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Reducing of Harmonic Distortion by Fuzzy System and Modified d-q Theory under Unbalanced Load

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Abstract. In this paper, a control method based on a fuzzy system with modified d-q theory is used to delete unwanted harmonic currents under an unbalanced load. The presence of these harmonics in the electric networks leads to many problems, such as overheating of rotating machines and distribution transformer, and perturbation of sensitive control equipment. Therefore, to address harmonic disturbances in power system networks, a Shunt Hybrid Filter (SHF) is proposed. In addition, in order to further improve the quality of electrical energy, making it compliant with international standards, we opted for fuzzy logic in the control method with a modified Phase Locked Loop (PLL). The principal objective is to improve the efficiency of HPF, suppress harmonic currents and consequently reduce Total Harmonic Distortion (THD) under 5%. The efficiency of a combined fuzzy logic and PI controller under an unbalanced load is evaluated by a simulation study using MATLAB/Simulink software, and the obtained results are presented.

Keywords: Fuzzy Logic System, Shunt Hybrid Filter, d-q Theory, Unit Vector Generation, Modified PLL.

1 Introduction

As is known, the nonlinear loads inject harmonic currents into electric networks. To prevent these harmonic currents from entering the power system and to limit their problems (like abnormal operation or damage of electric components), the energy distributors are required to apply the norms and solutions to protect against these problems. One of the used solutions is a filtering system (passive filter, active filter and hybrid filter).

Passive filters, specifically designed to exhibit low impedances at various predominant harmonic frequencies, are deemed unfavorable due to several critical deficiencies (The efficacy of these filters is highly sensitive to variations in component values as well as to the utility system impedance), which is typically not readily ascertainable.

The impedance characteristics of the passive filters can induce either a series or parallel resonance phenomenon with the utility system impedance at harmonic frequencies, thereby exacerbating issues related to current distortion within the power system and potentially the prescribed filter current ratings.

Active filters mitigate the limitations associated with passive filters by employing a switch-mode power electronic converter that generates harmonic currents that are equivalent to those present in the load current. The performance of the active filter, supplied by the current-regulated converter, is independent of the impedance of the utility system. Nevertheless, the volt-ampere rating of the power electronic converter integrated within these active filters tends to be significantly elevated, as it must endure the line-frequency utility voltage while simultaneously supplying harmonic currents.

This substantial volt-ampere converter rating is concomitant with elevated costs and heightened power losses. Consequently, these factors have resulted in the constrained implementation of active filters within power systems, with only a limited number of experimental units being deployed. Hybrid filters amalgamate both passive and active filter technologies to harness their respective advantages while mitigating their inherent disadvantages [1]-[4]. A schematic representation of the proposed shunt hybrid filter topology is presented in Fig. 1.

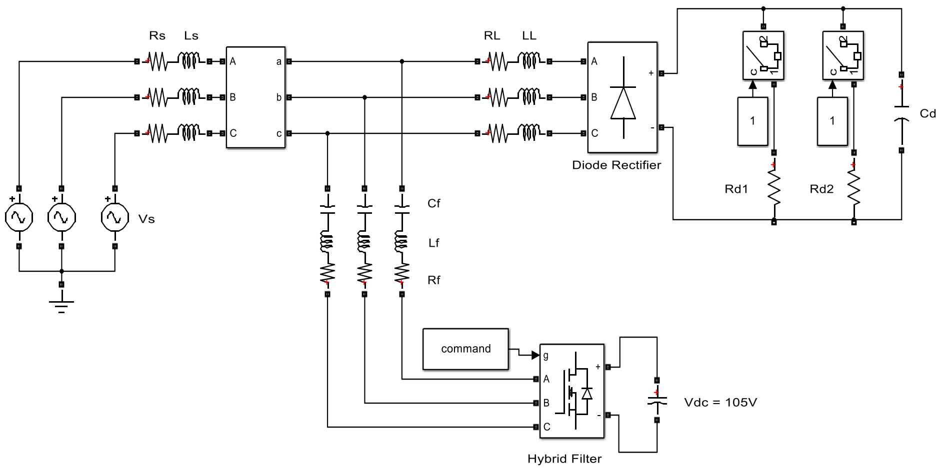

Fig. 1. Studied System Configuration

This filter is connected in parallel to the power grid. The principle of the SHF is to generate currents that are in phase opposition to the harmonic currents present in the grid, which are caused by nonlinear loads, such as/

$$I_F = I_L + I_S \qquad (1)$$

Where:

