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Current Controller with FOPI Modification for VSI-based Active Power Filter

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Abstract – *The integration of photovoltaic (PV) systems into the grid, combined with nonlinear loads and bidirectional power flows, significantly impacts grid voltage stability and total harmonic distortion (THD) in low-voltage distribution systems. This study proposes the application of an Active Power Filter (APF) to improve power quality (PQ) and mitigate harmonic distortion caused by nonlinear loads. Harmonic distortion from nonlinear loads poses a substantial risk of damaging electronic equipment and degrading overall power quality. The proposed APF utilizes a Fractional Order Proportional-Integral (FOPI) controller implemented through a Voltage Source Inverter (VSI). The effectiveness of the FOPI controller was evaluated through simulation and compared to a conventional PI controller. The results demonstrate that the FOPI-controlled system successfully reduces current THD to meet IEEE 519 standards (¡ 5%), highlighting the superior performance and robustness of the FOPI controller compared to traditional approaches.*

Keywords – *Non-linear Loads; Total Harmonic Distortion (THD); Shunt Active Power Filters (SAPFs); Fractional-order PI (FOPI) Controllers; Voltage Source Inverter (VSI).*

I. Introduction

RAPID advances in electrical equipment technology, especially in the field of power electronics, have brought significant benefits in energy conservation, such as in the application of fluorescent lamps (CFLs), LED lamps, and others. However, power electronics-based devices produce non-sinusoidal input currents containing harmonics, known as non-linear loads, which are measured through *Total Harmonic Distortion* (THD). THD, expressed as a percentage, indicates the ratio between the total harmonic components and the fundamental [1]. High THD can be harmful to electrical equipment, causing damage, reduced efficiency, and shortened device life.

Power quality issues are further exacerbated by high harmonic emissions from PV inverters and nonlinear loads on the low-voltage (LV) distribution network, which impact system stability and performance [2]. The reliability of solar PV (PV) generation depends on accurate system design and control to ensure a pure sinusoidal current waveform at the inverter output. The reliability of solar PV generation depends on accurate system design and control to ensure a pure sinusoidal current waveform at the inverter output. Various inverter topologies, modulation techniques, and control strategies have been developed to achieve this goal [3,4]. Sinusoidal pulse width modulation (SPWM) and closed-loop control schemes are commonly used to minimize output distortion and reduce total harmonic distortion (THD) [5,6]. Microcontrollers are often employed to generate PWM pulses and implement control algorithms [7]. Reliability analysis of PV systems considers factors such as component failure rates, environmental conditions, and maintenance strategies [8]. Simulation tools like MATLAB/Simulink are used to model and analyze PV systems before implementation [9]. Advanced control techniques, such as hysteresis current control, have shown promise in improving power quality and reducing harmonics in grid-connected PV systems [10]. However, dynamic non-linear loads can introduce harmonic distortion that propagates through the distribution system impedance and distorts the utility grid current waveform.

To overcome this problem, this study proposes the implementation of an *Active Power Filter* (APF) controlled by a *Fractional Order PI* (FOPI) controller.

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An APF is a type of filter that can be used to reduce power quality problems [11]. The APF, connected in parallel with the load, uses a power electronic converter to inject a compensation current that cancels the load harmonics [12]. Traditionally, APFs have been controlled using PI controllers [13]. The basic components of an APF in this case include a *Voltage Source Inverter* (VSI), a DC source, and a control system [14]. Compared to conventional PI controllers, FOPI controllers offer advantages such as increased robustness to parameter variations, faster response, and better reference signal tracking capability. The use of FOPI controllers in VSI-based APFs shows significant potential to improve power quality in power systems, following IEEE 519 standards.

