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Rapid Identification of Total Demand Distortion Using a Neural Network Model and Mitigation via an Integrated Filter Design

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Abstract: This paper proposed a filter for the mitigation of power harmonics based on an integration of filters namely double-tuned plus C-type filter (DTPC). The proposed DTPC filter is mainly aimed to filter the total demand distortion (TDD), as well as the total harmonic distortion (THD), based on IEEE-519 standards. The harmonic filter is presented within the framework of harmonic mitigation as a method of power quality control. Besides, a neural network estimation model to identify harmonic percentage in the power system is also proposed. Two modelling schemes are presented for the simulation of the harmonic filter, which are the load modelling and the source modelling, using the neural network technique. The load modelling is a scheme to predict the current distortion, while the source modelling is a scheme to predict the voltage distortion at the point of common coupling. These two methods may work as standalone tools at the customer's side; thus, it will not interfere with the online operation of the customer's power supply system. The load and source modelling are combined with the DTPC filter in mitigating both the THD and the TDD effects. As a result, the DTPC filter allows customers to maintain a THD and TDD percentage below 10%, and hence customers could meet the IEEE-519 standard.

Keywords: Capacitor-type filter; Double-tuned filter; Load modelling; Neural networks; Source modelling; Total demand distortion; Total harmonic distortion.

1. INTRODUCTION

As technology advances, the number of nonlinear loads is increasing, which affects the power quality in a power system and, consequently, the quality of the power delivered to other customers. A combination of AC and DC variable speed drives, along with arc furnaces, is among the most common large power nonlinear loads. In many industries, DC drives can be a significant plant load. They are commonly found in the oil and chemical industries and those of metals and mining. In applications requiring very fine control throughout a wide speed range and high torque, these drives remain the most popular large power motor speed control type. Because these drives have relatively poor power factors, especially when the motor is at a reduced speed, power factor correction is particularly important. There are additional transformer capacity requirements to handle poor power factor conditions, and more utilities are charging a power factor penalty, which can significantly impact the total bill for the facility. DC drives also produce significant harmonic currents. Power factor correction becomes more difficult when harmonics are present. In power factor correction capacitors, resonant situations may occur which may magnify harmonic currents, causing excessive distortion levels. Arc furnaces also present a very difficult load for the supplier and the customer in terms of reactive power compensation and harmonics filtering.

In order to prevent the adverse effects of nonlinear loads on the power network, passive filters are commonly used. However, different configurations should be considered before making a final design decision. The performance criteria are including current and voltage ratings for filter components, as well as filter and system contingency conditions. Before selecting any filter scheme, a power factor study should be performed to determine whether any reactive compensation is required. If power factor correction is not necessary, a minimum power filter can be designed; one that can handle fundamental and harmonic currents and voltages without involving reactive power. Tuned filters are sometimes needed in combination. In filter design, the capacitor and the reactor impedance must be predetermined. In case engineers do not know the appropriate initial estimates, the process must be repeated until all the values are determined.

In most cases, filter considerations are based on these simplifying assumptions: (a) the harmonic source is an ideal current source; (b) the inductance filter (LF) and the capacitance filter (CF) are lumped elements and their values are constant in the considered frequency interval; (c) the filter resistance can be sometimes neglected and the filter is mainly loaded with the fundamental harmonic and the harmonic to which it is tuned [1]. Recent works focus more on complex filter structures, or large numbers of filters connected in parallel, or their self-interaction and cooperation with the power system (the network impedance), as well as non-zero filter resistances, which may impede or even prevent an effective analysis. The new approach uses artificial intelligence methods, such as genetic algorithm (GA) as appeared in [2-4].

2. OVERVIEW OF THD AND TDD PREDICTION METHODS

The harmonic source can cause equipment failure at both in networks and users' installation systems subjected to voltage and current source that is produced. Effects such as exposure are usually not visible [5], however this may lead to serious consequences in the long and medium terms. The followings are the frequently encountered harmonic problems faced by the utilities industries:

i) Voltage distortion
ii) Increased of RMS currents, heating and line losses
iii) Need a higher K-factor transformer due to overheating on the power transformer.
iv) Derating on equipment performance
v) Overloading at neutral and phase conductors
vi) Tripping due to voltage harmonic sensitive, fuse blowing of power factor
vii) Failure of control system and reduced system stability.

Harmonic currents are injected from harmonic producing load into the utility network through distribution feeders. This will be affecting the operation of other electrical and electronic equipment which are connected to the distribution feeder, including the harmonic producing loads. It became difficult for the transmission and distribution systems to discern the direction of harmonic flow [6]. As a result, even small harmonic sources can cause high levels of harmonic current flow between customer and utility.

The 2nd harmonic has an impact on the voltage source. When the half-cycle has a higher peak voltage than the next cycle, this effect can be accentuated in the harmonic flow. There will be three main harmonic orders which give higher impact such as 3rd, 5th and 7th order of harmonic [7]. The 3rd harmonic is mainly zero direction. Mostly its rise at the potential of the neutral. This will have a much stronger impact on the communication lines compared to the 5th and 7th order of harmonic, because it creates additional losses in the neutral current path even if the load is balanced but nonlinear. The 5th harmonic stills a predominant component-mix that is observed on the voltage level [8]. The 5th harmonic travel in negative sequence in another term will be reverse rotation. Once the 5th harmonic, this will cause the motor to overheat and fail.

To resolve or minimize the harmonic related problems, IEEE-519 recommended a standard enforced by the utilities industries. IEEE-519 standard defines limits on total harmonic distortion (THD) as well as total demand distortion (TDD) with regards to both voltage and current. TDD is often the most important parameter to check for IEEE-519 compliance, as without each customer staying within limits, it will be difficult or impossible for the utility to meet the voltage requirements [9]. A small current may have a high THD value but does not give a significant effect on the system. Many adjustable speed drives will exhibit high THD for input current when operating at lower load. This is not a significant concern because the magnitude of harmonic current is low even though the current distortion level is high.

TDD is defined as total root-sum-square harmonic current distortion, in percent of the maximum demand load current or 30-minute demand. When the point of common coupling (PCC) is considered at the service entrance or utility metering point, IEEE-519 recommends that the maximum demand load current (IL) be calculated as the average current of the maximum demand for the preceding 12 months. To calculate TDD for new construction, prior to installation of equipment, one may use good engineering judgments to estimate the expected maximum demand load current [10].

