Harmonics Reduction on Electric Power Grid Using Shunt Hybrid Active Power Filter with Finite-Control-Set Model-Predictive Control

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Harmonics Reduction on Electric Power Grid Using Shunt Hybrid Active Power Filter with Finite-Control-Set Model-Predictive Control

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Abstract – *This paper discusses a technique of reducing harmonics in electric power grids using Shunt Hybrid Active Power Filter. The filter is controlled by a Model-Predictive Control technique. It can predict the output current magnitude based on its predictive model by noticing the constructed grid topology. Then, this current prediction has been compared to reference currents in order to get an optimal switching pattern concerning a cost function while the optimization has been conducted in order to figure out the maximum condition for the switching pattern. In addition, the Shunt Hybrid Active Power Filter has been compared by combining passive and active filters, which has been expected to be able to reduce harmonics optimally. The use of an LC filter in a single tuned has been also targetted in order to reduce the harmonics in the fifth-order, while the active filter would reduce harmonics due to their resonances. The constructed model has been tested in the simulation in order to evaluate how much harmonic reduction could be performed by the model, and how this model has coped with an unbalanced load, and later affecting the electric power quality. The simulation shows that Shunt Hybrid Active Power Filter along with the Model-Predictive Control method tested by non-linear loads, in terms of balanced and unbalanced loads, can reduce Total Harmonic Distortion of current loads to under 1%. As for unbalanced loads, the phase angle on source voltage does not encounter displacement. Therefore, the Model-Predictive Control on Shunt Hybrid Active Power Filter can effectively be used to reduce harmonics in the grid, during both balanced and unbalanced loading condition.* **Copyright © 2020 Praise Worthy Prize S.r.l. - All rights reserved.**

***Keywords**: Active Power Filter, Model-Predictive Control, Synchronous Reference Frame, Harmonic Compensation, Switching Pattern*

Nomenclature

CSI	Current Source Inverter
VSI	Voltage Source Inverter
GIPT	General Instantaneous Power Theory
SMC	Sliding Mode Control
IPT	Instantaneous Power Theory
FFT	Fast Fourier Transform
SHAPF	Shunt Hybrid Active Power Filter
FCS	Finite-Control-Set
MPC	Model-Predictive Control
THD	Total Harmonics Distortion
SRF	Synchronous Reference Frame
PPF	Passive Power Filter
APF	Active Power Filter
VSI	Voltage Source Inverter
IRPT	Instantaneous Reactive Power Theory
I_{Gn}	n phase grid current
I_{Ln}	n phase load current
I_{Cn}	n phase filter current
V_{sx}	Equivalent source voltage
I_s	Equivalent source current
R_s	Source resistance
L_s	Source inductance
Z_{pf}	Passive filter impedance
V_c	Converter voltage
I_{Lh}	Load harmonics current
V_{dc}	Capacitor voltage
a	Phase operator
v_{xn}	Phase to neutral voltage
i_d	Load current in d-axis
i_q	Load current in q-axis
i_0	Zero axis load current at synchronous reference frame
i_{abc}	Load current
i_{dq}	Load current at synchronous reference frame
i_d*	Reference current in d-axis
i_q*	Reference current in q-axis
i_{qAC}	AC component of the direct-axis Component of the load current
i_{qDC}	DC component of the direct-axis Component the load current
L_f	Filter inductance
R_f	Filter Resistance
C	Filter capacitance
V_{fabcn}	Filter voltage
V_{mn}	Voltage from m to n
T_s	Time sampling
$i_\alpha^*(k)$	Real part of the reference load current at k time

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$i_{\beta}^{*}(k)$	Imaginary part of the reference load current at time
$i_{\beta}^{*}(k+1)$	Imaginary part of the predicted load current vector
$i_{\alpha}^{p}(k+1)$	Real part of the predicted load current vector
S_x	Switching State Inverter
v_i	Inverter output voltage
$i_{ref\text{-}\alpha}$	Reference current in α frame
$i_{ref\text{-}\beta}$	Reference current in β frame
V_{abcn}	Inverter Voltage Switch
$i_{(k+1)}^{p}$	Prediction Current in (k+1) time
i_{refk}	Reference current in k time
g	Cost function