II. Research Methods

i. Non-linear Load

Non-linear loads are a type of electrical load that causes current to be disproportionate to voltage, resulting in harmonic distortion in the distribution system. Examples include welding machines, furnaces, variable frequency drives (VFDs), rectifiers, lighting ballasts, and modern electronic devices, which typically use semiconductor components such as diodes, thyristors, or transistors.

ii. Harmonic Distortion

Harmonic distortion is a power quality problem encountered in industrial and commercial power systems. Harmonics are elements of an electrical signal with an integer multiple of its fundamental frequency. When the system is operating, it manifests as a sinusoidal voltage or current with some frequency. Non-linear elements in the system can produce a grid voltage with a frequency different from the grid frequency or absorb current with a non-sinusoidal waveform [15]. The impact caused by harmonic distortion on the power system can affect system losses, system operation, and system performance. If harmonics are not controlled to acceptable limits, electrical or electronic equipment can be damaged, causing expensive system outages. The power quality of the system can be reduced due to voltages and currents containing harmonic components.

iii. Harmonic Standard

IEEE 519 defines the power quality standards that must be met at the PCC, which represents the link between the utility and the customer [16]. This standard aims to regulate harmonic generation and provide recommendations for mitigation [17], as seen in Table 1 below.

Table 1: Current Distortion Limits for General Distribution Systems

I_{SC}/I_L	$3 < h < 11$	$11 < h < 17$	$17 < h < 23$	$23 < h < 35$	$35 < h < 50$	THD (%)
< 20	4.0	2.0	1.5	0.6	0.3	5.0
$20 - 50$	7.0	3.5	2.5	1.0	0.5	8.0
$50 - 100$	10.0	4.5	4.0	1.5	0.7	12.0
$100 - 1000$	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

iv. Active Filter

Active filters can effectively cancel or eliminate harmonics and produce distortion-free sinusoidal currents. This process allows active filters to reduce the effects of harmonic distortion and ensure clean power delivery to the system. In addition, active filters can dynamically adapt to changing load conditions and provide real-time harmonic compensation, making them very effective in maintaining power quality.

Figure 1 illustrates the standard configuration of a parallel-connected harmonic filter and a non-linear load.

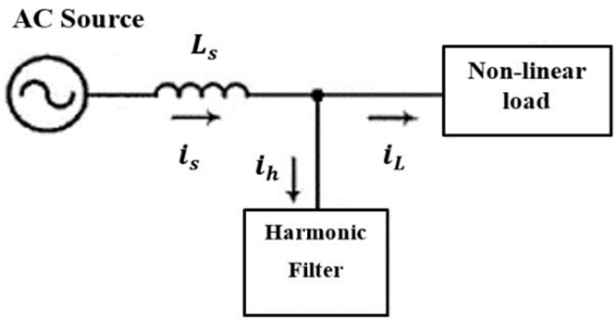

Figure 1: General Harmonic Filter Diagram

Shunt active power filters are commonly used with PWM-VSI (Pulse Width Modulation - Voltage Source Inverter) [18]. PWM-VSI functions as a current source. Systems connected to the AC bus typically use two-level PWM-VSI to operate [19]. A typical SAPF connected in parallel with a non-linear load is shown in Figure 2.

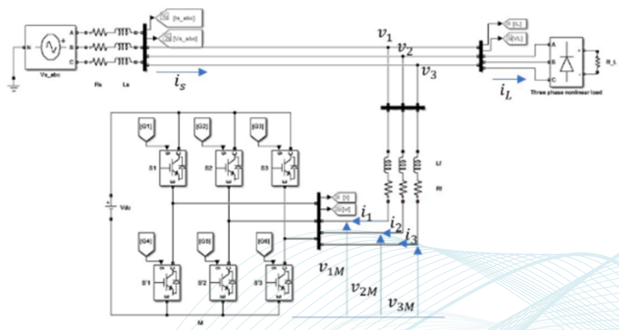

Figure 2: SAPF Basic Circuit connected to Electrical System

Regarding the general harmonic filter connection, applying Kirchhoff's rules to the differential equations in the stationary *abc* frame for voltages and currents, the following expressions are obtained:

$$v_1 = L_f \frac{d}{dt} i_1 + R_f i_1 + v_{1M} + v_{MN} \tag{1}$$

$$v_2 = L_f \frac{d}{dt} i_2 + R_f i_2 + v_{2M} + v_{MN} \tag{2}$$

$$v_3 = L_f \frac{d}{dt} i_3 + R_f i_3 + v_{3M} + v_{MN} \tag{3}$$

where v_1, v_2, v_3 represent the line-to-ground voltage of a three-phase balanced system measured at the PCC.