2.1 Available Evaluation Methods for TDD and Its Limitations

TDD which is the fundamental of the peak demand load current has served as the basis for guidelines in IEEE-519 Standards (2014) which is a new recommended practice and requirement for harmonic control in power system [11]. If the TDD percentage increases, this will indirectly impact the customer power factor and also the voltage distortion will be produced at the utility distribution side. By eliminating or minimizing the TDD percentage, this could help customers in preventing power sources from the effect of inadequate power factor. Apparently, TDD value needs to be monitored by the customer in order 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. Several methods have been found in the literature to address this problem by using hardware and statistical methods. In this work, an artificial neural network (ANN) estimation scheme will be introduced in characterizing the harmonics distortion point sources and its level in nonlinear power load networks.

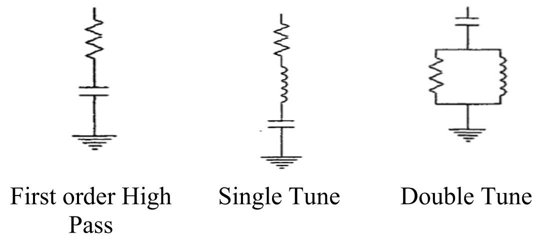

Figure 1. Passive shunt filter [15]

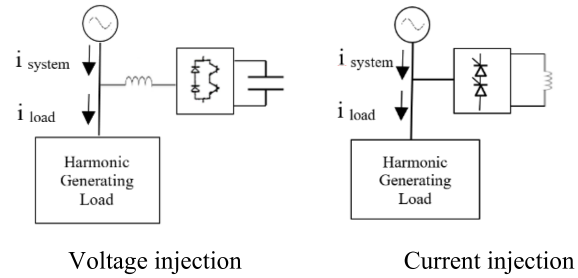

Figure 2. Voltage and current inverters for active filters [20]

2.2 Available Methods for Filtering the Power Distortions

Passive Filters: Passive harmonic filters can either shunt or block harmonic currents [12]. The harmonic currents injected by loads are short-circuited by shunt filters. They prevent harmonic currents from entering the supply system. Due to economic considerations and benefits such as power factor correction [l3], shunt filters are the most common type of filtering scheme used in industry. There are different types of shunt filters depending on the frequency response characteristics. Examples include a single-tune filter, a second order filter, and a high pass filter. Harmonic currents can be blocked by the series filter. The circuit offers a high inductance to the harmonic current because it is double tuned. As it is difficult to insulate and the load voltage is very distorted, it is not frequently used. A common application is in the neutral of a grounded capacitor, where it blocks zero sequence harmonics while maintaining a good ground at the fundamental frequency. Harmonic filters can be extremely difficult to design and are system dependent. Due to this, combinations of harmonic filters have not yet been developed. Passive shunt filters are the most utilized method of harmonic mitigation [l4-16]. They are designed to present a low impedance path to ground for the harmonics to be filtered [15]. Three types of passive shunt filters are presented left-to right as shown in Figure 1 in order of increasing complexity.

Active Filters: Filters that use active mechanisms compensate for distortions in signals by injecting signals that cancel them out. A distorted signal can either be analyzed in a time domain or in a frequency domain. Filtering in the time domain produces the desired sinusoidal signal by injecting signal [17]. The frequency domain filter analyzes the frequency content then injects signals of equal magnitude but opposite phase to cancel the harmonics. Figure 2 shows an active filter injects signals through an inverter that allows a DC current or voltage source to be disconnected, connected positively, or connected negatively from the system [18]. Most active filters have a complex control system for determining how the inverter should be controlled. Generally, they require more complex technologies, resulting in higher costs and difficulty in maintaining [19]. For these reasons, active filters are currently not an attractive option for reducing harmonics in industry [21-22].

There are several simple injection control systems, but they also tend to incur large losses and so are only suitable for low power applications. On the other hand, voltage injection systems can be added in parallel to increase the overall rating of the filter. The primary drawback of voltage injection is the complexity of the control system [20].

2.3 Research Contribution

This study contributes by reviewing existing methods proposed by researchers for distinguishing THD harmonics from power distribution and identifying harmonic direction. Existing methods highlights that many existing efforts assume a radial feeder supplying a single load with known feeder impedance or multiple loads connected to a PCC with sinusoidal voltage and zero impedance at the PCC. However, these approaches fall short in providing a robust solution to identify the TDD impact on the power system. Consequently, there is a need to introduce novel methods in this research to accurately capture both TDD and THD while incorporating an elimination function through harmonic filtering.

This research aims to redesign a Neural Network (NN) to enhance its effectiveness in handling nonlinear load relationships. The proposed NN is designed to generalize learning and generate reliable outputs for inputs not encountered during the training period. It functions as a black box model, specifically identifying THD and TDD impacts on the system and activating a filter to eliminate harmonic effects. Additionally, the study aligns with IEEE 519 standards, focusing on THD and TDD levels of harmonics to minimize their impact through appropriate filtering.

3. THE PROPOSED METHODS

3.1 The Proposed Filtering Strategy for Power Distortions Mitigation

A general procedure for analyzing harmonic problems is to identify the worst harmonic condition based on IEEE-519 standard and recheck for other harmonic conditions. Commonly, impedance versus frequency dependencies are analyzed for all reasonable operating contingencies. The filter component will be activated at each point in the system where harmonic sources are present, such as THD or TDD.

In this work, we introduce the integration of two types of filters to reduce the THD and TDD percentages in power systems simultaneously. The idea of the filtering scheme is illustrated in MATLAB Simulink simulation by the three-phase power line system as in Figure 3(a) (i.e., the high voltage (HV) filter block represented in green box). The details connection of the filter block is illustrated in Figure (b). The power line system contains of the utility equivalent circuit and the customer side load (i.e. represented by a transformer machine).

To simulate customer load, this design includes two control points, which are the universal bridge (IGBT control) and pulse width modulation (PWM) block. In this block, the IGBT circuit is used to convert AC to DC signal to drive the customer load. A PWM circuit with IGBT will create a non-linear load that can be used for studying harmonic distortion (i.e. THD and TDD). The block can control switching devices of single-phase half-bridge, single-phase full-bridge (unipolar or bipolar modulation), or three-phase bridge. In the synchronized mode of operation, second input is added to the block, and the internal generation of modulating signals is disabled. A double-tuned filter has been adopted to minimize harmonic distortion and a C-type (i.e., a type of capacitor bank) filter has been combined to filter the TDD percentage in power lines. The implementation is done in simulation by using MATLAB Simulink software.