I_F: Filter current

I_L: Load current

I_S: Source current

In this way, the current supplied by the power source remains sinusoidal. This hybrid filter has a parallel structure composed of two main blocks: the power section and the control-command section [5]-[7]. This configuration comprises a three-phase passive filter tuned to the 7^{th} harmonic frequency, and a low-rated three-phase voltage source PWM inverter. These components are connected in series directly without the use of a transformer. The hybrid filter is engineered to minimize the total harmonic distortion (THD) of the input signal below 5%.
The load is a diode rectifier with a capacitive load connected in parallel with the filter. Compared to a conventional pure shunt active filter, the hybrid filter requires a significantly lower volt-ampere rating for the inverter.
The SHF is regulated using a modified d-q control method, which incorporates fuzzy logic and unit vector generation, replacing the conventional Phase-Locked Loop (PLL) circuit. This approach contributes to improved power quality and achieves a significant reduction in harmonic currents.

2 Hybrid Filter Control Technique

This study introduces a three-phase hybrid filter along with a modified control strategy designed to reduce harmonic distortion effectively. The active filter complements the passive filter by enhancing its overall filtering performance. The control strategy is composed of two main components; the first component is a harmonic isolator, which is responsible for generating reference harmonic currents. The second component involves the generation of the inverter's switching signals.

The modified d-q method is used to generate reference currents, which is recognized as the simplest and easiest to implement technique in harmonic extraction. Fig. 2 illustrates the scheme of the d-q method, which integrates both feedback and feedforward control loops.

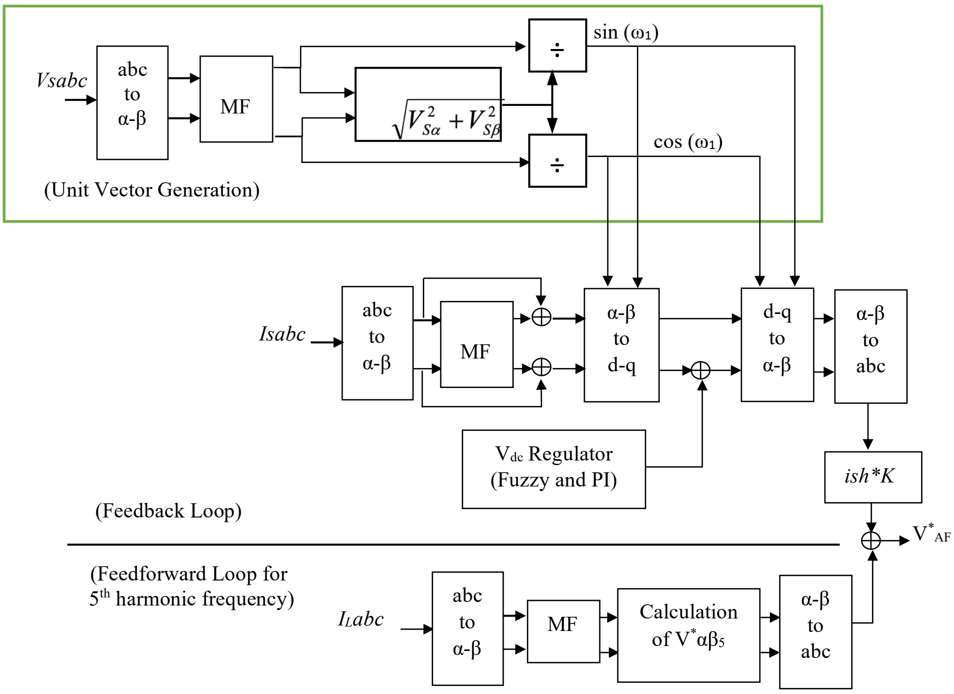

Fig. 2. Control Method with Fuzzy System and Unit Vector Generation.