By applying the Clarke transformation ($\alpha\beta$) to obtain the model in the $\alpha\beta$-zero frames (0-axis is ignored), and then using the $\alpha\beta$ to dq transformation, the AC dynamics can be expressed as:

$$L_f \frac{d}{dt} i_d + R_f i_d = L_f \omega i_q - V_{DC} d_{nd} + v_d \tag{4}$$

$$L_f \frac{d}{dt} i_q + R_f i_q = -L_f \omega i_d - V_{DC} d_{nq} + v_q \tag{5}$$

Equations (4) and (5) describe the decoupled dynamics of the AC current in the dq frame, where i_d and i_q can be independently controlled.

The equivalent input can be defined as:

$$u_d = L_f \omega i_q - V_{DC} d_{nd} + v_d \tag{6}$$

$$u_q = -L_f \omega i_d - V_{DC} d_{nq} + v_q \tag{7}$$

Through the input transformation of the specified equivalent inputs $u_d q$, the joint dynamics of the current tracking problem are transformed into decoupled dynamics. The currents $i_d q$ can be controlled independently by acting on their respective inputs $u_d q$.

The error signal for the current tracking problem is defined as:

$$\bar{i}_{dq} = i^*_{dq} - i_{dq} \tag{8}$$

where i^*_{dq} is the reference current generated by the current reference generator, and i_{dq} represents the actual compensated current in the dq frame (also written as i_{tdq}).

The proficiency of the APF in mitigating these harmonic problems relies on its capability to accurately track the reference current signal and minimize any deviation while compensating for distorted load currents [20]. The **Synchronous Reference Frame (SRF) controller**, used for harmonic extraction, is illustrated in Figure 3.

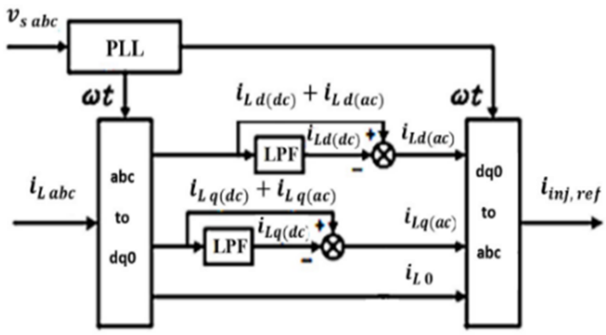

Figure 3: Synchronous dq0 reference frame for harmonic extraction

In the presence of non-linear loads, the load current in the dq frame becomes contaminated by the harmonics of the current generated [21], resulting in the formation of a modified load current expression, as represented by the following equation:

$$\begin{bmatrix} I_{Ld} \\ I_{Lq} \end{bmatrix} = \begin{bmatrix} I_{Ld(dc)} + I_{Ld(ac)} \\ I_{Lq(dc)} + I_{Lq(ac)} \end{bmatrix} \tag{9}$$

where I_{Ldq} represents the actual load current, $I_{Ldq(dc)}$ represents the fundamental component (dc), and $I_{Ldq(ac)}$ represents the harmonic components (ac) in the dq frame.

A tuned numerical low-pass filter (LPF) is used to detect the relevant DC components, and the detected DC components are then subtracted from the actual I_{Ldq} components to isolate the harmonic components:

$$\begin{bmatrix} I_{Ld(ac)} \\ I_{Lq(ac)} \end{bmatrix} = \begin{bmatrix} I_{Ld} - I_{Ld(dc)} \\ I_{Lq} - I_{Lq(dc)} \end{bmatrix} \tag{10}$$

v. *Fractional Order Method*

The design of the FOPI controller can be achieved by utilizing the Digital Fractional Order Differentiator and Integrator (DFOD) [22], which is obtained by using Continued Fraction Expansion (CFE) or recursive expansion formulas [23]. The DFOD output is a discrete system in the form of rational approximations, providing greater control flexibility.