3.2 Double-Tuned Harmonic Filter

The harmonics of very high-power converter systems (e.g. those with HVDC) shall be removed by using a double-tuned resonant filter. A single tuned filter has its advantages such as lower power losses at fundamental frequency, compact structure and using single breaker, as well as disadvantages such as more difficult tuning process and greater sensitivity of frequency characteristic to changes in components values. Such filters are economically viable only for very large power installations, hence they are not commonly used for industrial applications. However, there are rare instances in which such filter is justified. Figure 4 shows the double-tuned filter structure. The double-tuned filter performs the same function as two single-tuned filter although it has certain advantages. At the frequency of the parallel resonance that arises between the two tuning frequencies, the losses are lower, and the impedance magnitude is smaller. Figure 5 shows the frequency characteristics of a double-tuned filter. The graph shows the superimposed characteristic curves of the parallel branch. The double-tuned frequencies, *f1*, and *f2* points can be captured clearly. At the two tuned frequencies, the total impedance of the filter is zero, so a double-tuned filter can filter two different frequencies of harmonics. This relation graph is used a guide in the determination of the constructed filter's parameters.

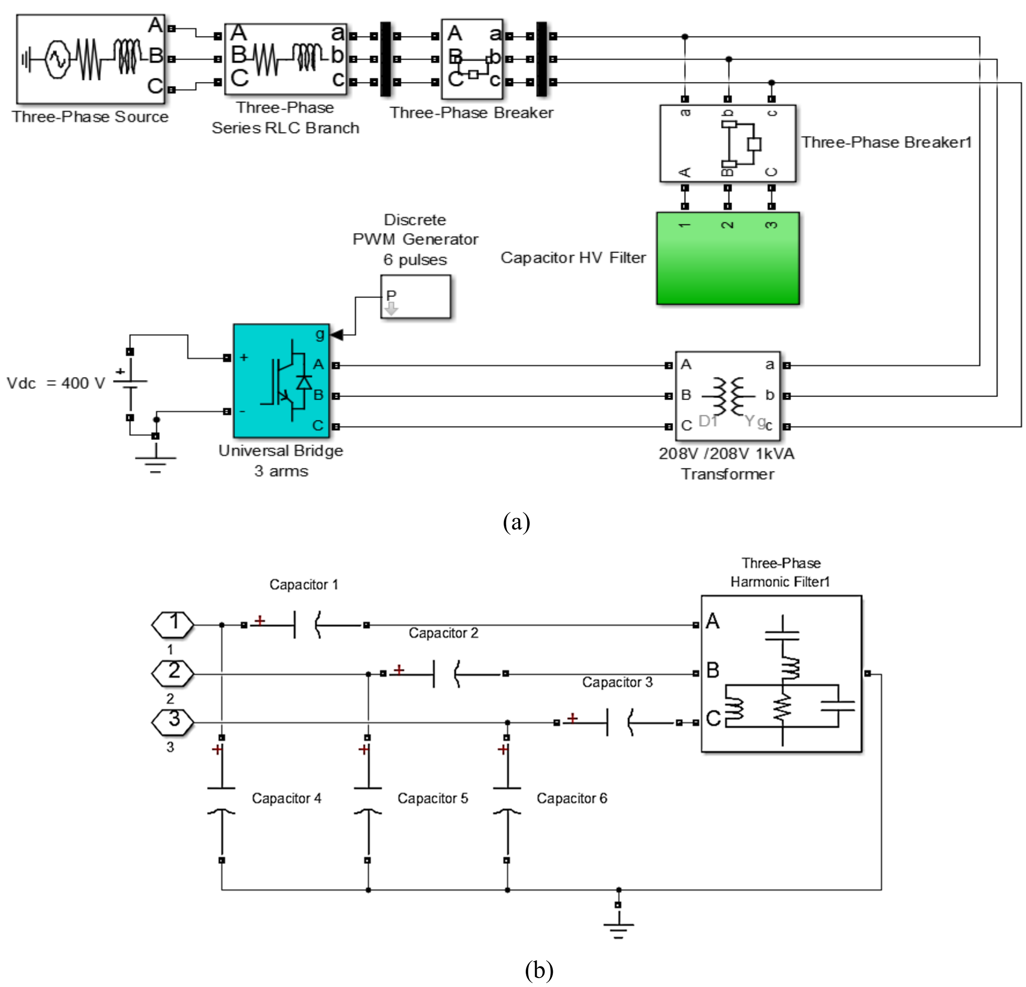

Figure 3. (a) The connection of the proposed filtering scheme in MATLAB Simulink; (b) HV capacitor filter block

To design the double-tuned filter components' parameters (i.e. L_1, L_2, C_1 and C_2), the relationship equations can be found in Equation (1) to Equation (9). In the equations, ω_R denotes as angular resonance frequency of the parallel part; ω_S denotes as angular resonance frequency of the series part; and ω_{n1} and ω_{n2} are the tuned angular frequencies of the double-tuned filter. An optimization method (i.e. genetic algorithm) is used to determine the values of C_1 and C_2 for which the impedance-frequency characteristic attains the least value (at chosen harmonic frequencies) for the given filter power. Other parameters' denotation are as follows: R_{C1}, R_{C2}, R_{L1} and R_{L2} are the equivalent capacitor and reactor resistances (which connected in series to each corresponding component); Q-factors (Q_F) is reactive power of the basic harmonic of the filter or group of filters; and U is RMS operating voltage. In this work, to design the double-tuned filter, the following parameters' values were considered: $Q_F = 1$ Mvar, $U = 6$ kV, $n1 = 5$, $n2 = 7$, $n_r = 6$ [21].