The fuzzy logic and PI controller are used to regulate the DC voltage of the source inverter (V_{dc}) and provide real power to compensate for the system losses. To reduce calculation steps and computational times further, we propose modifying and simplifying the d-q method by replacing PLL circuit with a unit vector generation circuit. Also, a multivariable filter (MF) is used instead of classical harmonics extraction filters based on a high passe filter (HPF) or a low passe filter (LPF).

The feedback loop targets the harmonic currents at the input of the diode rectifier. In contrast, the feedforward loop specifically addresses the dominant 5^{th} harmonic component, thereby enhancing the filtering performance of the hybrid filter [8][9].

For the Feedback loop, as shown in Fig. 2, the three source voltages V_{Sabc} are transformed into α-β reference frame using the Clarke transformation, serving as the input to the unit vector circuit to calculate the transformation angle. The output signals (*sin(ωt)* & *cos(ωt)*) from the unit vector circuit are then employed in the application of d-q the control method [10]. Accordingly, the desired source voltages can be expressed as:

$$V_{sa} = v_{sm} \sin(\omega t) \quad (2)$$

$$V_{sb} = v_{sm} \sin(\omega t - 120) \quad (3)$$

$$V_{sc} = v_{sm} \sin(\omega t + 120) \quad (4)$$

$$\begin{bmatrix} v_{S\alpha} \\ v_{S\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{Sa} \\ v_{Sb} \\ v_{Sc} \end{bmatrix} \quad (5)$$

From the circuit of multivariable filter presented in Fig. 3, following expressions can be obtained:

$$\hat{v}_\alpha = (\frac{K}{s}[v_\alpha(s) - \hat{v}_\alpha(s)] - \frac{\omega_1}{s} \cdot \hat{v}_\beta(s)) \quad (6)$$

$$\hat{v}_{\beta} = (\frac{K}{s}[v_{\beta}(s) - \hat{v}_{\beta}(s)] + \frac{\omega_1}{s} \cdot \hat{v}_{\alpha}(s)) \qquad (7)$$

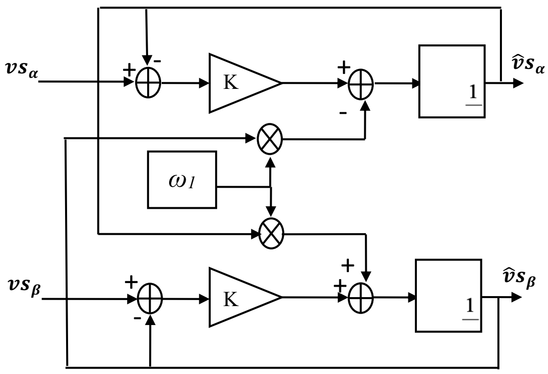

Fig. 3. Multivariable Filter Circuit.

Where (ω_1), is the fundamental frequency.

The use of a unit vector for sin (ω) and cos (ω) computation is, however, necessary in this loop. The computation of d-q current components is effectively necessary in this control loop for dc voltage (V_{dc}) regulation, and according to Fig.2, the three source currents, i_{sabc} are transformed into α-β reference frame:

$$\begin{bmatrix} i_{S\alpha} \\ i_{S\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{Sa} \\ i_{Sb} \\ i_{Sc} \end{bmatrix} \qquad (8)$$