I. Introduction

In the power grids, where the non-linear load is insignificant, harmonics have been usually solved by the use of passive filter [1]. However, the development of power electronic technology gives a significant impact on the electric power grid system with the existence of switching control devices used in both households and the industries. The significant effect of the harmonic generation eventually becomes the problem for electric power grids itself. The rapid development of non-linear load prohibits the passive filter from equalizing it due to the rigid character of the passive filter. In addition, passive filters are also problematic with harmonic resonance [2]. Various electric current compensation techniques have been developed by using the active power filter, as reported by Gugyi [1], [3]. This filter covers the flaws of the passive filter, although it is more expensive [4]. Another development in power filter configurations is a hybrid active filter that has multiple combined configurations between passive and active filters, with the main strength of decreasing rating device that results in cost reductions [5], as well as flexibilities and device reliabilities. Passive LC filters, in both single and double tune, are used in hybrid filters [5], [6] although they use different controls. Moreover, there is also a development of the harmonic filter, namely converter controls. As known before, the passive filter contains either Voltage Source Inverter or Current Source Inverter. This inverter control technique has been derivated from the application of a control system in other disciplines of power filters. At first, control techniques typically used in Voltage Source Inverter have been hysteresis [7]-[9], fuzzy [10]-[13] neural network [14]-[17], General Instantaneous Power Theory [18]-[20], Synchronous Reference Frame [21]-[23] Sliding Mode Control [24]-[26], [38], [39] methods, and the likes, which have been the optimization or combination of all the techniques above. In addition, there is also another developments in the control system used in power electronics which is called the predictive model or Model-Predictive Control. The model has been initially constructed in industrial processes [27], particularly chemical industries [28]. Model-Predictive Control has started to be used to control the switching process in power electronics [29], especially power converters and drive [30]. Model-Predictive Control with Finite-Control-Set is dynamic and has an optimal response for the state system as well as the ability to handle some condition variables in which their function is known as cost functions [28].

The previous study on harmonic reduction has been conducted by Othman [31], who has used the active power filter in terms of L filter, and Voltage Source Inverter control with using Model-Predictive Control.

This study has resulted in a Total Harmonics Distortion reduction of 5.4%. Meanwhile, another study conducted by Cherif [32] in connection with the implementation of Model-Predictive Control in a three-phase three-leg active filter, has indicated that the decrease of Total Harmonics Distortion has become 1.56% for the balanced load.

However, this study conducts the development by adding the filter by using the LC filter tuned on the fifth frequency known as Shunt Hybrid Active Power Filter.

By adding this LC filter, it is expected that the decrease of Total Harmonics Distortion for that order and Active Power Filter will be beneficial for reducing other orders and harmonics resulted from resonances. This paper discusses a modeling of an Active Power Filter and Model-Predictive Control on active power filter using the reference current-generation of dq axis and modeling current-prediction. Testing the model with Simulink Mathlab has been done in order to determine the proposed model's performance.

This paper is organised as follows. Section II presents the Shunt Hybrid Active Power Filter sequences that were investigated, then the equivalent circuit. Section III presents the filter control circuit in the form of Voltage Source Inverter with the control switch and its status, and then the reference current generation circuit using the dq method and Model-Predictive Control method which contains current model prediction and minimization of cost function. Section IV presents the simulation results of the model with various loading conditions, together with analysis of the test results. Finally, Section V contains the conclusions of the test results.

II. Shunt Hybrid Active Power Filter

The use of active filters brings more benefits compared to the passive one.

It does not only handle dynamic loads but also creates good responses in dealing with harmonic resonances. A topological circuit of hybrid active power filter is shown in Fig. 1, in which the passive filter is an LC filter tuned on the fifth harmonic order and serially connected to the active filter in a Voltage Source Inverter with a dc link, a capacitor with voltage controls.

Non-linear load in the form of a three-phase rectifier with RLC load is used to generate currents with harmonics.

The output is the result of uncontrolled rectifier loads connected to different passive loads.

