Grid-Connected Inverter using Model Predictive Control to Reduce Harmonics in Three-Phase Four-Wires Distribution System

Asep Andang, Rukmi Sari Hartati, Ida Bagus Gede Manuaba, and I Nyoman Satya Kumara

Abstract—**This paper presents a three-phase four-wire Grid-Connected Inverter with Model Predictive Control connected to a distribution Grid. The inverter functions as a filter for the harmonics caused by nonlinear loads, and this involves describing the harmonic currents using the dq0 transformation, after which the low pass filter's implementation is changed back to dq0 and used as the reference current for the Model Predictive Control in the current process. Therefore, the reference current was compared with the modeled prediction current with the smallest difference found in different switching states further used to switch the IGBT on the three-phase four-wire Inverter. The test results showed the model has the ability to reduce the THD of harmonic currents formed from nonlinear loads, and the MPC control was observed to have a fast response to reduce harmonic currents under dynamic load conditions.**

Index Terms—**Grid-Connected Inverter; Hybrid Active Power Filter; Model Predictive Control; Harmonics**

I. INTRODUCTION

THE power electronics technology developed using switching pulses for power transistors works at a frequency, which is not the same as the power supply's fundamental frequency and this produces harmonics that further spread to disrupt the power grid [1]. These harmonics can cause several disturbances to the distribution equipment and household appliances such as overheating of equipment, malfunction of protective equipment, and overheating power transformers [2].

The first harmonic reduction process was conducted using a passive filter [3], which works when the harmonic current in the desired harmonic sequence has a very low impedance restricting it from reaching the grid but allows it to flow to the neutral [4]. The Passive Power Filter becomes very efficient for a static load, which does not change but becomes a problem for a dynamic load. Some of its other disadvantages include having a large size, stiffness, and harmonic resonance [5]. Therefore, an active filter was built to overcome the passive filters' weaknesses such that it can handle changes in nonlinear loads dynamically and ensure a fast response to harmonic reduction [6]. Active filters work by injecting a harmonic current without a fundamental frequency of the opposite magnitude to reduce the grid's harmonics [7]. Meanwhile, in another development, a hybrid power filter [8] was formed to combine the advantages of both passive and active power filters to decrease the voltage and current rating [2].

Several methods have been used for current injection process and these include hysteresis [9]- [12], Fuzzy Logic Controller (FLC) [13]- [16], Synchronous Reference Frame (SRF) [17]- [19], Instantaneous Reactive Power Theory (IRPT) [20]- [23], Artificial Neural Network (ANN) [24]- [27], and Sliding Mode Controller (SMC) [28]- [32].

Another control method is the Model Predictive Control (MPC), which is currently being developed in electrical engineering [33]- [34], even though it has long been used in the chemical industry [35]. It predicts plant conditions in the future horizon using a model with the finite control condition set in the form of a switching state inverter and compared with future extrapolation, which considers the switching state condition with the smallest error in cost function [36].

This power filter development is divided into single-phase [37]- [40] for consumer use and three-phase topologies for distributions or consumers. Moreover, the three-phase topology is also divided into three-phase three-wire power filters [41], which are generally used to reduce phases-to-phase connected loads such as induction motors or three-phase loads without neutral. However, always balanced with a rare occurrence of unbalance. Moreover, the second is a three-phase four-wire power filter [42]- [43] which is used to anticipate when a single-phase load connected to the three-phase distribution produced an unbalanced load. The three-phase four-wire hybrid active power filter is presented in Fig. 1 and the nonlinear and unbalanced loads were observed to be posing a challenge, either in one of the phases or all three.

This paper discusses the three-phase four-wire Grid-Connected Inverter functioning as a hybrid active power filter with the ability to reduce harmonics and balance currents caused by unbalanced loads associated with the MPC method in the distribution where the prediction used is a limited unit referring to the switching conditions of Grid-Connected Inverter. Meanwhile, the model was verified by simulation using Matlab-Simulink.

II. GRID-CONNECTED INVERTER

The proposed Shunt Hybrid active filter is a combination of the passive power filter consisting of an LC and an inverter

Manuscript received June 7, 2021; revised November 3, 2021. This project is funded by the Ministry of Education and Culture through the Research Institutes and Community Service at Siliwangi University in Tasikmalaya.

Asep Andang is an Assistant Professor in the Department of Electrical Engineering Siliwangi University, Tasikmalaya, Indonesia and a PhD candidate in the Electrical Engineering, Udayana University, Denpasar, Indonesia (Corresponding author mail: andhangs@unsil.ac.id).

Rukmi Sari Hartati is a Professor in the Electrical Engineering, Udayana University, Denpasar, Indonesia (email: rukmisari@unud.ac.id).

Ida Bagus Gede Manuaba is an Associate Professor in the Department of Electrical Engineering, Udayana University, Denpasar, Indonesia (email: ibgmanuaba@unud.ac.id).

I Nyoman Satya Kumara is an Assistant Professor in the Department of Electrical Engineering, Udayana University, Denpasar, Indonesia (email: satya.kumara@unud.ac.id).

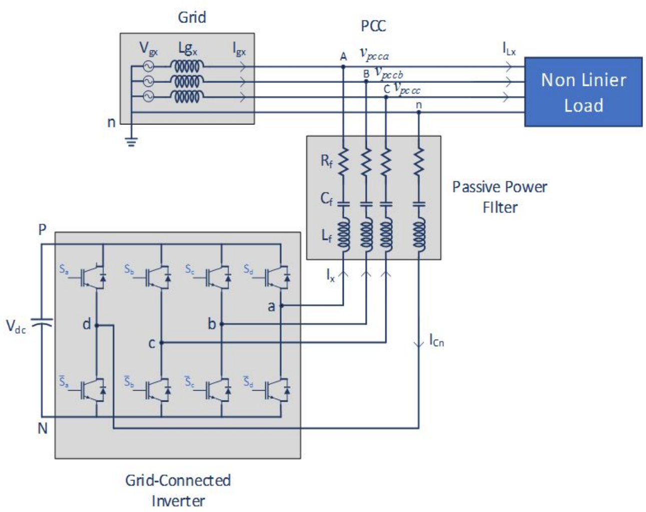


Fig. 1: Three-Phase Four-Wire SHAPF proposed

connected to the grid via an LC filter. The Grid-Connected Inverter is a three-phase four-wire inverter where the neutral leg is switched in contrast to the Neutral Point Clamp (NPC) topology or the divider capacitor [35]. It is used to control the occurrence of an unbalanced load and presented, as shown in Fig. 2. The current through the Inverter is (1)

$$i_n = i_a + i_b + i_c \quad (1)$$

This Inverter has four legs and eight switches, with each leg having two switches which negate each other according to (2)