A multivariable filter (MF) is then incorporated into the feedback loop to directly extract the AC components from the currents in the α-β axes. The resulting signals correspond to the harmonic components of i_{Sabc}_in the stationary reference frame. Subsequently, through computation based on the d-q transformation, the three-phase harmonic reference currents are obtained. Each harmonic current (i_{sh}) is then amplified by a gain (K) to generate the three AC voltage references for the feedback loop, expressed as:

$$V_{sh} = i_{sh} * K \qquad (9)$$

For the Feedforward loop, the implementation of an MF simplifies the control scheme's block diagram, enabling the elimination of the d-q transformation in this loop. As a result, only a conventional α-β transformation and its inverse within the stationary frame are required. Consequently, neither a unit vector circuit for computing sin($5\omega_1$) and cos ($5\omega_1$) nor a d-q transformation is necessary to establish the feedforward voltage references, as illustrated in Fig. 2. This approach significantly reduces the computational burden in the feedforward loop. The three load currents i_{Labc} are then transformed into the α-β reference frame using:

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \qquad (10)$$

The MF was tuned to the 5th harmonic frequency by replacing ω_1 with ω_5 in equations (6) and (7), in order to compute the DC components at the MF output, as follows:

$$\bar{i}_{\alpha 5} = (\frac{K}{s}[i_{\alpha}(s) - \bar{i}_{\alpha 5}(s)] - \frac{\omega_5}{s} \cdot \bar{i}_{\beta 5}(s)) \quad (11)$$

$$\bar{i}_{\beta 5} = (\frac{K}{s}[i_{\beta}(s) - \bar{i}_{\beta 5}(s)] + \frac{\omega_5}{s} \cdot \bar{i}_{\alpha 5}(s)) \quad (12)$$

Here, ω_5 ($= -5\omega_1$) represents the 5th-harmonic frequency, where the negative sign denotes the negative sequence. To determine the feedforward voltage references at the fifth harmonic frequency, we define:

$$V\alpha\beta_5 = V\alpha_5 + jV\beta_5 \quad (13)$$

By applying the α-β inverse transformation (14), the three-phase feedforward voltage references are obtained. These references are then added to the output voltage references generated by the feedback loop to determine the total voltage references for the hybrid filter.

$$\begin{bmatrix} v^*_{a5} \\ v^*_{b5} \\ v^*_{c5} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v^*_{\alpha 5} \\ v^*_{\beta 5} \end{bmatrix} \quad (14)$$

Finally, each voltage reference of the active filter is compared with a 10 kHz triangular carrier waveform to generate the switching signals for the six MOSFET devices.

3 Fuzzy System for Voltage regulation (V_{dc})

The regulation of the DC capacitor voltage (V_{dc}) is a crucial aspect of this control method, as it ensures improved performance of the hybrid filter and enhances system stability. To achieve this, both fuzzy logic and PI controllers are employed in this study. A Fuzzy Controller is the basic control action that is defined by a set of linguistic rules, which are derived from the system behaviour [11]-[13]. As the numerical variables are converted into linguistic variables, the fuzzy control approach eliminates the need for an explicit mathematical model of the system. The Fuzzy Controller consists of three main stages (Fuzzification, inference engine, defuzzification).

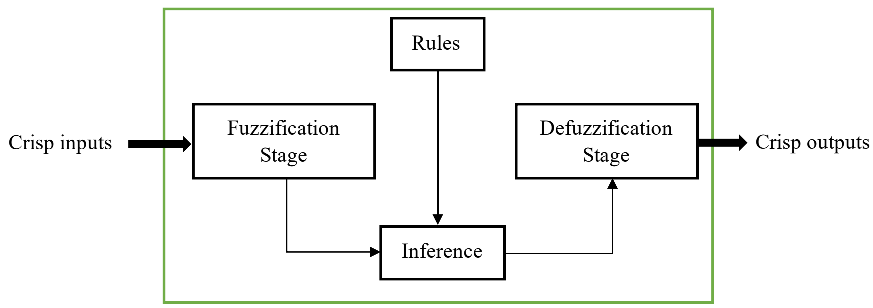

Fig. 4. General Diagram of Fuzzy Logic Controller.