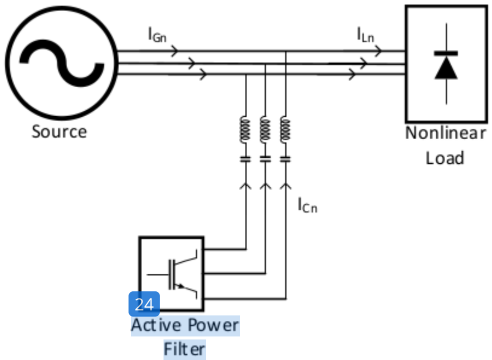


Fig. 1. Hybrid power filter topology in the three-phase electric grid

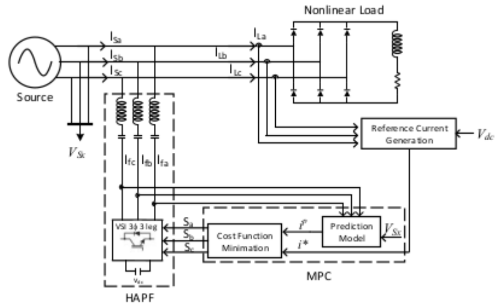


Fig. 3. Control scheme of model-predictive control on hybrid power filter

Meanwhile, the simulation is also needed to be performed in order to know Shunt Hybrid Active Power Filter controls on the unbalanced load, in which the RLC load is set with a different value on each phase.

The principle of the hybrid filter as compensation is shown in Fig. 2. V_{sx} is a source power supply; the non-linear load is considered as a harmonic current source of A proposed passive filter is an impedance of Z_{pf}, and Active Power Filter is considered as a controllable current source. Active Power Filter will result in currents based on Model-Predictive Control in order to export harmonic currents without fundamental currents but with different angles.

Fig. 2 shows a one-phase equivalent circuit in which the passive filter circuit of Z_{pf} is in terms of RLC serial circuit with a quite low value of R, so it is often neglected. Meanwhile, the non-linear load is analogised as a current source of I_{Lh} containing harmonics.

III. Reference Current Generation And Filter Control Circuit With Model-Predictive Control

A hybrid filter controlling the circuit using Model-Predictive Control can be seen in Fig. 3. There are current sensors to get non-linear load current signals that contain harmonics, and voltage sensors to be used in the process of reference signal generations.

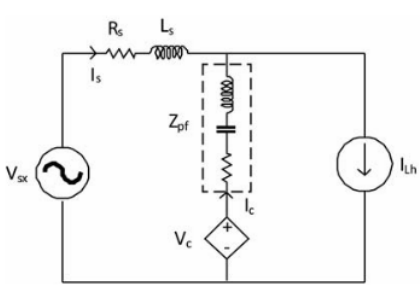


Fig. 2. Equivalent circuit of single-phase electric grid

III.1. Control Circuit

The primary control circuit of this hybrid filter consists of three main blocks, such as a reference current generation that takes data from load currents, in which source voltages in the block is a separate circuit of Model-Predictive Control system [33], [34]. The reference current can use various methods in terms of Synchronous Reference Frame and Instantaneous Power Theory, and then a prediction current that refers to a Model-Predictive control system and cost function minimization. This hybrid power filter is divided into two parts. The first one is the Passive Power Filter that refers to an LC circuit that is tuned on the fifth harmonic.

The second one is the Active Power Filter that works using an inverter from Voltage Source Inverter, which aims to reduce harmonic currents and resulting in harmonic current waveform without different fundamental waves and phases from the inverter leg switching, based on the switching pattern with Model-Predictive Control. By using three-phase three-legs Voltage Source Inverter, there are 2^3 switching conditions. These switching conditions for each phase toward its switching are the followings:

$$S_a = \begin{cases} 1, & \text{if } S_1 \text{ on and } S_4 \text{ off} \\ 0, & \text{if } S_1 \text{ off and } S_4 \text{ on} \end{cases} \quad (1)$$

$$S_b = \begin{cases} 1, & \text{if } S_2 \text{ on and } S_5 \text{ off} \\ 0, & \text{if } S_2 \text{ off and } S_5 \text{ on} \end{cases} \quad (2)$$

$$S_c = \begin{cases} 1, & \text{if } S_3 \text{ on and } S_6 \text{ off} \\ 0, & \text{if } S_3 \text{ off and } S_6 \text{ on} \end{cases} \quad (3)$$

Therefore, the inverter output voltage can be indicated, as follows:

$$v_i = \frac{2}{3}(v_{aN} + a v_{bN} + a^2 v_{cN}) \quad (4)$$

where:

$$a = e^{j\left(\frac{2}{3}\pi\right)} \quad (5)$$

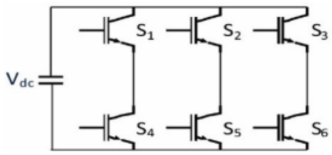


Fig. 4. Switching on voltage source inverter

Therefore, the inverter switching will result in the output voltage, as shown in Table I.