$$if\ S_x = 1 \text{then} \bar{S}_x = 0 \quad (2)$$

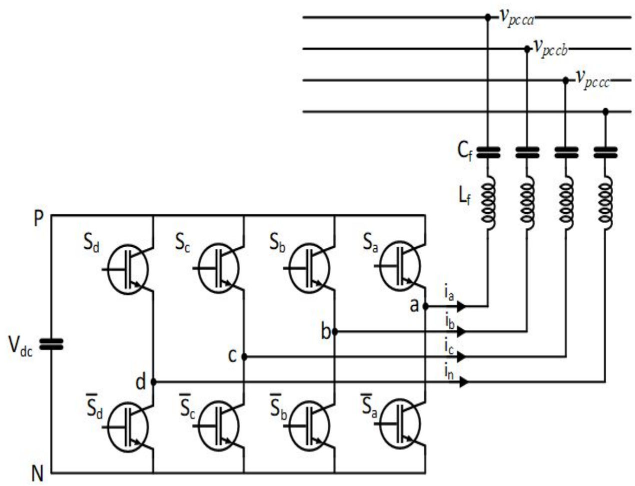


Fig. 2: Three-Phase Four-Wire Grid-Connected Inverter

The voltage produced from point N dc-link is in line with (3)

$$v_{aN} = S_a v_{dc} v_{bN} = S_b v_{dc} v_{cN} = S_c v_{dc} v_{nN} = S_n v_{dc} \quad (3)$$

Where the netral voltage of the load is v_{nN}. Meanwhile, the inverter output voltage becomes [43]

TABLE I: SWITCHING STATE AND OUTPUT VOLTAGE OF GRID-CONNECTED INVERTER [44]

Switching State	S_a	S_b	S_c	S_d	v_{ad}	v_{bd}	v_{cd}
1	1	0	0	0	v_{dc}	0	0
2	1	1	0	0	v_{dc}	v_{dc}	0
3	0	1	0	0	0	v_{dc}	0
4	0	1	1	0	0	v_{dc}	v_{dc}
5	0	0	1	0	0	0	v_{dc}
6	1	0	1	0	v_{dc}	0	v_{dc}
7	1	1	1	0	v_{dc}	v_{dc}	v_{dc}
8	0	0	0	0	0	0	0
9	1	0	0	1	0	$-v_{dc}$	$-v_{dc}$
10	1	1	0	1	0	0	$-v_{dc}$
11	0	1	0	1	$-v_{dc}$	0	$-v_{dc}$
12	0	1	1	1	$-v_{dc}$	0	0
13	0	0	1	1	$-v_{dc}$	$-v_{dc}$	0
14	1	0	1	1	0	$-v_{dc}$	0
15	1	1	1	1	0	0	0
16	0	0	0	1	$-v_{dc}$	$-v_{dc}$	$-v_{dc}$

$$v_{ad} = (S_a - S_d) v_{dc} v_{bd} = (S_b - S_d) v_{dc} v_{cd} = (S_c - S_d) v_{dc} \quad (4)$$

The switching combination and output voltage v_{ad}, v_{bd}, and v_{cd} are presented in TABLE I.

III. HYBRID ACTIVE POWER FILTER FCS-MPC

The Shunt Hybrid Active Power Filter (SHAPF) circuit, which was based on MPC control, consists of an LC passive power filter circuit and an inverter circuit connected to the distribution at a common coupling point (PCC). The MPC control system generates a reference current with input from the load current and the PCC voltage followed by a prediction model and a cost function block, which determines the switching state with the smallest error value used in the Inverter. The circuit schematic is shown in Fig. 3.

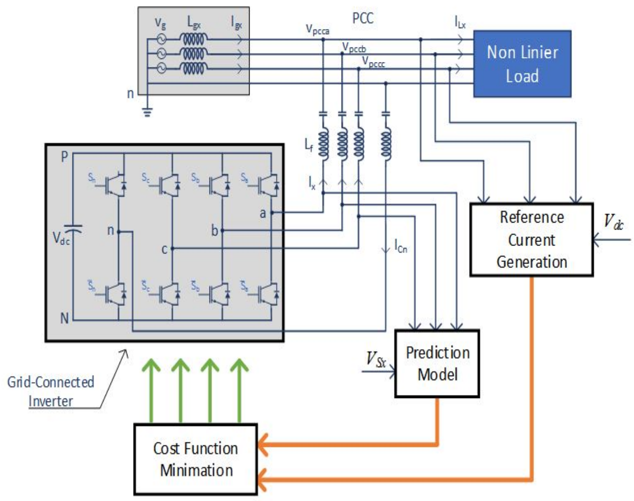


Fig. 3: Three-Phase Four-Wire Shunt Hybrid Active with FCS-MPC

A. Hybrid Active Power Filter Circuit

Fig. 4 shows the hybrid active power filter circuit consists of an RLC circuit where R is the resistance in an inductor connected to a grid-connected inverter. The circuit consists of 8 power transistor switches, which produce a combination of $4^2 = 16$ switching states while the best switching state to reduce harmonics was conducted through the Predictive Control Model, which has a finite control set of 16 switching states.

Fig. 4 was designed to simplify Fig. 1 using the Kirchhoff voltage equation on the loop to produce

$$v_{pccx} = L_f \frac{di}{dt} + R_f i + \frac{1}{c_f} \int idt + v_{inv} \tag{5}$$

Where v_{pccx} is the distribution voltage connected to the PCC while L_f, C_f, and R_f are respectively the filter inductance, capacitance, and resistance, which are the inductor's resistance and usually negligible, meanwhile, V_{inv} is the voltage generated by the Inverter and also the switching state for the four legs of the Inverter combined.

The discretization of the derivative [45] was further used to produce the following

$$\frac{di}{dt} \approx \frac{i(k+1) - i(k)}{T_s} \tag{6}$$

The integrals using Forward Euler [46] were used to produce

$$\frac{1}{c_f} \int idt = \frac{T_s}{c_f}(i(k+1) + i(k)) \tag{7}$$

Meanwhile, it is possible to rearrange (5) using (6) and (7) to produce

$$i(k+1) = \frac{1}{\left(\frac{L_f}{T_s} + R_f + \frac{T_s}{C_f}\right)} \left(v_{pccx} - v_{inv} - \left(\frac{T_s}{C_f} - \frac{L_f}{T_s}\right)(i(k))\right) \tag{8}$$

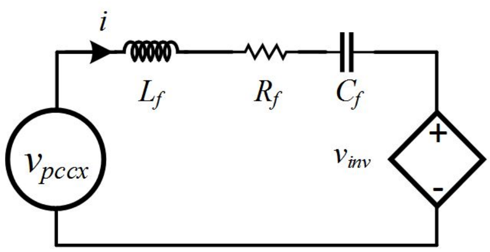


Fig. 4: Equivalent Circuit for Shunt Hybrid Active Filter

B. Reference Current Generation

The Grid-Connected Inverter circuit was controlled using the dq transformation, and the reference current obtained from the load current containing harmonics i_{La}, i_{Lb}, and i_{Lc} was transformed using the dq0 transformation to produce i_d, i_q, and i_0. The id was further passed by an LPF filter at a cutoff point of 20Hz with tolerance to optimize the value and speed of the process [46] to produce $\bar{i}_d$ as shown in the circuit of Fig. 5.