The controller is characterized by: seven fuzzy sets defined for each input and output, triangular membership functions for simplicity, fuzzification based on a continuous universe of discourse, implication performed using Mamdani's 'min' operator; and defuzzification carried out through the height method.

3.1 Fuzzification stage:

In a control system, the reference signal is compared with the output signal to compute the error, which is classified into seven linguistic variables: Positive Big (PB), Positive Medium (PM), Positive Small (PS), Zero (Z), Negative Small (NS), Negative Medium (NM), and Negative Big (NB).

For fuzzification, a triangular membership function is adopted to ensure simplicity. This process converts crisp numerical inputs into fuzzy input sets represented by linguistic variables, thereby enabling the application of fuzzy logic rules. The membership functions of the fuzzy controller are presented by Fig. 5. The controller is designed with two inputs, the error and its derivative and a single output, which corresponds to the control command.

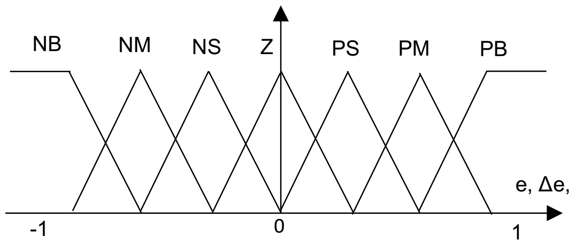

Fig. 5. Membership Functions of Fuzzy Logic.

3.2 Defuzzification stage:

Based on the rules defined in the fuzzy logic, the fuzzification process generates outputs in the form of linguistic variables represented as fuzzy numbers. However, since linguistic variables cannot be directly applied in real-world applications, they must be converted into crisp numerical values. Defuzzification is the process of transforming fuzzy output sets into crisp outputs, thereby providing quantifiable values required for practical system implementation.

3.3 Rules stage:

The rule evaluator in the fuzzy logic relies on a set of linguistic control rules stored in the rule base table, which guides the decision-making process. The elements of this table are defined according to both the transient and steady-state conditions, requiring coarse control in the former and fine control in the latter. Coarse control is applied when the system exhibits significant errors, utilizing broader input/output variables, whereas fine control is employed for minor errors, relying on more precise input/output variables. The constructed rule base table is presented in Table 1.

Table. 1. Rules Table.

Δe \ e	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

Fig. 6, illustrates the schematic representation of the fuzzy logic system combined with a PI controller. The fuzzy process takes two inputs: the error e(k) and its variation Δe(k). These are defined as follows:

- $e(k) = V_{dc}(k) - V^*_{dc}(k)$, where V^*_{dc} (105 V) is the reference voltage and V_{dc} is the measured voltage [14].
- $\Delta e(k) = e(k) - e(k-1)$.
-

In addition, the PI controller is employed to regulate the DC bus voltage (V_{dc}) and to compensate for inverter losses. The resulting error e(k) is fed into the PI regulator, with proportional and integral gains set to to 2 Ω^{-1} and 0.6 $\Omega^{-1}s^{-1}$ respectively.

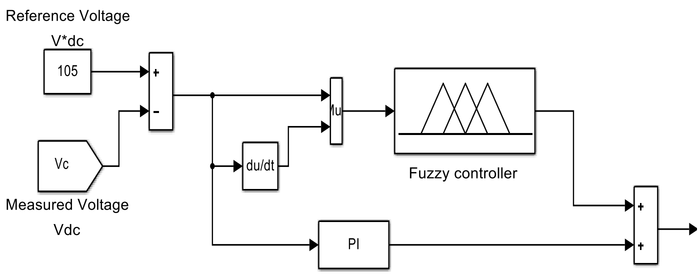

Fig. 6. General Diagram of Fuzzy Logic Controller.