III.2. Reference Current Generation

The reference current generation used here is the Synchronous Frame Reference with the utilization of dq transformation to produce αβ reference current. This method is more reliable in compressing Total Harmonics Distortion compared to the Instantaneous Reactive Power Theory method [30], [35]. Its blocks can be seen in Fig. 5.

I_{abc} load current is changed using the park transformation to I_{dq} to be used as a reference current.

Additionally, I_{dq} is obtained by decomposing a three-phase grid current with using park transformation to get the magnitude of dq. In the process of this transformation, a phase of q angle is needed to be synchronised with source voltages, which will be used as shown in the following equation (6):

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & -\sin\theta & \frac{1}{2} \\ \cos\left(\theta-\frac{2\pi}{3}\right) & -\sin\left(\theta-\frac{2\pi}{3}\right) & \frac{1}{2} \\ \cos\left(\theta+\frac{2\pi}{3}\right) & \sin\left(\theta+\frac{2\pi}{3}\right) & \frac{1}{2} \end{bmatrix}\begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (6)$$

TABLE I
THE INFLUENCE OF SWITCHING TO THE OUTPUT VOLTAGE

No	S_a	S_b	S_c	v_i
1	0	0	0	$v_0 = 0$
2	1	0	0	$v_1 = \frac{2}{3}V_{dc}$
3	1	1	0	$v_2 = \frac{1}{3}V_{dc} + j\frac{\sqrt{3}}{3}V_{dc}$
4	0	1	0	$v_3 = -\frac{1}{3}V_{dc} + j\frac{\sqrt{3}}{3}V_{dc}$
5	0	1	1	$v_4 = -\frac{2}{3}V_{dc}$
6	0	0	1	$v_5 = -\frac{1}{3}V_{dc} - j\frac{\sqrt{3}}{3}V_{dc}$
7	1	0	1	$v_6 = \frac{1}{3}V_{dc} - j\frac{\sqrt{3}}{3}V_{dc}$
8	1	1	1	$v_7 = 0$

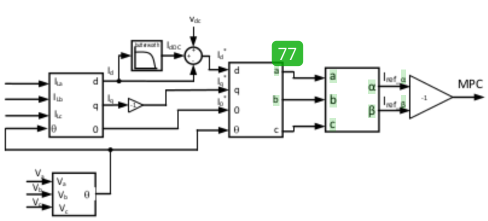


Fig. 5. Reference current generation diagram block

The phase of q angle is obtained by using a Phase-Locked Loop, with the voltage source of V_{abc}. After that, the current magnitude of d i_d axis will be extracted to separate dc and ac components by using the Butterworth filter with a cut off frequency of 50 Hz. The filtering result becomes i_{dDC} to produce references that will be used as a switching signal. Consequently, the result of the Butterworth filter is reduced by id to get i_d*=-i_{dAC} that has different phases as much as 180° from the previous signal. Meanwhile, i_q*=-i_{qAC}-i_{qDC}. After i_d* and i_q* reference currents are obtained, and they are transformed again into a three-phase current of i_{abc}.

The abc reference is transformed into αβ deals using the following formula:

$$\begin{bmatrix} i_{ref-\alpha} \\ i_{ref-\beta} \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (7)$$

Reference currents of i_α and i_β refer to harmonic currents that are then inverted to the 180° phase in order to get opposite harmonic currents that will be used as reference currents through Model-Predictive Control.

III.3. Current Prediction

A prediction current that will be used in the process of predictive model control is obtained from a circuit model [36]. Namely, the input in terms of load currents is transformed into αβ, the source voltages, and the inverter voltages are switched, so, the formula is the following equation (8):

$$V_{abcn} = -L_f\frac{di_c}{dt} - R_f i_c - \frac{1}{C}\int i_c\,dt + V_{fabcn} + V_{mn} \quad (8)$$

The formula above is transformed into a discrete pattern and rearranged again to get the following blueprint:

$$i^p_{(k+1)} = \frac{1}{\frac{L_f}{T_s} + R_f + \frac{T_s}{C_f}}\left(-v_{c(k)} + \frac{L_f}{T_s}\right)i_{(k)} + -\left(\frac{T_s}{C_f}\right)i_{(k)} + sV_{dc} \quad (9)$$

After that, the optimization of the cost function is conducted to help switch the positions closer to reference currents using a formula.