$$\omega_R = \frac{1}{\sqrt{L_2 C_2}} \rightarrow L_2 = \frac{1}{\omega_R^2 C_2} \tag{1}$$

$$\omega_s = \frac{1}{\sqrt{L_1 C_1}} \rightarrow L_1 = \frac{1}{\omega_s^2 C_1} \tag{2}$$

$$\omega_s = \frac{\omega_{n1}\omega_{n2}}{\omega_R} \tag{3}$$

$$C_2 = \frac{\omega_s^2}{\omega_{n1}^2 + \omega_{n2}^2 - \omega_R^2 - \omega_s^2} C_1 \tag{4}$$

$$C_1 = \left\{\omega_1 \left(\frac{\omega_g}{\omega_{n1}\omega_{n2}}\right)^2 - \frac{1}{\omega_1} + \frac{\omega_1[(\omega_{n1}^2 + \omega_{n2}^2 - \omega_R^2)\omega_R^2 - \omega_{n1}^2 + \omega_{n2}^2]}{\omega_{n1}^2 \omega_{n2}^2 (\omega_R^2 - \omega_1^2)}\right\} \frac{U^2}{Q_F} \tag{5}$$

$$R_{L1} = \frac{U^2}{n_r^3 Q_F^2 k \omega_s L_1} \sqrt{U^4 - Q_F^2 k^2 \omega_s^2 L_1^2} \tag{6}$$

$$R_{L2} = \frac{U^2}{n_r^3 Q_F^2 k \omega_R L_2} \sqrt{U^4 - Q_F^2 k^2 \omega_R^2 L_2^2} \tag{7}$$

$$R_{c1} = \frac{U^2}{n_r^3 Q_F^2 k \omega_R C_1} \sqrt{U^4 - Q_F^2 k^2 \omega_R^2 C_1^2} \tag{8}$$

$$R_{c2} = \frac{U^2}{n_r^3 Q_F^2 k \omega_R C_2} \sqrt{U^4 - Q_F^2 k^2 \omega_R^2 C_2^2} \tag{9}$$

Parameters of the analyzed double tuned filter are listed in Table 1. In this work, a genetic algorithm approach is adopted, which described in [21]. The primary goal of the genetic algorithm is to make the filter structures similar to the basic structures by minimizing the influence of additional resistances. The obtained result is in term of the optimization of the frequency characteristic pattern is shown in Figure 5. The optimal values of the filter parameters obtained from the optimization process are given in Table 1.

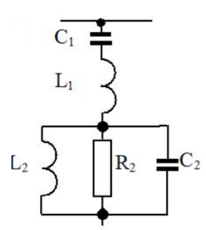

Figure 4. Double-tuned filter structure

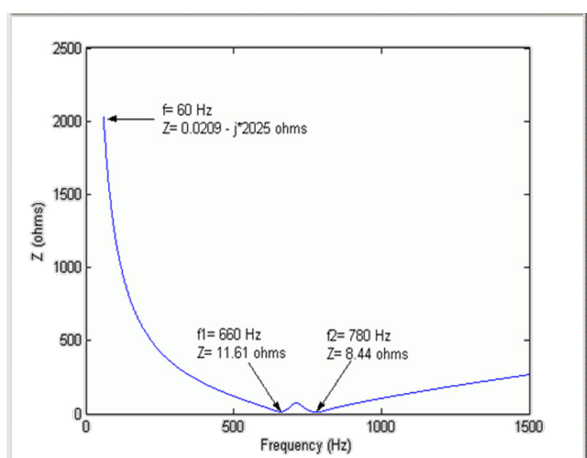

Figure 5. Double-tuned filter frequency characteristics

Table 1. Optimised values of the double-tuned filter parameters

Parameters	Values	Parameters	Values	Parameters	Values
C_1 [µF]	85.52	L_2 [mH]	0.384	R_{C1} [mΩ]	7.44
C_2[µF]	732.72	R_{L1} [mΩ]	10.94	R_{C2} [mΩ]	0.868
L_1[mH]	3.482	R_{L2} [mΩ]	1.207	R_2 [MΩ]	1

3.3 C-type Filter (Capacitor Filter)

The primary disadvantage of most filter-compensating device structures is that they perform poor at filtering high frequencies region. C-type filter is usually used to eliminate this disadvantage by using broadband (damped) filters of the first, second or 3rd order of harmonic distortions [22]. Another advantage of broadband type filter is the significant of their cooperation with power electronic converters in which they damp commutation notches more effectively than single branch filters, since they have a larger bandwidth. The inter-harmonic components (in sidebands adjacent to characteristic harmonics) that are generated by static frequency converters are also eliminated more effectively with these methods. Figure 6 shows the C-type filter design used in this work. In the design, the capacitor branches are tuned to the fundamental harmonic frequency which can achieve a significantly better reduction of active power losses as compared to single branch filters.

Capacitor unit ratings are specified in kVAR. Low voltage systems tend to have capacitors with ratings between 2.5 and 100 kVAR per unit. The capacitors are capable of continuous operation, but not exceeding 135% of the nameplate kVAR. In Table 2, the typical rating for each capacitor is given [23]. Based on Equation (10), if the operating voltage increases or decreases from the nominal operating voltage, then the kVAR delivered changes accordingly.

$$kVAR_{delivered} = Rated\ kVAR \times \left(\frac{Operating\ Voltage}{Rated\ Voltage}\right)^2 \tag{10}$$

To select the suitable capacitor values for a three-phase of 415 V, 50 Hz supply system, the capacitor filter bank design is connected to the neural network source modelling (will be discussed in the next section) to analyze the amount of TDD produced. In this setup, different kVAR values of capacitor unit rating are tested to obtain the percentage of TDD before and after implementation of C-type filter. When TDD drop to below 10%, the kVAR model is chosen. The results of the simulation testing are shown in Table 3.

The IEEE-519 standard requires that TDD be less than 10%, which led to the decision to design the capacitor with 10 kVAR. If the power system is generating high power and high TDD level, the harmonics level generated from load will increase. Therefore, it is proposed to expand the existing reactive power compensation and harmonic mitigation system. For the improvement, the system will comprise of the calibrated double-tuned filter expanded with the C-type filter, namely double-tuned plus C-type filter (DTPC). The series capacitors in the radial system can be used to improve the voltage profile on distribution systems. The basic components used in a series capacitor scheme in a radial system were explained. To summarize, the application of series capacitors for the transmission line tend to increase the transfer capability.