vi. *Proposed FOPI Controller*

The proposed FOPI controller is designed to enhance the performance of conventional PI control, particularly under dynamic load variations. The transfer function of the FOPI controller is defined as:

$$C(s) = k_p + \frac{k_i}{s^\lambda} \tag{11}$$

The active power control for $V_{td(eq)}$ can be expressed as follows:

$$V_{td(eq)} = V_{sd} - \omega L_{eq} I_{tq} + \left(\left(k_p + \frac{k_i}{s^{\lambda}} \right) (I_{Ldref} - I_{td}) \right) \quad (12)$$

Similarly, the reactive power control for $V_{tq(eq)}$ is given by:

$$V_{tq(eq)} = V_{sq} + \omega L_{eq} I_{td} + \left(\left[k_p + \frac{k_i}{s^{\lambda}} \right] (I_{Lqref} - I_{tq}) \right) \quad (13)$$

vii. VSI-based SAPF Design

This system consists of a three-phase network, a non-linear load, and a harmonic filter. The non-linear load produces a non-sinusoidal current (I_{sabc}), which is processed by the current reference generator and current controller to produce the compensation current (I_{tabc}).

The current controller regulates the voltage source inverter (VSI) using PWM signals, thereby generating the appropriate AC waveform to cancel harmonics in the system. The overall architecture of the proposed VSI-based SAPF system is illustrated in Figure 4.

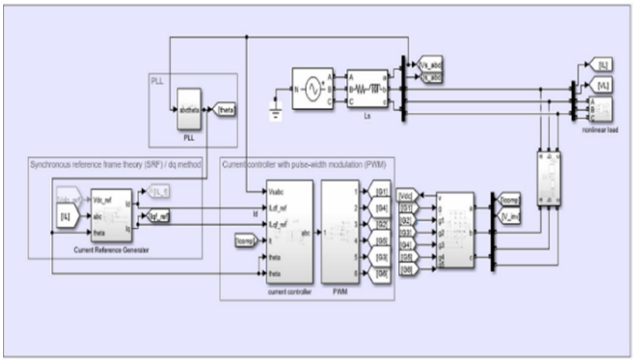

Figure 4: VSI-based SAPF connection

III. Results and Discussion

The proposed PI and FOPI controllers are implemented and simulated to evaluate their performance. Table 2 provides an overview of the characteristics and specific values used in the simulation setup.

Figure 5 visually represents this evaluation, depicting the differences observed before and after applying the harmonic filter.

Case I consists of the grid source and load on the AC side, while the PV system, battery, and EV are on the DC side. Case II consists of the grid source and load on the AC side, while the PV system, battery, and EV are on the DC side, as shown in Figure 6.

Table 2: System Parameters Used for Simulation

Parameter	Symbol	Value	Unit
Grid voltage ($V_{\text{rms ph-ph}}$)	V_s	380	V
Grid frequency	f	60	Hz
DC-link voltage	V_{dc}	800	V
Grid inductance	L_s	0.001	mH
Grid resistance	R_s	0.001	Ω
Filter inductance	L_f	3.69	mH
Line resistance	R	0.15	Ω
Switching frequency	f_{sw}	10000	Hz

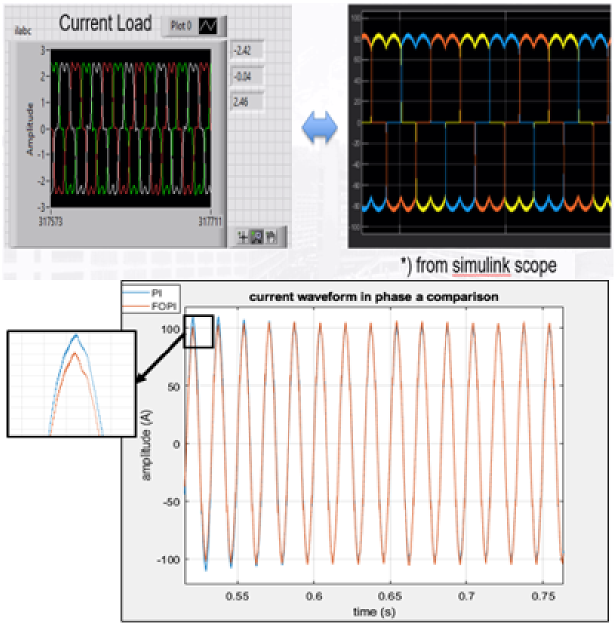

Figure 5: HIL and Offline Results of Non-linear Load Current (top). Current Waveform Using APF (bottom)

The bar chart provides a clear visualization of the varying levels of harmonic distortion achieved through the utilization of the filter (before and after the application of the harmonic filter), which is shown in Figure 7.