The cost function is used to minimize the error that occurs between the prediction current and differences current after doing a sampling using the difference between the reference current at (k) time and the prediction current at (k+1) time [37], as shown in the following formula (10)

$$g = \left|I_{ref_k} - I^p_{(k+1)}\right|$$
$$g = \left|i^*_\alpha(k) - i^p_\alpha(k+1)\right| + \left|i^*_\beta(k) - i^p_\beta(k+1)\right| \quad (10)$$

From the cost function, it is known that the smallest inverter-switching results in errors towards reference currents, in each sampling. Hence, it has been posible to figure out the optimal switching pattern in order to reduce harmonics on grids.

IV. Result and Discussion

The model constructed in Simulink shown in Fig. 6. needs to be done ahead with a testing simulation toward balanced loads, so, the effectiveness and ability of hybrid filters in reducing harmonics could be reflected. The test is conducted using two different loads, in which the first one is a balanced non-linear load, while the second one is an unbalanced. Additionally, the parameters can be seen as shown in the following Table II. Filter capacitance and inductance are the passive filter circuit that is shunt connected to the loads and serially connected to the Active Filter Circuit that refers to a Voltage Source Inverter.

IV.1. Balanced Non-Linear Load

Connecting sources lead this load to the uncontrollable three-wire three-phase rectifier circuit with load resistors and serial connection inductors that represents the magnitude, as seen in Fig. 7. From the simulation of non-linear load, it can be seen that non-linear load results in load currents containing harmonics, as shown in Figs. 8. In order to confirm that this system works well, the test with the linear load not resulting in harmonics has been conducted. It indicates that the model can work well without waveform transformations in source loads.

The waveform above shows the forms that have been distorted by harmonic waveform from rectifier loads.

Additionally, an analysis using Fast Fourier Transform is conducted to find out the harmonic distorting load's current magnitude. While non-linear loads on the circuit refer to balanced loads, the analysis is only conducted in one phase, which is obtained a harmonic chart spectrum result for phase as shown in Fig. 9.

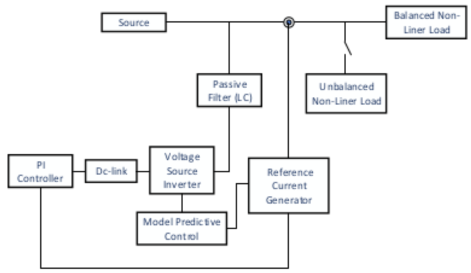


Fig. 6. Implementation in simulink

TABLE II
SIMULATION PARAMETERS

Description	Symbol	Value
Filter Capacitance	C_f	8,8 µf
Filter Inductance	L_f	40 mH
dc Capacitor	C_{dc}	679 µF
Source Inductance	L_s	0,1 µH
Source Resistance	R_s	0,01 Ω

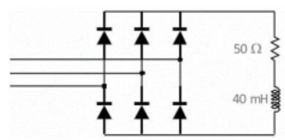
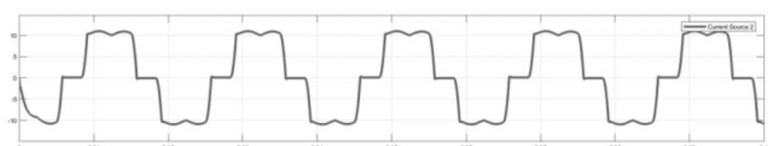
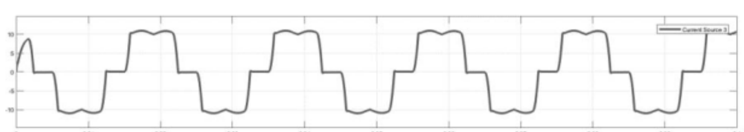


Fig. 7. Balanced non-linear load

(a) Phase a



(b) Phase b



(c) Phase c

Figs. 8. Grid current waveform before applying shunt hybrid active power filter

The Fast Fourier Transform result shows that the result of currents flowing through a non-linear load contains 26.28% Total Harmonics Distortion. Since the non-linear load has similar impedance values, the current waveforms output from three phases is also similar.