The $\bar{i}_d$ is the active dc component on the d axis which was subtracted from the i_d to produce $\tilde{i}_d$ which is an ac component with a harmonic frequency and without a fundamental. Moreover, $\tilde{i}_d$ was later corrected by i_{cm} from the inverter dc voltage regulator - a power supply connected to

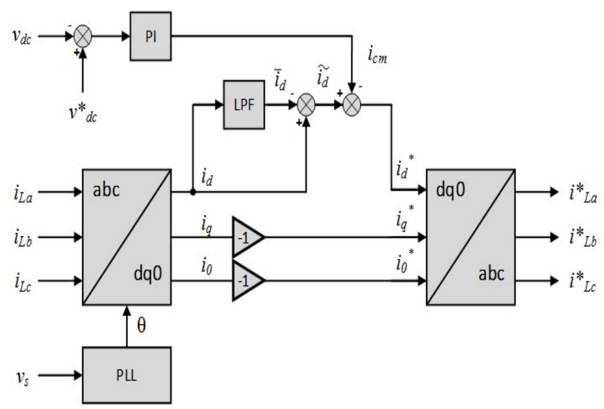


Fig. 5: Reference Current Generation using dq method

an inverter circuit with PI control to maintain the magnitude and transient condition of the reference current [47] and the process generated i_d*. The magnitude was, however, reversed for quadrature and zero axis currents. Meanwhile, the process on the dq0 axis was transformed again to become the quantity abc to produce $i*_{La}, i*_{Lb}$, and $i*_{Lc}$.

C. Model Predictive Control

The predictive control model in this system started from the input current from the dq0 to abc re-transformation process, which produced $i*_{La}, i*_{Lb}$, and $i*_{Lc}$ - the inputs used in the extrapolation process to produce an extrapolated reference current for the time after (k) which is described as $i_{ref}(k+1)$ [48].

The predictive control model with input in the form of PCC distribution voltage, previous filter current, and inverter voltage with equation (8) will produce $i_{pre}(k+1)$, which is a predictive current with 16 sets of switching states which will compare everything with the reference current to be sought. Switching state, which has the smallest error in the cost function equation [49]. The switching state, which has the slightest error, is then used to activate the Grid-Connected Inverter (CGI) to produce the desired filter current. This process can be seen in Fig. 6.

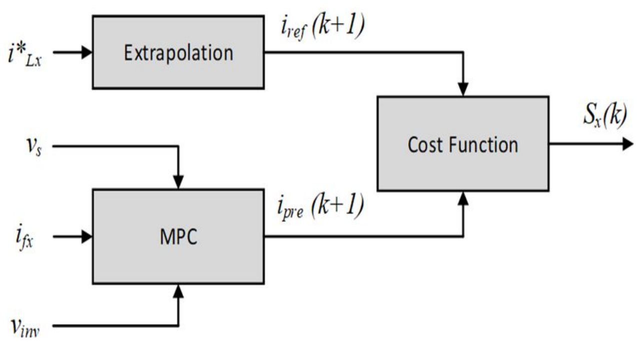


Fig. 6: MPC process consisting of extrapolation, modeling predictions and comparing current in cost function

IV. RESULTS AND DISCUSSION

To validate the model that has been built, whether it can work and reduce harmonic currents in the load, a simulation is performed using MATLAB Simulink using the parameters as in TABLE II.

TABLE II: TESTING PARAMETER

Description	Symbol	Value
Grid Voltage	V_{pcc}	400 Volt
Grid Inductance	L_g	0,5 mH
Grid Resistance	R_g	0,001 Ω
dc Voltage	V_{dc}	725 Vdc
dc Capacitance	C_{dc}	2.350 μF
Filter Inductance	L_f	4 mH
Filter Capacitance	C_f	500 μF
Fundamental Frequency	f	50 Hz

The test is carried out using a balanced nonlinear load circuit and a combined balanced nonlinear load circuit using intermittent intervals.

A. Balanced Load

Balanced nonlinear load testing was conducted by connecting three single-phase rectifiers on the system with wiring, as shown in Fig. 7.

The type of load connected to each of these rectifiers is in the form of resistors and inductors whose values are the same as in TABLE III.

TABLE III: LOAD PARAMETER

Parameter	Value
$R_{La} = R_{Lb} = R_{Lc}$	20 Ω
$L_{La} = L_{Lb} = L_{Lc}$	70 mH

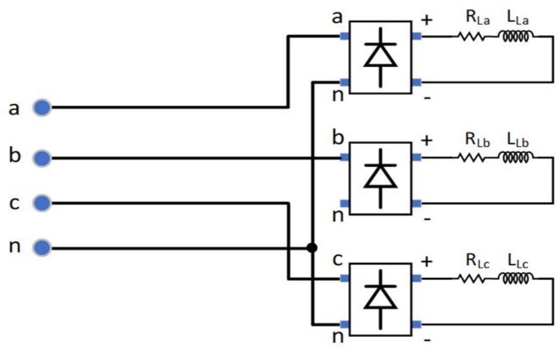


Fig. 7: Single phase rectifier as non-linear load

This test was conducted to determine the extent to which the harmonic reduction capability conducted by SHAPF with MPC control affected the grid, and the results are presented in Fig. 8.

The installation of a balanced nonlinear load produced a working voltage which contains the harmonics shown in Fig. 8(a), and the load current was found to have produced the significant load harmonics. Moreover, Fig. 8(b), founded on the FFT analysis, indicated the THD of the load caused the harmonic currents to reach 36.10% and evenly divided into each phase. This reference current was later used in the MPC process and reduce harmonic currents due to the generation of a balanced reference current for each phase by the balanced load, as presented in Fig. 8(c). The distribution currents were observed to have decreased the harmonics, as shown in Fig. 8(d), while the harmonics current spectrum before and after installation of GCI are presented in Fig. 9.

The test results showed a substantial decrease in harmonics with FFT analysis, and the THD of the harmonics on the distribution current side was confirmed to be 4.72%. This decrease occurred in odd orders ranging from order 3 to an average below 1%. The same was observed with the rms fundamental current, which decreased from 9.49 A to 9.14 A after installing SHAP. The spectrum of harmonic current reduction is, however, shown in Fig. 9.

