technique needs to precise detect the individual current harmonic components amplitude and phase.

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