However, filter current forms resulted from Voltage Source Inverter are the process of Model-Predictive Control with prediction optimization and reference currents using the Synchronous Reference Frame method. It will be used for Insulated Gate Bipolar Transistor (IGBT) switching on Voltage Source Inverter.

These currents waveforms are realised in Figs. 10. The filter current generation on Voltage Source Inverter produces waveforms that are identical for each phase but they have different angles due to the balanced non-linear load. In consequence, filter waveforms also have similar magnitude. By the filter current generation on Voltage Source Inverter that has been resulted from the prediction and reference current components following the solving method of Synchronous Reference Frame, the current waveform is indicated as shown in Figs. 11, in which the current waveforms are close to pure sinusoidal waveforms.

From Figs. 11, it can be seen that waveforms are close to pure sinusoidal, but in a transient condition, current fluctuations still occur due to the condition of the DC regulator. Furthermore, determining the harmonic reduction after the hybrid-power installation of the hybrid-power filter is made by using Fast Fourier Transform analysis, as shown in Fig. 12.

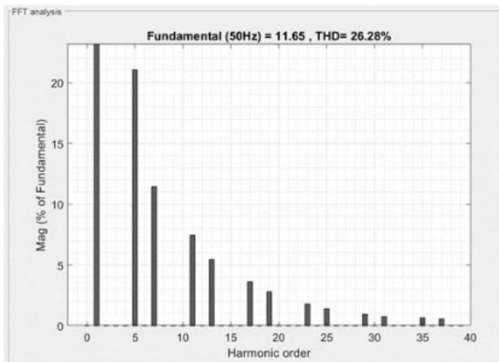
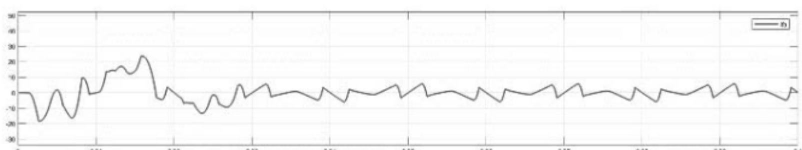
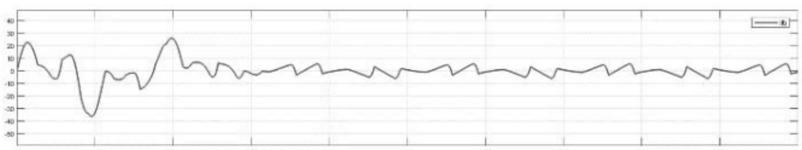