B. Dynamic Load

The dynamic load was tested using three sets of three-phase four-wire balanced loads added over time and connected via a switch turned on at a specific time as shown in the series of Fig. 10. The value of the load connected to this filter circuit is also presented in TABLE IV.

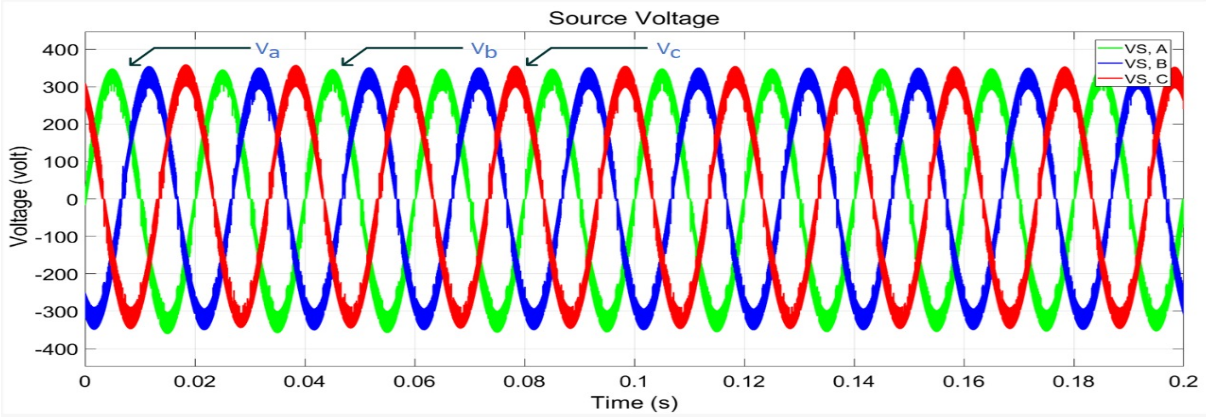
TABLE IV: DYNAMIC TESTING LOAD PARAMETERS

Parameter	Value
R_{L1}	20 Ω
R_{L2}	20 Ω
R_{L3}	7 Ω
L_{L1}	70 mH
L_{L2}	10 mH
L_{L3}	5 mH

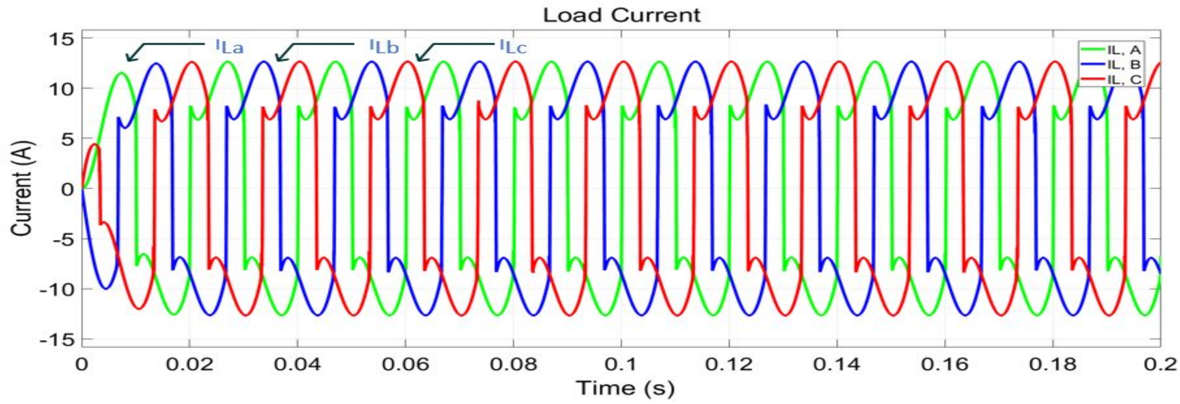
The test was conducted using two sets of nonlinear loads in a single-phase rectifier with a load RL and a linear load RL. The connected loads are single-phase rectifiers with R_{L1} and L_{L1} when switched on, and after running 0.05 seconds, the two loads were connected in the form of an RL load with R_{L2} and L_{L2} quantities. Then, after $t = 0.15s$, the third load was connected to the rectifier with loads R_{L3} and L_{L3}, and results are shown in Fig. 12. Fig. 12(a) presents the shape of the distribution voltage at PCC, which is not affected by the dynamic changes in the load, Fig. 12(b) indicates the difference in load current with the load increased at 0.5 and 0.15 seconds, Figs. 12(c)-12(e) shows the reference current for the three phases a, b and c while Fig. 12(f) illustrates the improved flow in the grid due to the installation of SHAPF. The first load results produced an rms current of 9.45 amperes with 36.59% THD, loads 1 and 2 tested had 20.86 amperes with 16.31%, while the last test with load 1 plus 2 and 3 produced 52.16 amperes with a THD of 9.81%.

The current THD due to nonlinear loads in this test was, however, reduced to 4.37% at load 1, 3.84% at loads 1 and 2, 1.45% at load 1, 2, and 3 by installing a hybrid filter. The decrease in the load current THD was observed to be increasingly significant with the increment in the load current even though the passive filter was designed to handle load 1 but was discovered to be responsive with a substantial increase in load.

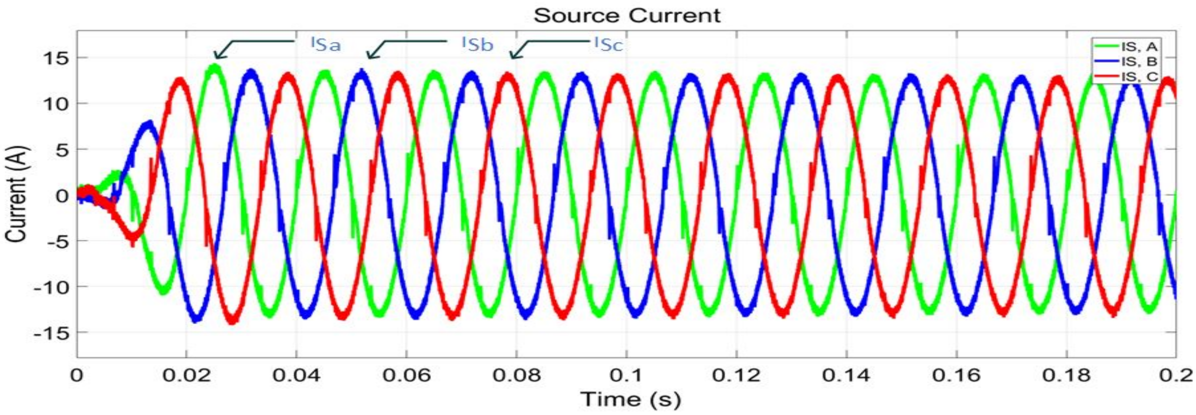
The changes in load at conditions $t_1 = 0.05s$ produced a dynamic process of harmonic reduction that was relatively high without any symptoms of inrush currents reduced by the harmonics. Meanwhile, at the addition of load $t_2 = 0.15s$, a