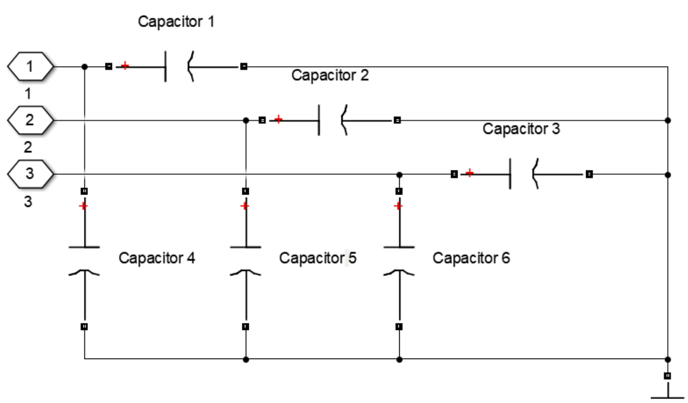

Figure 6. The C-type filter circuit

Table 2: Voltage and kVAR ratings of the capacitor units

Terminal to Terminal Voltage	kVAR Rating	No. of Phases	kV
216 V	5, 7.5,13.3, 20, and 25	1 and 3	30
240 V	2.5, 5, 7.5, 10, 15, 20, 25, and 50	1 and 3	30
480 V	5, 10, 15, 20, 25, 35, 50, 60, and 100	1 and 3	30
600 V	5, 10, 15, 20, 25, 35, 50, 60, and 100	1 and 3	30
2.4 kV	50, 100, 150, and 200	1	75
2.7 kV	50, 100, 150, and 200	1	75
4.1 kV	50, 100, 150, and 200	1	75
4.8 kV	50, 100, 150, and 200	1	75
6.6 kV	50, 100, 150, 200, 300, and 400	1	95

Table 3: Capacitor filter design test with source modelling

Capacitor kVAR	TDD Average (without filter)	TDD Average (with C-type filter)
2.5	20.0%	18.7%
5.0	21.0%	13.0%
7.5	18.7%	10.8%
10	22.0%	5.8%
15	19.6%	5.8%
20	18.0%	5.8%
25	19.2%	5.8%
50	22.0%	5.8%

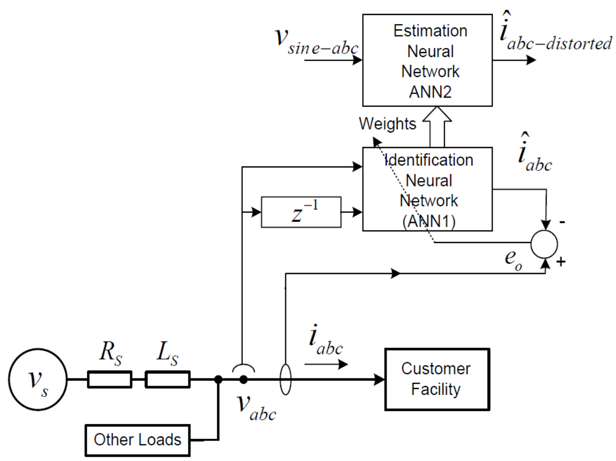

Figure 7. Implementation of the load model identifier for the estimation of power distortions (i.e. THD and TDD)

3.4 Neural Network Load Modelling Combined with the Harmonic Distortion Filter

In this work, a neural networks-based method (namely the Load Model Identifier) is proposed to predict the true harmonic current distortion that can be attributed to a customer, without disrupting the operation of any customer. To illustrate this concept, reconsider the three-phase power line diagram as depicted in Figure 3(a). The whole concept of the neural network-based Load Model Identifier (LMI) is illustrated in Figure 7. In order to filter the harmonic losses, the DTPC filter will be included in this network. When the load modelling predicts THD and TDD percentage, the customer can activate the filter circuit to reduce the harmonic loses in power line. The load modelling predicts the true harmonic current distortion that can be attributed to a load. Instead of using traditional neural network topologies, the load modelling method now uses the identification and the estimation neural network, denoted as ANN1 and ANN2, respectively. In Figure 7, a one-line diagram of a three-phase supply network having a sinusoidal voltage source V_s, network impedance (L_s and R_s), and several loads (one of which is nonlinear) connected to a PCC.

The nonlinear load injects distorted three-phase line current i_{abc} into the network. ANN1 is trained to identify the nonlinear characteristics of the load. ANN2 predicts the true harmonic current that would be injected by the load into the network if it were possible to isolate the load and supply it from a pure sinusoidal source. ANN2 is an exact replica of the trained ANN1 structurally. When the harmonic THD and TDD exceed the predefined percentage (e.g. 10%), the customer shall activate the DTPC filter to minimize the distortion.

3.5 Neural Network Source Modelling Combined with the Harmonic Distortion Filter

By using neural network approach, the second method is proposed to predict the change in the distortion level of the voltage at the PCC if the customers were to draw only fundamental current and filter out its harmonics. This method called as source modelling. Looking back into the utility side from the nonlinear load, the equivalent circuit now consists of all the other loads (i_h) and the actual source voltage. The proposed schematic for the implementation of source modelling method is shown as a single line diagram with DTPC filter embedded as shown in Figure 8.

The nonlinear load injects distorted line current i_{abc} into the network. The voltage at the PCC with all operating load is obtained at V_{abc} point. The input current i_{abc} is used as the input to the ANN1. ANN1 is trained to identify the voltage characteristics at the PCC. At any moment in time after the *ANN1* training has been completed, its weights are transferred to the ANN2. If the nonlinear load were to draw a sinusoidal current, then the distortion level of the voltage at the PCC would change due to the absence of harmonics in the nonlinear load's current. Hence, the *ANN2* based on neural network algorithm is able predict the THD and TDD percentage. When the THD and TDD are higher than predefined percentage (e.g. 10%), DTPC filter will be activated by the customer and this can minimize the harmonic losses in customer network. When harmonic distortion is being eliminated, this can simultaneously improve customer power factor (PF).

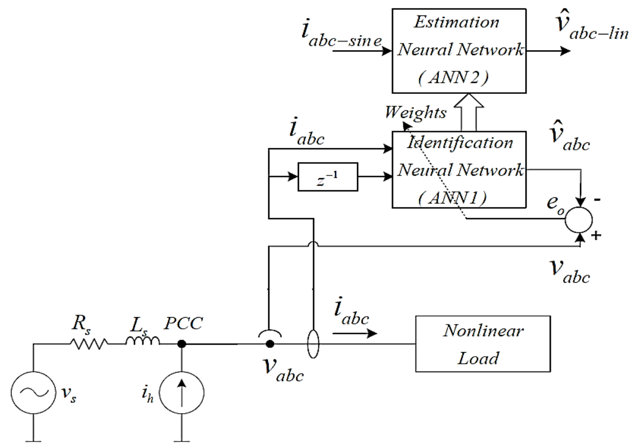

Figure 8. Implementation of the source model for the estimation of power distortions