Fig. 9. Harmonic Spectrum in Phase-a



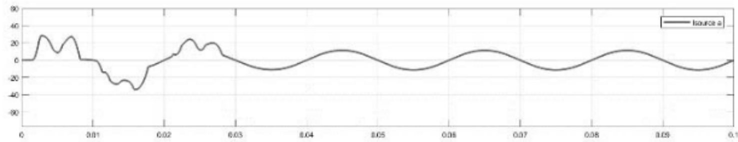
(a) Phase a



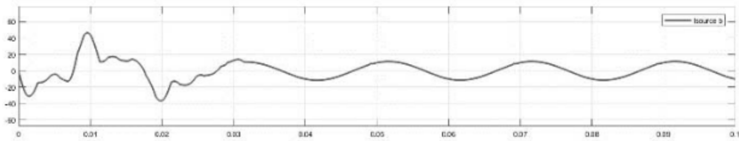
(b) Phase b

(c) Phase c

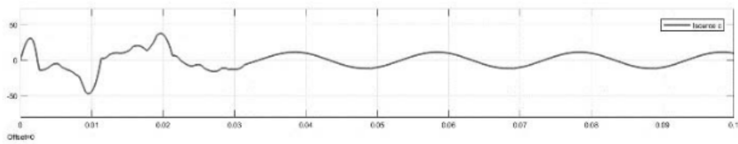
Figs. 10. Reference current waveform



(a) Phase a



(b) Phase b



(c) Phase c

Figs. 11. Current waveform after applying shunt hybrid active filter

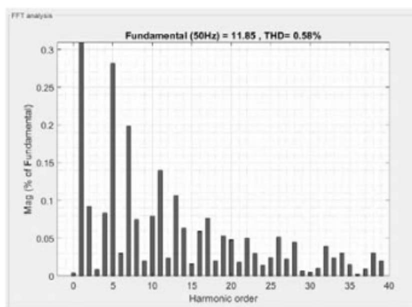
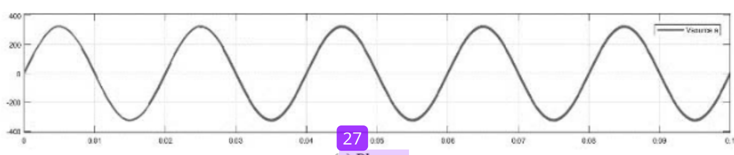
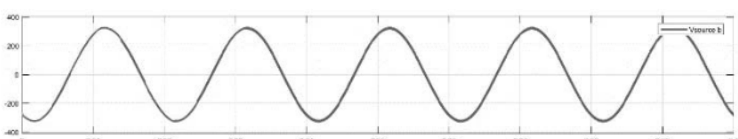


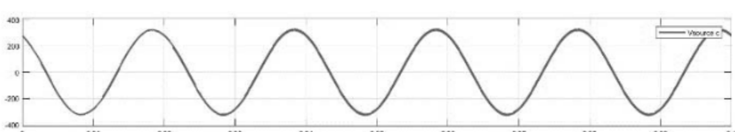
Fig. 12. Source current harmonic spectrum of phase-a
after applying shunt hybrid active power filter



(a) Phase a



(b) Phase b



(c) Phase c

Figs. 13. Output voltage waveform after applying hybrid filter

The result of Fast Fourier Transform analysis for the source current of phase a shows Total Harmonics Distortion of 0.58%, indicating that there is more than a 25% decrease compared to the initial source current without using Shunt Hybrid Active Power Filter.

Moreover, the source voltage wave after applying the hybrid-power filter is reflected in Figs. 13. Shunt Hybrid Active Power Filter works well in reducing expected harmonic currents, including the fifth order from 21% to 0.275%, the seventh order from 12% to 0.2%, the eleventh order from 7.5% to 0.14%, and other odd harmonic orders reduced to under 0.12%. Output voltage waveforms when a non-linear load is still sinusoidal, and it is analysed using Total Harmonics Distortion, shows a value of 1.9%. It indicates that Shunt Hybrid Active Filter can reduce harmonics in voltages, so Total Harmonics Distortion is still under the recommended standard.

IV.2. Unbalanced Non-Linear Load

Testing an unbalanced load is conducted to know hybrid filter responses toward current and harmonic differences in each phase. This has to be done by adding RL variant load in each phase with a different magnitude as presented in the following Fig. 14. The testing method has been conducted similarly to testing a balanced load, whose results can be seen in Fig. 14, which shows that currents on each phase have different magnitudes. Measured RMS currents for each phase include Phase-a of 15.26 A, phase b of 12.03 A, and phase c of 18.24 A. Due to the unbalanced load, the harmonics constructed become varied, and Total Harmonics Distortion is not similar. Namely phase a of 13.81%, phase b of 17.23%, and phase c of 10.66%.

Harmonic reductions of unbalanced load use the LC passive filter circuit topology with the Model-Predictive Control, which is resulting in the decrease of harmonics, which becomes lower, so current waveforms from Shunt Hybrid Active Power Filter filtering have waveforms in the side of source currents as shown in Figs. 15. Although the load is unbalanced and non-linear, filtering currents obtain similar significant reductions with having Total Harmonics Distortion value of under 1%, including 0,55%, 0,65%, and 0.48% for phase a, b, and c. In the waveforms, the distortions of transient time obtained from the control on dc-link Voltage Source Inverter still exist, so it affects currents of the filtering Shunt Hybrid Active Power Filter result. In filter currents generated by the Model-Predictive Control to reduce harmonic currents, as shown in Figs. 16, filter currents of each phase depend on the current of each phase.