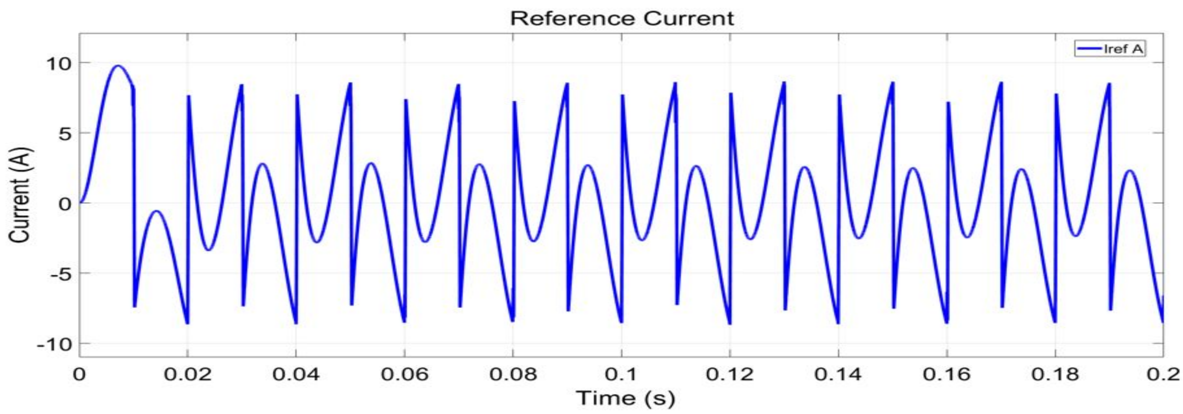
(a)



(b)



(c)



(d)

Fig. 8: Perfomance FCS-MPC three-phase four-wire shunt active power filter in balanced load non-linear.(a) Grid voltage $(V_L = V_g)$, (b) Load current I_L (c) Grid current after SHAPF implemented I_s, (d) Reference current I_{ref}

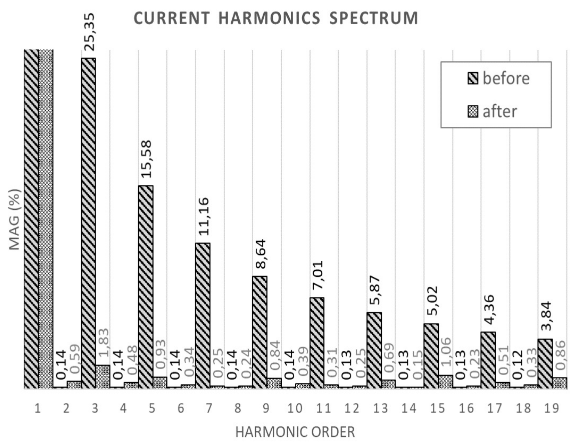


Fig. 9: Current harmonics spectrum

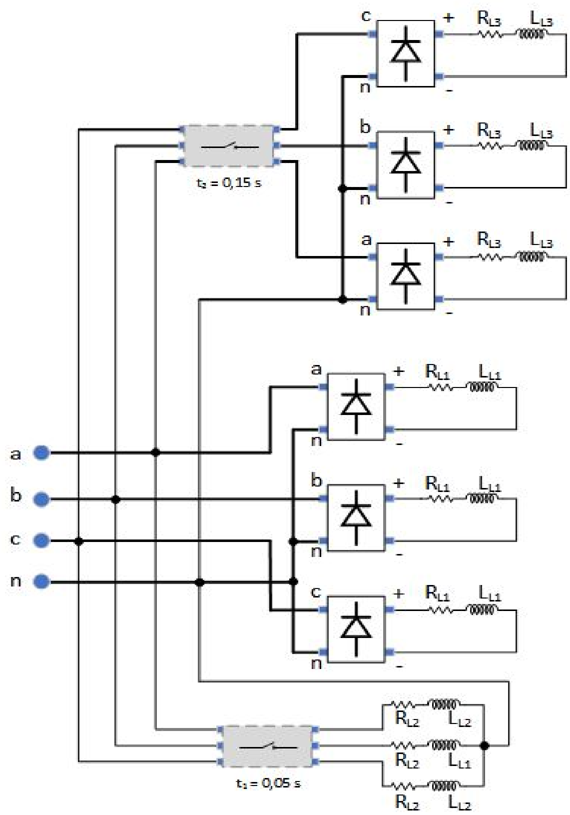


Fig. 10: Dynamics load circuit

significant increase was observed, and the transient process is indicated in Fig. 11.

All the phases change a waveform when turned on at $t_2 = 0.15s$, and the fastest recovery was found in phase c while, in contrast, phases a and b that experienced initial negative currents had up to 2 transient periods while phase a had 1, both for 5 periods. This means phase c had the fastest transient, and this is first considered a positive condition. Another factor observed was the influence of DC voltage regulation on GCI, which was discovered not to be optimal, thereby causing current spikes.

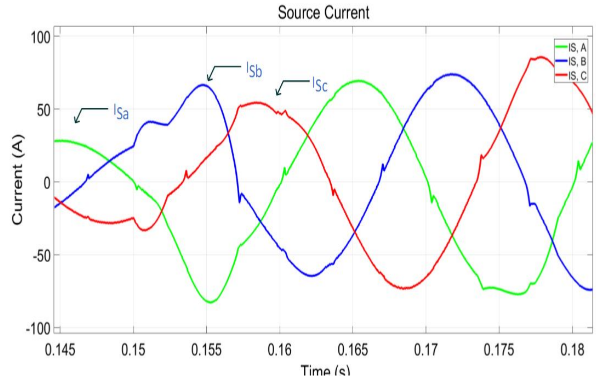


Fig. 11: Zoom transient conditions of load change yellow = phase a, blue = phase b, and red = phase c

V. Conclusion

This paper presents a three-phase four-wire shunt hybrid active power filter model with Predictive Control Model using a passive LC filter and it was tested with balanced and dynamic nonlinear loads.

The results showed the MPC control on SHAPF succeeded in reducing the THD of current harmonics at the load and ensuring it meets the IEEE standard below 5%. Moreover, the transient condition time produced was the longest in the phase, and it experienced an initial negative current condition with the transient state found to be twice the fundamental frequency period.

References

[1] Nagaraj C and Sharma K M, "Improvement of Harmonic Current Compensation for Grid Integrated PV and Wind Hybrid Renewable Energy System," in 2016 IEEE 6th International Conference on Power Systems, 4-6 March, New Delhi, India, 2016.