4 Simulation Results

In this study, the effectiveness of the revised control approach, based on the modified d-q theory and integrating unit vector generation with a Fuzzy controller, has been validated. A detailed simulation model of the system was developed and analysed using MATLAB/Simulink together with the Sim Power Systems Block set. The performance of the hybrid filter, particularly its capability in harmonic mitigation, was thoroughly evaluated and confirmed under both steady-state and transient load conditions. The system parameters applied in the simulations are summarised in Table 2.

Table. 2. Simulation Parameters

LC Filter	Capacitor: C_F	57.6 µF
	Inductor: L_F	2.5 mH
Source	Inductor: L_S	0.15 mH
	Voltage: V_s	480 V, 60 Hz
Load	Capacitor: C_d	1500 µF
	Resistor: R_{d1}	21 Ω
	Resistor: R_{d2}	42 Ω
Active Filter	Capacitor: C_{dc}	1500 µF
	DC bus voltage	105V

4.1 Results Obtained under Balanced Load Conditions

The simulation results demonstrate that the hybrid filter exhibits excellent performance under balanced load conditions. As illustrated in Fig. 7, the (THD) of the nonlinear load current reaches 25.12% prior to filtering due to the significant presence of harmonic components. After filtering, however, the THD of the source current is reduced to 2.4%.

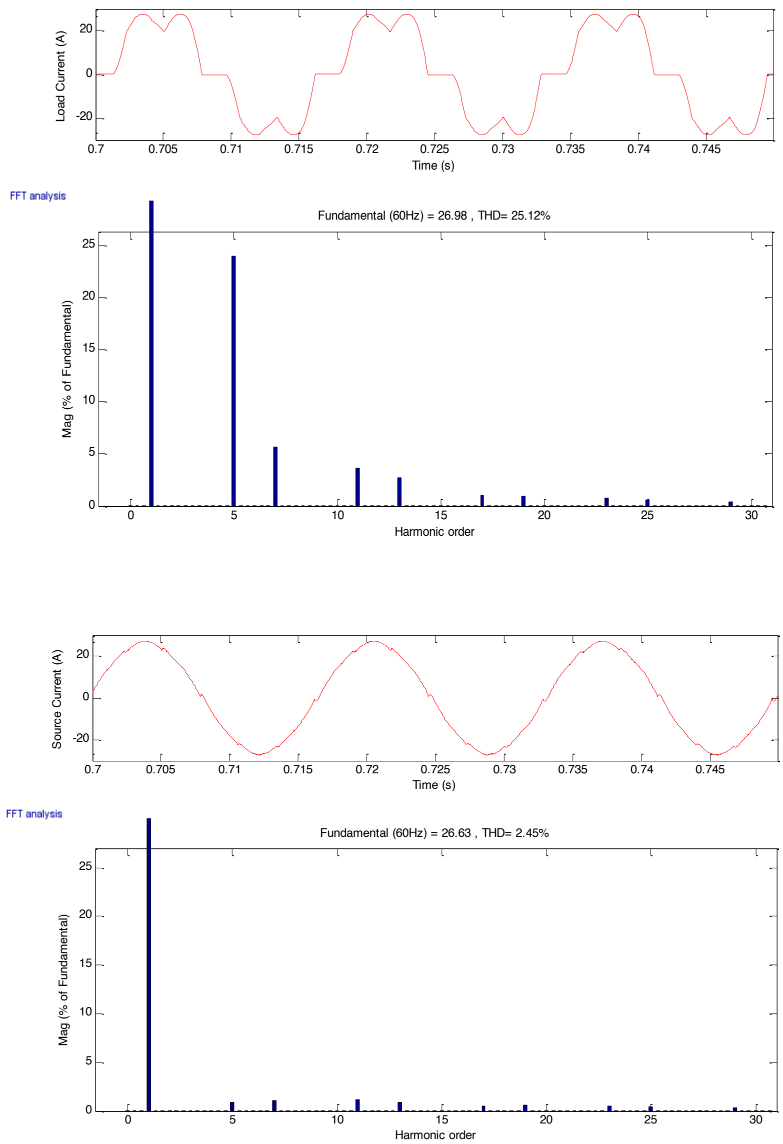

Fig. 7. Simulation Results of Load and Source Currents under Balanced Load.