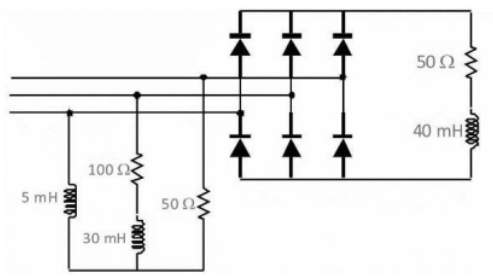
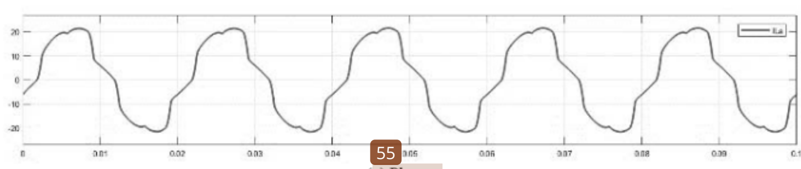
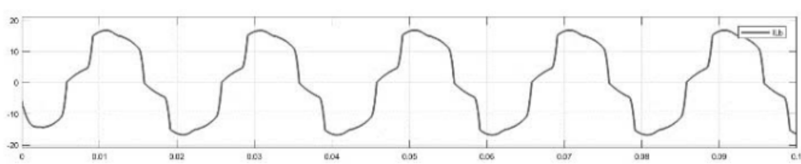


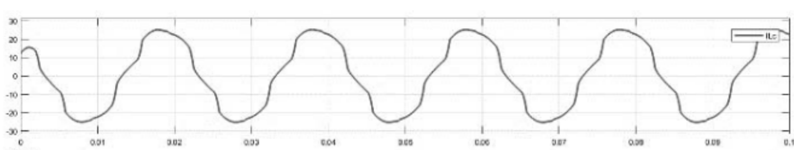
Fig. 14. Unbalanced non-linear load



(a) Phase a

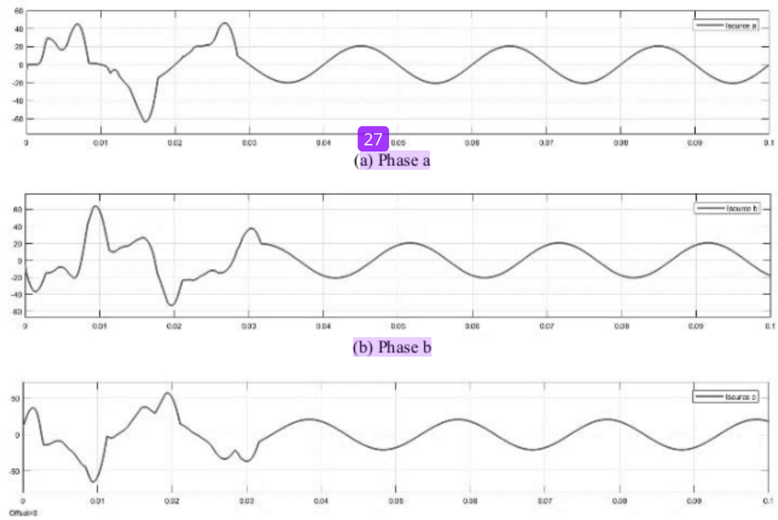


(b) Phase b



(c) Phase c

Figs. 15. Unbalanced non-linear load waveform without applying shunt hybrid active power filter



(a) Phase a

(b) Phase b

(c) Phase c

Figs. 16. Load current waveform applying shunt hybrid active power filter

The influence of dc voltage regulation control on Voltage Source Inverter is reflected in the transition indication, so the process of filtering is still imperfect in regards to the condition of under 0.03 second, due to the existence of the unbalanced condition in the transition indication. From the result of the simulation, it is indicated that LC hybrid filter with Model-Predictive Control can work well in reducing harmonic currents in unbalanced and balanced load conditions resulting in Total Harmonics Distortion of under 1%.

V. Conclusion

This paper has presented the use of Model-Predictive Control in Hybrid active filters using three-phase LC filters. The dq method is used to extract a harmonics signal to the reference signal and also for dc-link voltage control using a PI regulator. Simulations are carried out with a balanced non-linear load to determine the ability of harmonic reduction and unbalanced nonlinear load, in order to find out the ability of the model to reduce harmonics when the current is unbalanced. The results of the simulation models with balanced non-linear loads have demonstrated that the model can reduce the current harmonics to Total Harmonics Distortion less than 1%. The testing with unbalanced nonlinear loads has demonstrated that the model can reduce the harmonics so that the Total Harmonics Distortion is less than 1%.

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