[2] Lam C S and Wong M C,*Design and Control of Hybrid Active Power Filters*, Springer, Berlin, Germany, 2014.

[3] Senini S T and Wolfs P J, "Systematic Identification and Review of Hybrid Active Filter Topologies," in 2002 IEEE 33rd Annual IEEE Power Electronics Specialists Conference. Proceedings (Cat. No.02CH37289), 23-27 June, Cairns, Australia, 2002.

[4] DAS J C, *Power System Harmonics and Passive Filter Designs*, Jhon Wiley & Sons, New Jersey, USA, 2015.

[5] Akagi H and Fujita H, "A Practical Approach to Harmonics Compensation in Power Systems - Series Connection of Passive and Active Filters," IEEE Transactions on industry applications, vol. 27, no. 6, pp. 1020-1025, 1991

[6] Peng F Z, Akagi H and Nabae A, "A New Approach to Harmonic Compensation in Power Systems," IEEE Transactions on Industry Applications, vol. 26, no. 6, pp. 983-990.

[7] Wang L, Wong M C and Lam C S,*Adaptive Hybrid Active Power Filters*, Springer, Singapore, 2019.

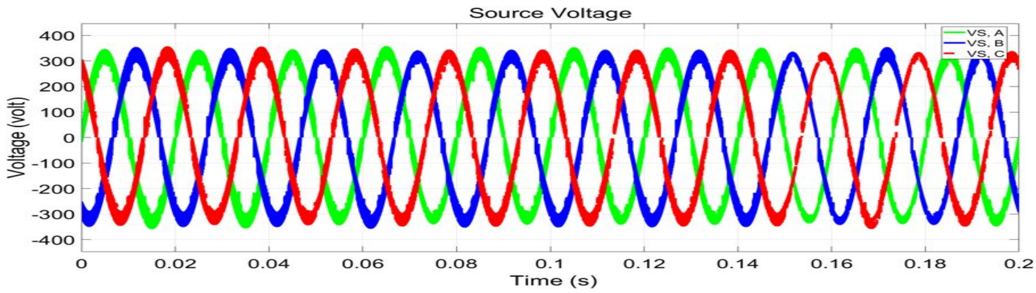
[8] Singh B, Chandra A and Al-Haddad K, *Power Quality Problems and Mitigation Techniques*,John Wiley & Sons, Chichester, United Kingdom, 2015.

[9] Harshithananda B, Priyashree S and Vidya H A, "Mitigation of Harmonics using Hysteresis Hontrol Technique of VSI based Active Power Filter," in 2017 International Conference on Smart grids, Power and Advanced Control Engineering, 17-19 August, Bangalore, India, 2017.

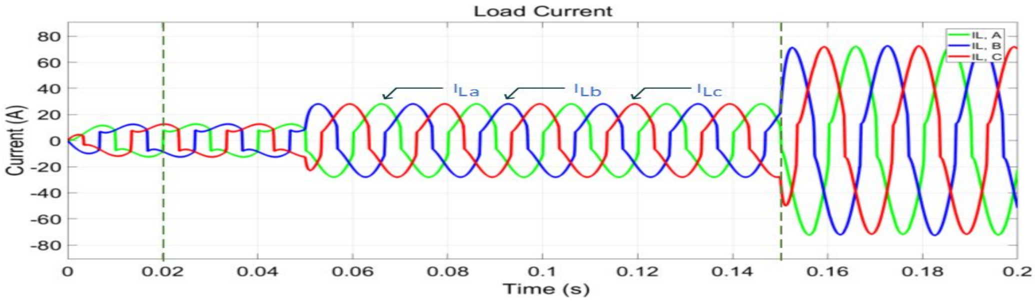
[10] Andang A, Hiron N and Priatna E, "Implementation Modified PQ in Single-Phase Harmonic Reduction Using Hybrid Shunt Active Power Filter with Hysteresis Control," in 2019 IEEE Conference on Energy Conversion, 16-17 October, Yogyakarta, Indonesia, 2019.

[11] Tahmid R and Ahmad S, "Active Power Filter," in International Conference on Electrical, Computer and Communication Engineering, 16-18 February, Cox's Bazar, Bangladesh, 2017.

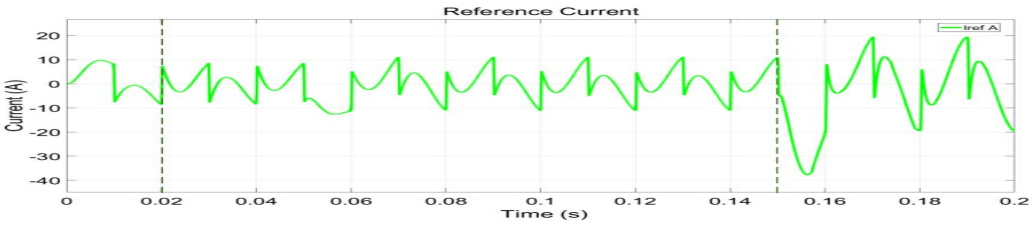
[12] Pandya J, Jadeja R and Trivedi T, "Cascaded Three Level Inverter Based Shunt Active Power Filter with Modified Three Level Hysteresis Current Control," International Review on Modelling and Simulations, vol. 11, no. 3, pp. 125-197, 2018.



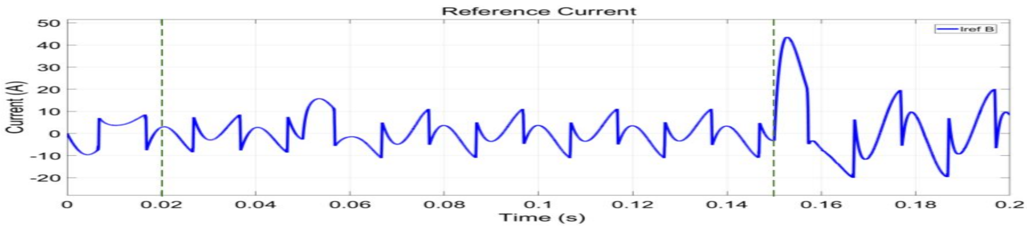
(a)



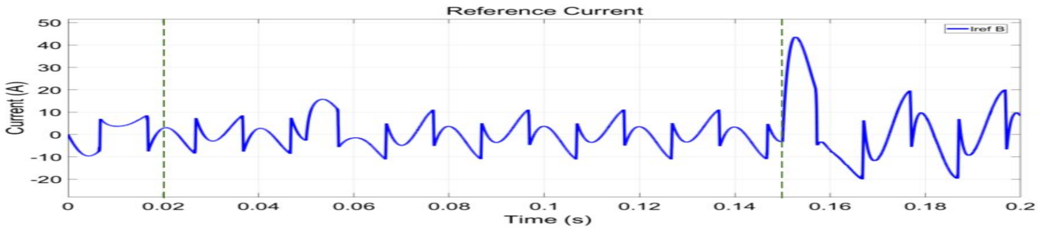
(b)