The passive filter is tuned to the 7th harmonic frequency while simultaneously absorbing the network voltage at the fundamental frequency. Furthermore, an evaluation of the DC-link voltage behaviour of the SHF was carried out to verify its proper operation under balanced load conditions, while employing the fuzzy logic controller and the d-q control method with unit vector generation.

The corresponding result is presented in Fig. 8. As observed, the DC-link voltage (V_{dc}) is effectively regulated and maintained at the desired reference level of 105 V, without noticeable ripples. These findings confirm that the hybrid filter operates reliably under balanced load conditions using the proposed control approach. Moreover, this voltage reduction enables the use of low-voltage MOSFETs, offering a more cost-effective solution.

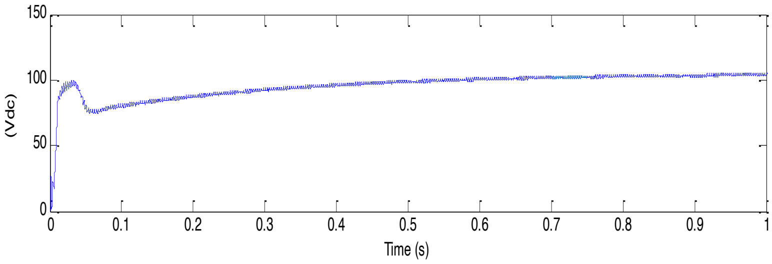

Fig. 8. Simulation Result of DC-link Voltage V_{dc} under Balanced Load.

4.2 Results Obtained under Unbalanced Load Conditions

The primary focus of this paper is the control and performance evaluation of a hybrid filter using Fuzzy logic with a PI controller and modified d-q control theory during unbalanced load. To investigate this scenario, a sudden change in load was considered by reducing the load power from 20 kW to 10 kW, achieved through varying the load resistance R_d from 21 Ω to 42 Ω.

Fig. 9 and 10 shows the simulated waveforms of the load and source currents and their harmonic spectrum under a load variation from 20 kW to 10 kW, highlighting the effectiveness of the hybrid power filter in dynamic compensation.

Following the load change, the source current experienced distortion for approximately one cycle with THD equal to 12.10% before rapidly returning to its sinusoidal form and a THD of 1.9 % after this transient period. A slight deviation observed during this distorted regime does not adversely affect the overall performance of the hybrid filter.

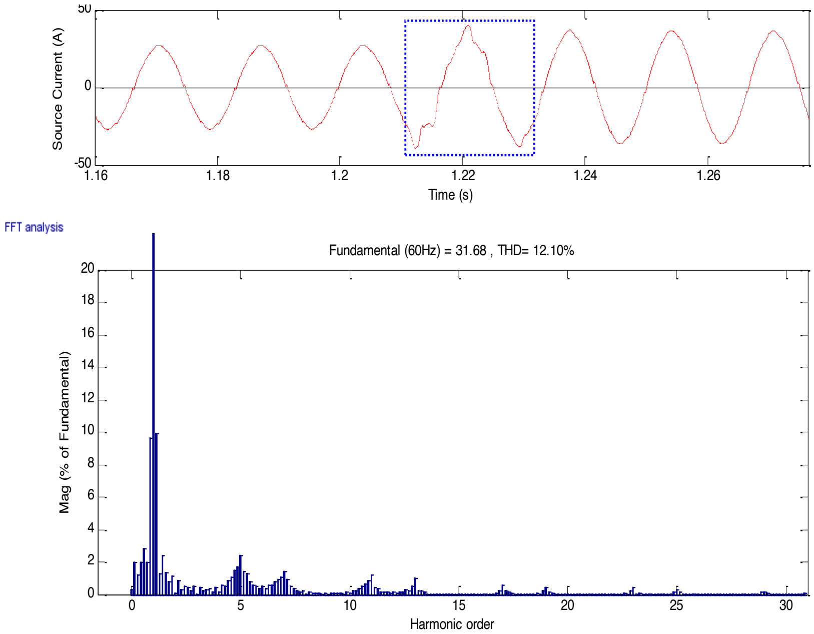

Fig. 9. Simulation Result for Source Current During Transient Period.