As can be seen in Figure 8, the blue bars represent the harmonic levels generated by the non-linear load without APF, the red bars for the system connected to APF in Case I, and the yellow bars for the system connected to APF with FOPI current controller in Case II. Table 3 provides an overview of the specific values from Figure 8.

Figure 8 represents the comparison of THDi between Case I and Case II with dynamic non-linear load in the form of a waveform graph from Table 3. The results show that the FOPI current controller successfully reduces the harmonic level very significantly, which is indicated by the green line curve.

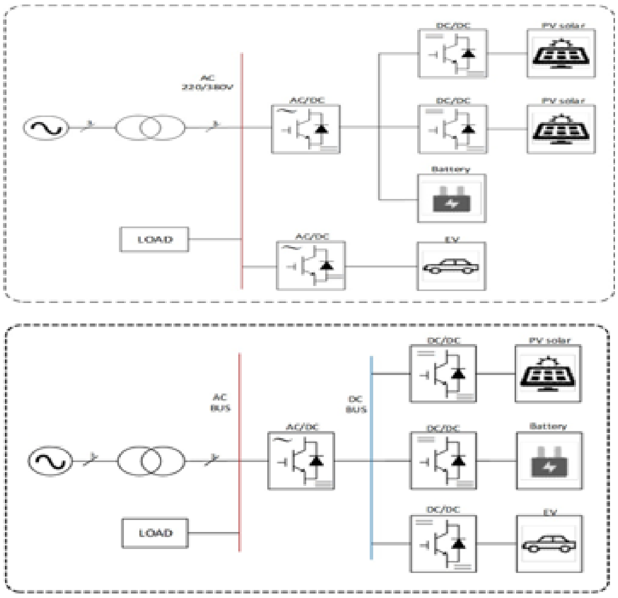

Figure 6: Power System for Case I (top) and Case II (bottom)

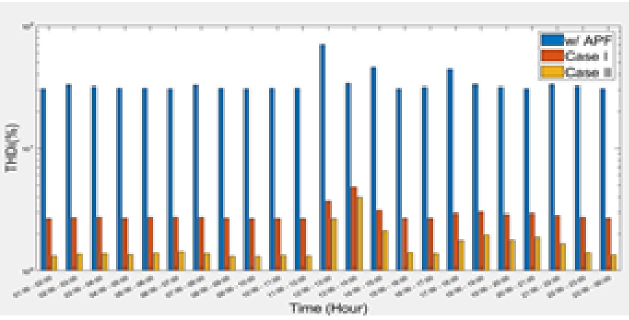

Figure 7: Comparison of THDi (%) for Case I and Case II

Table 3: THDi Case I and Case II with Dynamic Non-linear Load

Time	Non-linear load (without APF)	Case I (PI)	Case II (FOPI)
01:00 – 02:00	30.78	2.68	1.32
02:00 – 03:00	32.87	2.72	1.37
03:00 – 04:00	31.82	2.74	1.39
04:00 – 05:00	30.99	2.71	1.36
05:00 – 06:00	30.92	2.74	1.40
06:00 – 07:00	30.76	2.76	1.44
07:00 – 08:00	32.63	2.74	1.38
08:00 – 09:00	30.87	2.71	1.31
09:00 – 10:00	30.83	2.68	1.31
10:00 – 11:00	30.89	2.57	1.33
11:00 – 12:00	31.01	2.67	1.32
12:00 – 13:00	70.32	3.68	2.67
13:00 – 14:00	34.02	4.83	3.99
14:00 – 15:00	45.93	3.12	2.12
15:00 – 16:00	30.82	2.71	1.41
16:00 – 17:00	31.60	2.69	1.38
17:00 – 18:00	44.26	2.96	1.77
18:00 – 19:00	33.42	3.02	1.96
19:00 – 20:00	31.48	2.91	1.79
20:00 – 21:00	30.76	2.95	1.87
21:00 – 22:00	33.33	2.86	1.67
22:00 – 23:00	32.17	2.75	1.41
23:00 – 00:00	30.76	2.70	1.35