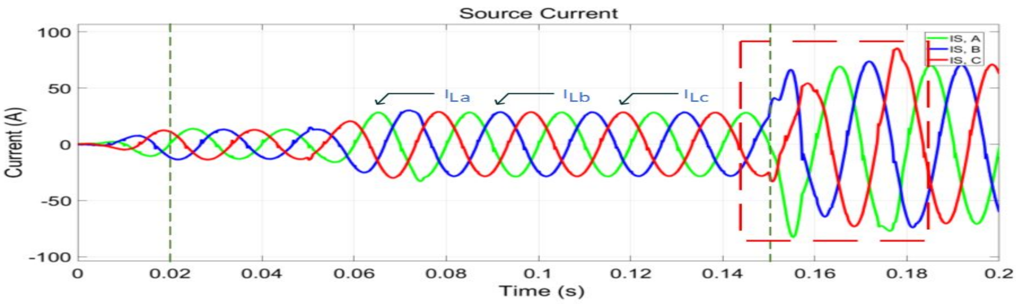
(c)



(d)



(e)



(f)

Fig. 12: (a) Grid voltage ($V_L = V_g$), (b) Load current I_L, (c) Grid current after SHAPF implemented Iref (A), (d) Grid current after SHAPF implemented Iref (B),(e) Grid current after SHAPF implemented Iref (C), (f) Reference current I_{ref}

[13] Naushad K A, Obula Reddy K C and Bhakre P, "Fuzzy Based Active Filter For Power Quality Mitigation," in 2018 IEEE International Conference on System, Computation, Automation and Networking, 6-7 July, Pondicherry, India, 2018.
[14] Salim C, "Five-Level (NPC) Shunt Active Power Filter Performances Evaluation using Fuzzy Control Scheme for Harmonic Currents Compensation," in 2017 6th International Conference on Systems and Control, 7-9 May, Batna, Algeria, 2017.
[15] Unnikrishnan S and Biji G, "Hybrid Series Active Power Filter for Mitigating Power Quality Problems," in 2017 International Conference on Energy, Communication, Data Analytics and Soft Computing, 1-2 August, Chennai, India, 2017.
[16] Chavan U M, Thorat A R and Bhosale S S, "Shunt Active Filter for Harmonic Compensation Using Fuzzy Logic Technique," in 2018 International Conference on Current Trends towards Converging Technologies, 1-3 March, Coimbatore, India, 2018.
[17] Musa S, Radzi M, Hizam H, Wahab N, Hoon Y and Zainuri M, "Modified Synchronous Reference Frame Based Shunt Active Power Filter with Fuzzy Logic Control Pulse Width Modulation Inverter," Energies, vol. 10, no. 6, art. id. 758, 2017.
[18] Jayasankar V N, Gururaj M V and Vinatha U, "A study on hybrid Renewable Energy Source Interface to the Non-Ideal Grid at Distribution Level with Power Quality Improvements," in 2016 IEEE 6th International Conference on Power Systems, 4-6 March, New Delhi, India, 2016.
[19] Santiprapan P, Areerak K and Areerak K, "The Enhanced – DQF Algorithm and Optimal Controller Design for Shunt Active Power Filter," International Review in Electrical Engineering, vol. 10, no. 5, pp. 578-590, 2015.
[20] Chowdhury A, Rajagopalan C and Mulla M A, "Hardware Implementation of Series Hybrid Active Power Filter using a Novel Control Strategy based on Generalized Instantaneous Power Theory," IET Power Electronics, vol. 6, no. 3, pp. 592-600, 2013.
[21] Hoon Y, Mohd Radzi M, Hassan M and Mailah N, "A Refined Self-Tuning Filter-Based Instantaneous Power Theory Algorithm for Indirect Current Controlled Three-Level Inverter-Based Shunt Active Power Filters under Non-sinusoidal Source Voltage Conditions," Energies, vol. 10, no. 3, art. id. 277, 2017.
[22] Lam C S, Wang L, Ho S I and Wong M C, "Adaptive Thyristor-Controlled LC-Hybrid Active Power Filter for Reactive Power and Current Harmonics Compensation With Switching Loss Reduction," IEEE Transaction on Power Electronic, vol. 32, no. 10, pp. 7577-7590, 2017.
[23] Zahzouh Z, Khochmane L and Haddouche A, "Command of the Novel Multilevel Active Power Filter by an Algorithm Through the P-Q Developed," International Review on Modelling and Simulations, vol. 8, no. 1, 41-47, 2015.
[24] Das S R, Ray P K and Mohanty A, "Improvement in Power Quality using Hybrid Power Filters based on RLS Algorithm," Energy Procedia, vol. 138, pp. 723-728, 2017.
[25] Ravikumar A, Mohan N and Soman K, "Performance Enhancement of a Series Active Power Filter using Kalman Filter based Neural Network Control Strategy," in 2018 International Conference on Advances in Computing, Communications and Informatics, 19-22 September, Bangalore, India, 2018.
[26] Mahajan V, Agarwal P and Gupta H O, "Neural Network and Fuzzy Logic Controllers for Three-Phase Three-Level Shunt Active Power Filter," in 2015 IEEE Workshop on Computational Intelligence: Theories, Applications and Future Directions, 14-17 December, Kanpur, India, 2015.
[27] Agrawal S, Kumar P and Palwalia D K, "Artificial Neural Network based Three Phase Shunt Active Power Filter," in 2016 IEEE 7th Power India International Conference, 25-27 November, Bikaner, India, 2016.
[28] Abuzied M, Hamadi A, Ndtoungou A, Rahmani S and Al-Haddad K, "Sliding Mode Control of Three-Phase series Hybrid Power Filter with Reduced cost and Rating," in IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society, 21-23 October, Washington, DC, USA, 2018.
[29] Mane M and Namboothiripad M K, "PWM based Sliding Mode Controller for Shunt Active Power Filter," in 2017 International Conference on Nascent Technologies in Engineering, 27-28 January, Vashi, India, 2017.
[30] Mobayen S, Fekih A, Vaidyanathan S and Sambas A, "Chameleon Chaotic Systems With Quadratic Nonlinearities: An Adaptive Finite-Time Sliding Mode Control Approach and Circuit Simulation," IEEE Access, vol. 9, pp. 64558-64573, 2021.
[31] Vaidyanathan S, Dolvis L G, Jacques K, Lien C H and Sambas A, "A new five-dimensional four-wing hyperchaotic system with hidden attractor, its electronic circuit realisation and synchronisation via integral sliding mode control," International Journal of Modelling, Identification and Control, vol. 32, no. 1, pp. 30-45, 2019.
[32] Khongkhachat S and Khomfoi S, "A Sliding Mode Control Strategy for a Grid-Supporting and Grid-Forming Power Converter in Autonomous AC Microgrids," International Review of Electrical Engineering, vol. 14, no. 2, pp. 118-129, 2019.
[33] Vazquez S, Leon J I, Franquelo L G, Rodriguez J, Young H A, Marquez A and Zanchetta P, "Model Predictive Control: A Review of Its Applications in Power Electronics," IEEE industrial electronics magazine, vol. 8, no. 1, pp. 16-31, 2014.
[34] Geyer T,*Model Predictive Control of High Power Converters and Industrial Drives*, John Wiley & Sons, New York, USA, 2017.
[35] Antoniewicz K, Jasinski M, Kazmierkowski M P and Malinowski M, "Model Predictive Control for Three-Level Four-Leg Flying Capacitor Converter Operating as Shunt Active Power Filter," IEEE transactions on industrial electronics, vol. 63, no. 8, pp. 5255-5262, 2016.
[36] Rashid H M, *Power Electronics Handbook*, Butterworth-Heinemann, Cambridge, 2018.
[37] Andang A, Hartarti R S, Manuaba I and Kumara I, "The Investigation of a Single-Phase Shunt Hybrid Active Power Filter with FCS MPC and Hysteresis Control," in 2019 International Conference on Sustainable Engineering and Creative Computing, 20-22 August, Bandung, Indonesia, 2019.
[38] Talebkhah A, Shadlu M S and Majid Fatemi S, "Control Strategy of a Single Phase Active Power Filter with Adjustable DC Link Capacitor Voltage for THD Reduction in Non-linear Loads," in 2019 10th International Power Electronics, Drive Systems and Technologies Conference, 12-14 February, Shiraz, Iran, 2019.
[39] Andang A, Hiron N, Chobir A and Busaeri N, "Investigation of ultrasonic sensor type JSN-SRT04 performance as flood elevation detection," IOP Conference Series: Materials Science and Engineering, vol. 550, no. 1, art. id. 012018, 2019.
[40] Chaithanakulwat A and Kinnares V, "Implementation of a Low-Cost Single-Phase Grid-Connected Photovoltaic System with Active Power Filtering Mechanism," International Review of Electrical Engineering, vol. 12, no. 2, pp. 175-182, 2017.
[41] Andang A, Hartarti R S, Manuaba I B G and Kumara I N S, "Harmonics Reduction on Electric Power Grid Using Shunt Hybrid Active Power Filter with Finite-Control-Set Model-Predictive Control," International Review of Electrical Engineering, vol. 13, pp. 52-65, 2020.
[42] Antoniewicz K and Malinowski M, "Comparison of Current Control Strategies for Four-Leg Shunt Active Power Filter in Matlab-Simulink," Prz. Elektrotechniczny, vol. 90, no. 10, pp. 214-218, 2014
[43] Chelladurai J, Vinod B and Joe Brislin J, "Finite Control Set based Optimized Model Predictive Current Control of Fourleg Shunt Active Power Filter," Journal of Control Engineering and Applied Informatics, vol. 19, no. 1, pp. 67-76, 2017.
[44] Yaramasu V, Rivera M, Wu B and Rodriguez J, "Model Predictive Current Control of Two-Level Four-Leg Inverters—Part I: Concept, Algorithm, and Simulation Analysis," IEEE Transactions on Power Electronics, vol. 28, no. 7, pp. 3459-3468, 2013.
[45] Du S, Dekka A, Wu B and Zargari N, *Modular Multilevel Converter, Analysis, Control, and Application*. John Wiley & Sons, New Jersey, 2018.
[46] Y. Hoon, M. A. M. Radzi, M. K. Hassan, N. F. Mailah, and N. I. A. Wahab, "A Simplified Synchronous Reference Frame for Indirect Current Controlled Three-level Inverter-based Shunt Active Power Filters," *J. Power Electron.*, vol. 16, no. 5, Sep. 2016, pp. 1964-1980.
[47] Wang Y, Xie Y X and Liu X, "Analysis and Design of DC-link Voltage Controller in Shunt Active Power Filter," Journal of Power Electronics, vol. 15, no. 3, pp. 763-774, 2015.
[48] Li S, Wei D, Wang J S, Yan Z and Wang S Y, "Predictive control method of simulated moving bed chromatographic separation process based on piecewise affine," IAENG International Journal of Applied Mathematics, vol. 50, no. 4, 2020, pp. 734-745.
[49] Antoniewicz K and Rafal K, "Model Predictive Current Control Method for Four-Leg Three-Level Converter Operating as Shunt Active Power Filter and Grid Connected Inverter," Bulletin of the Polish Academy of Sciences. Technical Sciences, vol. 65, no. 5, pp. 601-607, 2017.