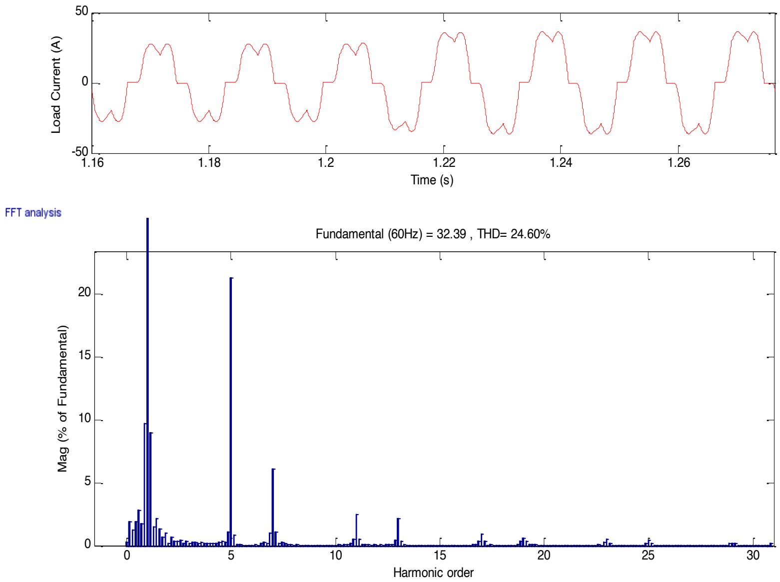

Fig. 10. Simulation Result for Load Current During Transient Period.

Fig. 11, illustrates the impact of the transient regime on the DC voltage waveform V_{dc}. A slight deviation in the DC bus voltage is observed; however, it recovers rapidly and stabilises around its initial value of 105 V. During this period, the maximum value of V_{dc} reached is 108 V, corresponding to an increase of 3 V. The results clearly confirm the effectiveness of the Fuzzy logic combined with PI control in maintaining system stability under unbalanced operating conditions, while simultaneously regulating the inverter voltage at its desired reference value.

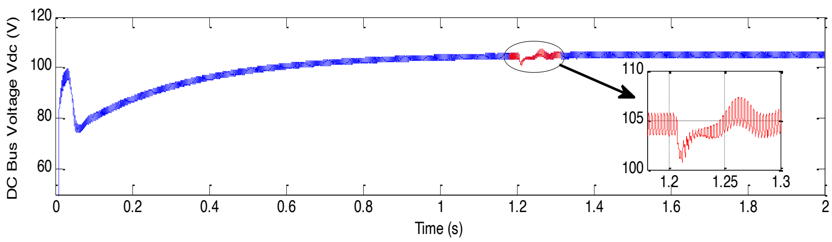

Fig. 11. Simulation Result for DC Bus Voltage V_{dc} During Transient Period.

Conclusion

This paper presents SHF with modified d-q control theory based on Fuzzy Logic and PI controllers and unit vector generation to compensate for harmonic currents under unbalanced load. In this study, the conventional d-q control method has been enhanced by introducing unit vector generation using a multivariable filter, replacing the traditional PLL circuit. This modification provides the required sine and cosine angles for synchronization purposes and generates the reference currents to regulate the operation of a three-phase SHF. The proposed control technique ensures enhanced harmonic compensation performance and maintains minimal THD across operating conditions. The achieved THD remains within the IEEE-519 standard (below 5%), in addition the simulation results demonstrated the improved efficiency of employing the Fuzzy Logic and PI controller in combination with the d-q control method for the control of the hybrid filter under unbalanced load.

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