IV. Conclusion

The proposed system is a SAPF implemented with VSI and controlled by FOPI. Simulation tests are conducted

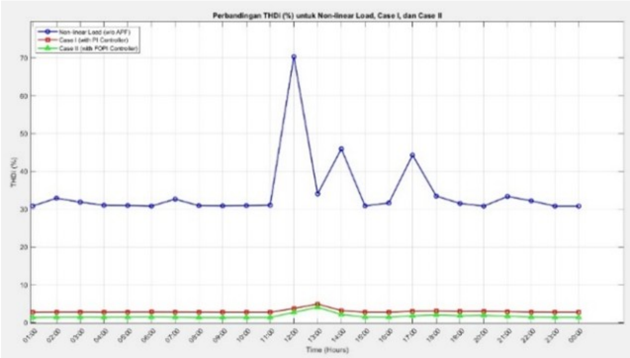

Figure 8: THDi (%) comparison for non-linear Load

to compare the performance of the FOPI controller with the traditional PI controller. Simulation results show that the FOPI controller significantly reduces the overshoot and improves the control precision compared to the conventional PI controller. In addition, HIL simulations confirm the reliability and validity of the proposed method, proving that it is practical and functional for real-world implementation. Based on the simulation results, the THDi value in the system without the harmonic filter is higher than the IEEE 519 standard, indicating the necessity of implementing a harmonic filter. The FOPI current-controlled system for the VSI-based SAPF is proven to meet the IEEE 519 standard, with THDi below 5%.

References

[1] A. D. T. Prasetyo, E. M. Silalahi, S. Stepanus, B. Widodo, and R. Purba, "Reducing of total harmonic distortion by simulating passive filters to suppress harmonic currents with the case: Faculty of engineering building, universitas kristen indonesia jakarta," *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 878, no. 1, p. 012060, Oct. 2021. [Online]. Available: https://doi.org/10.1088/1755-1315/878/1/012060

[2] S. M. Ahsan, H. A. Khan, A. Hussain, S. Tariq, and N. A. Zaffar, "Harmonic analysis of grid-connected solar pv systems with nonlinear household loads in low-voltage distribution networks," *Sustainability*, vol. 13, no. 7, p. 3709, Mar. 2021. [Online]. Available: https://doi.org/10.3390/su13073709

[3] E. S., M. Ali, and O. J., "Pv Inverters and Modulation Strategies: A Review and A Proposed Control Strategy for Frequency and Voltage Regulation," 2020.

[4] Y. A. K. Muhammad, L. Haoming, Y. Zhihao, and Y. Xiaoling, "A Comprehensive Review on Grid Connected Photovoltaic Inverters, Their Modulation Techniques, and Control Strategies," 2020. [Online]. Available: https://www.mdpi.com/1996-1073/13/16/4185/pdf?version=1597315863

[5] S. K. C. Ahmed, S. S. M., A. A. M., and R. M., "Design and implementation of a highly efficient pure sine-wave inverter for photovoltaic applications," *International Conference on Informatics, Electronics and Vision*, 2013.

[6] H. Rafid, A. Rajin, B. Y. Nafisa, and S. K., "Design and construction of single phase pure sine wave inverter for

photovoltaic application," *International Conference on Informatics, Electronics and Vision*, 2012.

[7] D. S. and A. K. Dr., "Highly Efficient Pure Sine-Wave Inverter for Photovoltaic Applications with MPPT Technique," 2014.

[8] O. O. Samuel, "Reliability Overview of Grid-Connected Solar PV System: A Review," *Archives of Advanced Engineering Science*, 2024. [Online]. Available: https://ojs.bonviewpress.com/index.php/AAES/article/download/3083/974

[9] K. S., M. K. J., and M. D., "A Matlab/Simulink modeling for reliability analysis of inverter applied to MPPT based PV system," *IEEE India Conference*, 2015.