Asep Andang received a Master of Electrical Engineering from the Bandung Institute of Technology in 2006. He now works as a lecturer at the Department of Electrical Engineering at Siliwangi University in Tasikmalaya - Indonesia. He is currently a Ph.D. candidate at Udayana University - Indonesia. His research interests include Power Quality, Power Electronics and Drives, Internet of Things and Automation.

Rukmi Sari Hartarti completed her undergraduate program at Sepuluh Nopember Institute of Technology (ITS), Surabaya - Indonesia in 1978. She then received a Master of Technology from Bandung Institute of Technology (ITB), Bandung, Indonesia in 1994 and Doctor of Philosophy from the University of Dalhousie - Canada in 2002. Currently, she is a Professor at the Department of Electrical Engineering at Udayana University. Her research interests include Power Quality and Power System Analysis, and System Optimization.

Ida Bagus Gede Manuaba received a Bachelor's degree in Electrical Engineering from Udayana University in Denpasar - Indonesia, in 1996 and a Master in Electrical Engineering from the Institute of Technology Sepuluh Nopember (ITS), Surabaya - Indonesia, in 1999 and Doctoral degree in Electrical Engineering in 2016. He is a lecturer at Udayana University and has been working there since 1999. His research interests are Modeling and Power Plant Control, Operation, Optimization, and Intelligent Control Systems. He is also a member of The Institute of Electrical and Electronics Engineers (IEEE) since 2016.

I Nyoman Satya Kumara received a Bachelor's degree in Electrical Engineering from Udayana University, Denpasar - Indonesia in 1995, a Master in Electrical Power from the University of Newcastle upon Tyne in 1999, and a Ph.D. from Department of Electrical Electronic and Computer Engineering in the United Kingdom in 2006. His research interests include Renewable Energy Technology, Energy Management, Power Electronics, and Drive and Smart Systems.