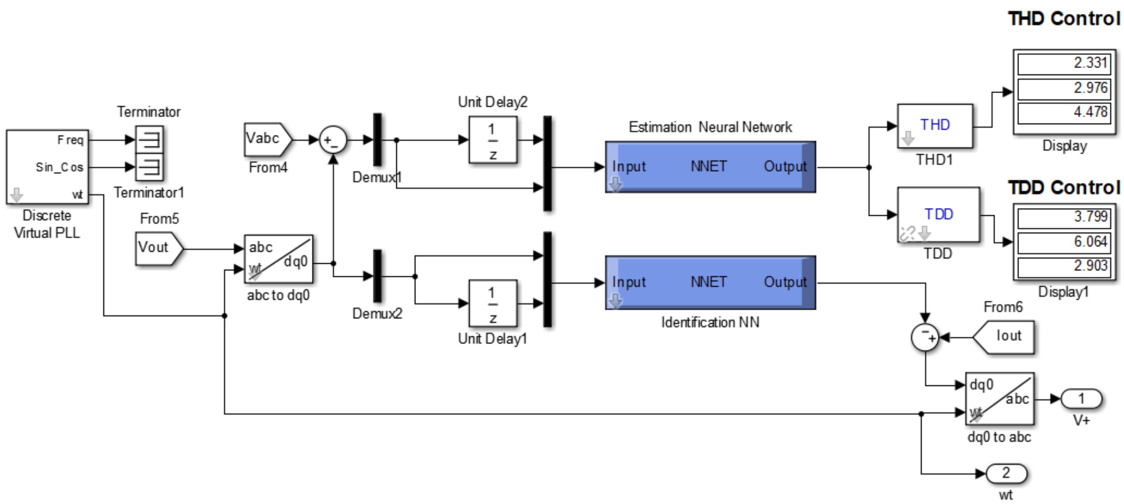

Figure 9. Implementation of load modelling scheme in MATLAB Simulink

4. RESULTS AND DISCUSSION

4.1 Load Modelling with DTPC Filter

Figure 9 shows the proposed schematic in MATLAB Simulink for the implementation of load modelling method, as discussed in Section 3.4. This model can be implemented for single phase as well as for three-phase system. This schematic has inter-relationship with the main power line diagram as illustrated in Figure 7, i.e. V_{abc} block in Figure 9 is connected to V_{abc} power source bus in Figure 7. A number of simulations has been conducted using the load modelling topology to see the effect of the harmonic distortion with and without the implementation of DTPC filter. The test results are listed in Table 4.

According to the IEEE standard, the minimum specification of THD and TDD is 10%. In Table 4, the red results indicate that the distortion readings are out of specification. From the table, it is found that when customer load is connected to the non-linear load, it generates higher harmonics and when the harmonic THD and TDD levels are higher than 10% it creates energy loss. To reduce harmonic loss, the DTPC filter is activated. Once the filter starts the process, it minimizes the harmonic distortion to the lower level and can meet the IEEE-519 standard.

Figure 10 shows the waveform of the AC voltage at the PCC point before activating the DTPC filter to the customer network, which includes the distortion signals. Figure 11 shows the FFT graph for the THD percentage before activating the DTPC filter. The current has a THD of 10.1% and the harmonic in this current includes the contributions from the load. By implementing the DTPC filter, the higher order noise can be filtered out beginning from 2nd order to the 9th order. When the filter starts operating, the noise will be cancelled, and a clean sinewave will be generated. Figure 12 shows a clean sinewave AC signal. The DTPC plays a large role in reducing THD and TDD losses in the power network, hence the customer can meet IEEE519 standards. The FFT graph in Figure 13 shows the THD percentage after activating the DTPC filter. The THD percentage dropped from 10.1% to 4.8%. With these, customers can meet industry standards, which require harmonic levels below 10%.

Table 4. Test data without and with filter mode for load modelling system using THD and TDD specification of 10%

Test Data Without DTPC Filter		
	THD, % (for each phase)	**TDD, % (for each phase)**
Test 1	12,7,8	9,10,7
Test 2	14,8,10	9,10,7
Test 3	17,12,12	9,10,7
Test 4	20,19,15	10,10,7
Test 5	14,13,11	10,10,7
Test Data with DTPC Filter (for each phase)		
	THD, % (for each phase)	**TDD, % (for each phase)**
Test 1	2,2,3	4,6,2
Test 2	1,2,3	5,8,4
Test 3	1,2,3	4,6,3
Test 4	2,2,3	3,6,2
Test 5	2,2,3	4,6,2

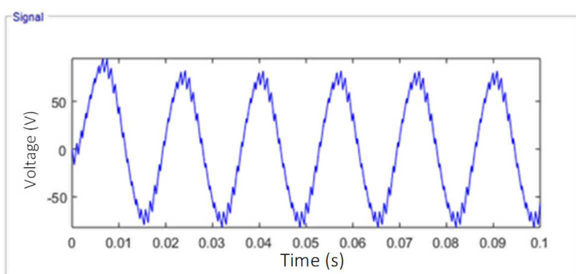

Figure 10. The THD and TDD noise impact at the PCC point without DTPC filter

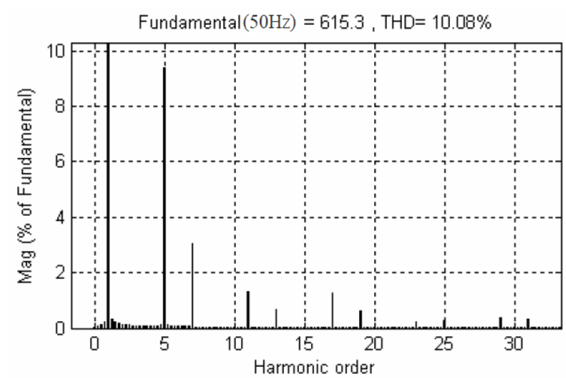

Figure 11. FFT analysis graph without the DTPC filter

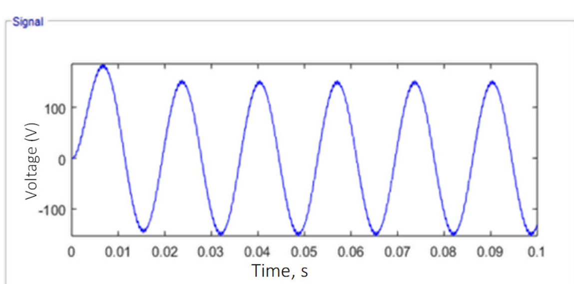

Figure 12. Clean waveform without noise signal at PCC point with DTPC filter

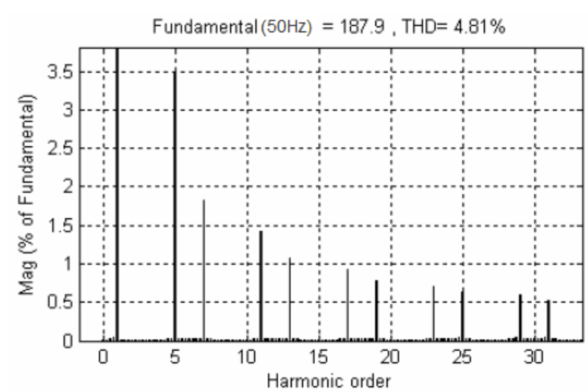

Figure.13. FFT analysis graph with DTPC filter

4.2 Source Modelling with DTPC Filter

Figure 14 shows the proposed schematic in MATLAB Simulink for the implementation of source modelling method, as discussed in Section 3.5. This model can be implemented for single phase as well as for three-phase system. This schematic has inter-relationship with the main power line diagram as illustrated in Figure 3(a).