[10] O. Dakka and S. M., "Design of a novel control hysteresis algorithm for photovoltaic systems for harmonic compensation," *Bulletin of Electrical Engineering and Informatics*, 2024. [Online]. Available: https://beei.org/index.php/EEI/article/download/6038/3513

[11] A. Zobaa, *Power Quality Issues*. Rijeka: IntechOpen, 2013. [Online]. Available: https://www.intechopen.com/books/3073

[12] M. Büyük, M. İnci, A. Tan, and M. Tümay, "Improved instantaneous power theory based current harmonic extraction for unbalanced electrical grid conditions," *Electric Power Systems Research*, vol. 177, p. 106014, Dec. 2019. [Online]. Available: https://doi.org/10.1016/j.epsr.2019.106014

[13] H. Abu-Rub, M. Malinowski, and K. Al-Haddad, Eds., *Power Electronics for Renewable Energy Systems, Transportation and Industrial Applications*, 1st ed. Wiley, 2014. [Online]. Available: https://doi.org/10.1002/9781118755525

[14] K.-H. Tan, F.-J. Lin, and J.-H. Chen, "A three-phase four-leg inverter-based active power filter for unbalanced current compensation using a petri probabilistic fuzzy neural network," *Energies*, vol. 10, no. 12, p. 2005, Dec. 2017. [Online]. Available: https://doi.org/10.3390/en10122005

[15] M. M. Almelian, "Optimal design of passive filter to mitigate harmonic in power frequency," Jun. 2015.

[16] M. Alhasheem, P. Mattavelli, and P. Davari, "Harmonics mitigation and non-ideal voltage compensation utilizing active power filter based on predictive current control," *IET Power Electronics*, vol. 13, no. 13, pp. 2782–2793, 2020. [Online]. Available: https://doi.org/10.1049/iet-pel.2019.0985

[17] M. Z. M. Radzi, M. M. Azizan, and B. Ismail, "Observatory case study on total harmonic distortion in current at laboratory and office building," *J. Phys.: Conf. Ser.*, vol. 1432, no. 1, p. 012008, Jan. 2020. [Online]. Available: https://doi.org/10.1088/1742-6596/1432/1/012008

[18] P. Sudhakar, S. Malaji, B. S. Vesh, and U. L. Rose, "Protection and control challenges of a distributed generation injected distribution networks," *IJAREEIE*, vol. 3, no. 11, pp. 13 212–13 223, Nov. 2014. [Online]. Available: https://doi.org/10.15662/ijareeie.2014.0311039

[19] L. Morán and J. Dixon, "Active filters," in *Power Electronics Handbook*. Elsevier, 2011, pp. 1193–1228. [Online]. Available: https://doi.org/10.1016/B978-0-12-382036-5.00041-0

[20] C. Kamalakannan, L. P. Suresh, S. S. Dash, and B. K. Panigrahi, Eds., *Power Electronics and Renewable Energy Systems: Proceedings of ICPERES 2014*, ser. Lecture Notes in Electrical Engineering. Springer India, 2015, vol. 326. [Online]. Available: https://doi.org/10.1007/978-81-322-2119-7

[21] Y. Hoon, M. A. M. Radzi, M. K. Hassan, and N. F. Mailah, "Three-phase three-level shunt active power filter with simplified synchronous reference frame," in *2016 IEEE Industrial Electronics and Applications Conference (IEACon)*. Kota Kinabalu, Malaysia: IEEE, Nov. 2016, pp. 1–6. [Online]. Available: https://doi.org/10.1109/IEACON.2016.8067346

[22] M. Rustemovic and T. Uzunovic, "Comparison of different methods for digital fractional-order differentiator and integrator design," in *2018 41st International Conference on Telecommunications and Signal Processing (TSP)*. Athens: IEEE, Jul. 2018, pp. 1–6. [Online]. Available: https://doi.org/10.1109/TSP.2018.8441509

[23] Y. Chen, B. M. Vinagre, and I. Podlubny, "A new discretization method for fractional order differentiators via continued fraction expansion," in *Volume 5: 19th Biennial Conference on Mechanical Vibration and Noise, Parts A, B, and C*. Chicago, Illinois, USA: ASMEDC, Jan. 2003, pp. 761–769. [Online]. Available: https://doi.org/10.1115/DETC2003/VIB-48391