Table 5 shows a number of test results before and after implementing the harmonic filter. The DTPC able to eliminate the harmonic noises from THD and TDD to the lower level to meet the IEEE-519 standards. This will indirectly help the customer to meet IEEE-519 standards. Without each customer staying within limits, it will be difficult or impossible for the utility distribution authority to meet the voltage requirement. At the maximum load, TDD and total harmonic percentage remain the same. As the load is varied below the maximum load, the TDD value will have a better response as compared to without the filter. This is the significant result obtained from this work.

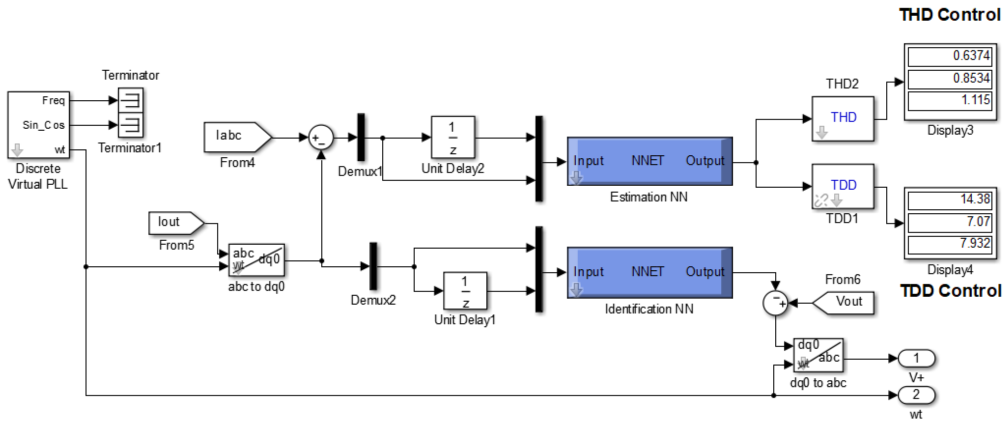

Figure 14. Implementation of source modelling scheme in MATLAB Simulink

Table 5. Test data without and with filter mode for source modelling system using THD and TDD specification of 10%

Test Data without Load and without Filter		
	THD (%) (for each phase)	**TDD (%) (for each phase)**
Test 1	1,2,1	20,15,14
Test 2	2,0.8,0.8	36,20,26
Test 3	2,1,1	28,17,23
Test 4	3,0.8,0.8	36,19,26
Test 5	1,0.8,0.8	35,20,26
Test Data with load and without Filter		
	THD (%) (for each phase)	**TDD (%) (for each phase)**
Test 1	2,0.8,1	32,18,25
Test 2	1,0.8,0.8	29,17,23
Test 3	2,1,1	29,17,24
Test 4	1,0.4,1	30,9,18
Test 5	0.7,0.4,0.8	30,9,15
Test Data with load and with Filter		
	THD (%) (for each phase)	**TDD (%) (for each phase)**
Test 1	0.8,1,1	6,2,3
Test 2	0.8,1,1	6,2,3
Test 3	0.7,0.8.1	3,1,3
Test 4	0.4,0.8,0.8	2,1,3
Test 5	0.4,0.7,0.8	1,1,3

Figure 15 shows the customer's AC current network before DTPC filter is being activated. The sinewave having distortion due to the harmonics that present in the network. Based on IEEE-519 standard, customer needs to maintain the THD and TDD percentage below than 10%. After activating the DTPC filter, the higher order noises have been filtered out and a clean sinewave signal could be obtained which meets the IEEE-519 standard, as shown in Figure. 16.

The most important requirement for any filter is the precise detection of the individual harmonic component's amplitude and phase [23]. To predict the THD and TDD, the load modelling and source modelling concepts have been introduced. With the aid of simulation data from three phase circuits, it has been verified in principle that the proposed method can indeed learn the impedance of the nonlinear load and predict the change in the voltage distortion levels at the PCC.

This is an extremely important parameter which would clearly indicate whether a nonlinear load is responsible for the violation of the IEEE519 voltage limits at the PCC [24-25]. In general, the aim of IEEE-519 is to limit the harmonic current coming from individual consumers as well as to reduce the distortion of the system voltage provided by the utilities.

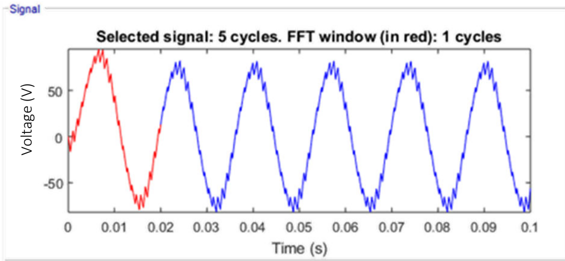

Figure 15. The THD and TDD noise impact at the PCC point without DTPC filter

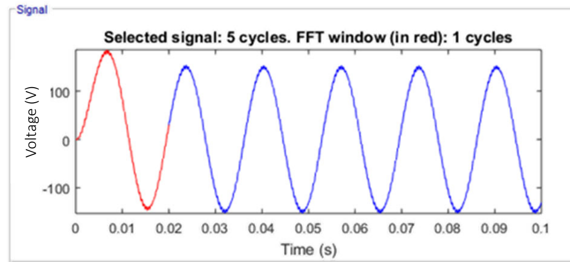

Figure 16. Clean waveform without noise signal at PCC point with DTPC filter

4. CONCLUSION

In this paper, a DTPC filter has been proposed to mitigate harmonic currents injected by the industrial loads. Several selected case studies of power electronic systems analysis are presented, particularly with respect to the occurrence of high harmonics and reactive power compensation. A good way to minimize harmonics in electric power systems is to measure harmonic level in power system and limit them with filter method. This could prevent equipment from any operational problems. Furthermore, the proposed filter is incorporated by a neural network modelling approach for estimating the distortion level, especially the estimation of TDD which in practical the process is too hassle as requires to disrupt the customers' power supply (i.e. measurement in offline mode). By using neural networks, the obtained results are very similar to those obtained by the measurement methods. The neural network model will ease the utility owner and customer in determining the percentage of THD and TDD without disrupting any running process.

These two suggested methods will operate at 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 runs the neural network algorithm. The utility company may penalize the customer based on the load modelling scheme. The proposed load and source modelling will give some idea on the harmonic filtering method. The DTPC filter will be activated to filter out the THD and TDD, based on IEEE-519 percentage guide.

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DECLARATION OF CONFLICTING INTERESTS

The authors declare no potential conflicts of interest with respect to the research and publication of this article.

REFERENCES

[1] P. M. Ivry, *Predicting Stochastic Harmonics of Multiple Converters in a Power System (Microgrid),* Ph.D. Dissertation, University of Nottingham, 2016.

[2] Y. Hoon, M. Mohd Radzi, M. K. Hassan and N. F. Mailah, A dual-function instantaneous power theory for operation of three-level neutral-point-clamped inverter-based shunt active power filter, *Energies*, 11(6), 2018, 1592.

[3] W. Gu, J. Bai, X. Yuan, S. Zhang and Y. Wang, Power quality early warning based on anomaly detection, *Journal of Electrical Engineering & Technology*, 9(4), 2014, 1171-1181.

[4] IEEE Std. 3002.8-2018, IEEE Recommended practice for conducting harmonic studies and analysis of industrial and commercial power systems, *IEEE Std 3002.8-2018*, 2018, 1-179.

[5] E. Cazacu, L. Petrescu and V. Ionita, Derating of power distribution transformers serving nonlinear industrial loads, *2017 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM) & 2017 International Aegean Conference on Electrical Machines and Power Electronics (ACEMP)*, Barasov, Romania, 2017, 90-95.

[6] A. Ulinuha, The impact of harmonic filter locations on distortion suppression, *2016 International Seminar on Intelligent Technology and Its Applications (ISITIA)*, Mataram, Indonesia, 2016, 503-508.

[7] Y. Wang, J. Yong, Y. Sun, W. Xu and D. Wong, Characteristics of harmonic distortions in residential distribution systems, *IEEE Transactions on Power Delivery*, 32(3), 2016, 1495-1504.

[8] R. Senra, W. C. Boaventura and E. M. Mendes, Assessment of the harmonic currents generated by single-phase nonlinear loads, *Electric Power Systems Research*, 147, 2017, 272-279.

[9] A. Ulinuha, The influence of nonlinear loads on optimal operation control of electrical distribution system, *Proceedings of the International Conference on Industrial Engineering and Operations Management*, Bandung, Indonesia, 2018, 1599-1610.

[10] V. Sheelvant, R. Kalpana, B. Singh and P. P. Saravana, Improvement in harmonic reduction of a zigzag autoconnected transformer based 12-pulse diode bridge rectifier by current injection at DC side, *IEEE Transactions on Industry Applications*, 53(6), 2017, 5634-5644.

[11] B. P. Das and Z. Radakovic, Is transformer kVA derating always required under harmonics? A manufacturer's perspective, *IEEE Transactions on Power Delivery*, 33(6), 2018, 2693-2699.

[12] G. W. Chang, S. Y. Chu and H. L. Wang, A new method of passive harmonic filter planning for controlling voltage distortion in a power system, *IEEE Transactions on Power Delivery*, 21(1), 2005, 305-312.

[13] V. Kolář and S. Kocman, Filtration of harmonics in traction transformer substations, positive side effects on the additional harmonics, *Przegląd Elektrotechniczny (Electrical Review)*, 12a, 2011, 44-46.
[14] S. Piasecki, M. Jasiński, K. Rafał, M. Korzeniewski and A. Milicua, Higher harmonics compensation in grid-connected PWM converters for renewable energy interface and active filtering, Przegląd Elektrotechniczny (Electrical Review), 6, 2011, 85-90.
[15] S. Wang, Y. Pei, H. Yi and J. L. Zhang, A new high control precision active power filter, *2019 IEEE 10th International Symposium on Power Electronics for Distributed Generation Systems (PEDG),* Xi'an, China, 2019, 1109-1112.
[16] Y. Bing, D. Jiang, Y. Liang, C. Jiang, T. He, L. Yang and P. Hu, Modified modeling and system stabilization of shunt active power filter compensating loads with μF capacitance, *Energies*, 12(11), 2019, 2084.
[17] A. Lange and M. Pasko, Compensation of the reactive power and filtration of high harmonics by means of passive LC filters, *Przeglad Elektrotechniczny*, 86(4), 2010, 126-129.
[18] S. Torabi Jafrodi, M. Ghanbari, M. Mahmoudian, A. Najafi, E. MG Rodrigues and E. Pouresmaeil, A novel control strategy to active power filter with load voltage support considering current harmonic compensation, *Applied Sciences*, 10(5), 2020, 1664.
[19] M. Popescu, A. Bitoleanu, C. V. Suru, M. Linca and G. E. Subtirelu, Adaptive control of DC voltage in three-phase three-wire shunt active power filters systems, *Energies*, 13(12), 2020, 3147.
[20] D. Rivas, L. Morán, J. W. Dixon and J. R. Espinoza, Improving passive filter compensation performance with active techniques, *IEEE Transactions on Industrial Electronics*, 50(1), 2003, 161-170.
[21] R. Klempka, Z. Hanzelka and Y. Varetsky, Bank harmonic filters operation in power supply system–cases studies, *Power Quality Issues*, Intech Open Access, 2013.
[22] K. Ryszard, S. Boguslaw and K. Stanislaw, Minimization of the source current distortion in systems with single-phase active power filters and additional passive filter designed by genetic algorithms, *2005 European Conference on Power Electronics and Applications*, Dresden, Germany, 2005, 1-10.
[23] R. Natarajan, *Power System Capacitors*. *CRC Press*, Boca Raton, Florida, 2018.
[24] Y. Varetsky and Z. Hanzelka, Filter characteristics in a DC drive power supply system, *2008 13th International Conference on Harmonics and Quality of Power*, Wollongong, Australia, 2008, 1-6.
[25] V. Verma and B. Singh, Genetic-algorithm-based design of passive filters for offshore applications, *IEEE Transactions on Industry Applications*, 46(4), 2010, 1295-1303.