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Automatic Power Factor Correction using Shunt Active Power Filter for Industrial Loads

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Abstract : Advancement in electrical power transmission has led to the revolution in industrial and domestic application of electrical appliances. Poor power quality will degrade the efficiency and life span of electrical devices increasing financial losses as well. To enhance power quality, it is necessary to address reactive power compensation and maintain a power factor close to unity. This paper proposes a Shunt Active Power Filter based system which is capable of maintaining the power factor near unity in real-time by continuously detecting load voltage and current in the system using a zero crossing method and thus switching the capacitance value of subsequent value to compensate it. The presented system is developed in the MATLAB Simulink environment and the results are meeting to IEEE-519 standard.

IndexTerms **- SAPF, Power Quality, VSI, Power Factor**

I. Introduction

APFs excel over passive filters in mitigating harmonics and fulfilling reactive power demands of non-linear loads. They offer dynamic reactive power compensation and handle current imbalances. Shunt active filters, with advancements in power electronics, have become popular due to their ability to overcome the limitations of passive filters [1].

Shunt Active Power Filters (SAPF) are tailored for 4-wire distribution systems, mitigating harmonic phase currents, neutral currents, reactive power, and unbalanced nonlinear load currents [2]. They regulate and equalize dc-link capacitor voltages, addressing imbalances caused by DC components in neutral currents. SAPFs, utilizing current-controlled voltage source PWM converters, have proven effective even with highly nonlinear industrial loads [3].

In commercial and industrial applications, power distribution often occurs through 3-Ø, 4-wire systems. However, load imbalances and the use of 1-phase nonlinear industrial loads can lead to excessive neutral currents [4]. These excessive neutral currents can result in overloaded power feeders, transformers, voltage distortion, and common-mode noise. Researchers, including [5], have conducted surveys to examine the neutral currents generated by CFL and computer loads.

To address these concerns, researchers have proposed controller designs for shunt active power filters. For instance, [6] introduced a synchronous detection method for compensating reactive power and eliminating harmonics in 3-Ø, 4-wire systems [7]. [8] proposed an SAPF that exclusively utilizes a notch filter for neutral current compensation. [9] extended the concept of instantaneous reactive power theory to 3-Ø, 4-wire systems by incorporating a capacitor mid-point inverter.

II. MATHEMATICAL ANALYSIS OF TRADITIONAL 3-Ø, 3-WIRE AND 4-WIRE SAPF SYSTEMS:

(a) Analysis with 3-wire Active Filter:

In the 3-wire APF configuration (Fig.1), the neutral current is handled using a shared capacitor in the dc link. However, conventional 3-wire AF in a 4-wire system cannot compensate for the neutral current, as shown by simulations. The analysis considers a power supply connected to three single-phase nonlinear loads, with non-sinusoidal currents containing odd harmonics, including triplens. The mathematical representation of the load current is as follows:

$$i_L(t) = \sum_{h=1,3,5} i_{Lh} \operatorname{Sin}(n\omega i + \varphi_h) \quad (1)$$

Where, h is the order of harmonics

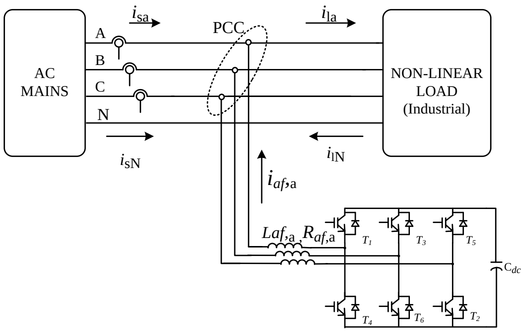

Fig. 1 Conventional Three-phase Active Filter connected to three-phase, four-wire system

Supply current without active filter are expressed as –
isa = iLa = iLa1 + iLah
isb = iLb = iLb1 + iLbh (2)
isa = iLc = iLc1 + iLch
Where, iLa1, iLb1, iLc1 are the fundamental component of load currents, iLah, iLbh, iLch are the total harmonic component of load currents.
And neutral current without active filter is expressed as –
iN = - (iLa + iLb + iLc) (3)
Due to lack of 4th wire in the SAPF
iaf,a + iaf,b + iaf,c = 0 (4)
Where, iaf,a ,iaf,b and iaf,c are the APF currents.
The uncompensated part of the current (iua, iub, iuc) are given as –
iua = iLah - iaf,a
iub = iLbh - iaf,b (5)
iuc = iLch - iaf,c
Total uncompensated part is given as –
iua + iub + iuc = iLah + iLbh + iLch – (iaf,a + iaf,b + iaf,c)
Substituting iLah, iLbh, iLch from eq. (2)
= (iLa + iLb + iLc) - (iLa1 + iLb1 + iLc1) – (iaf,a + iaf,b + iaf,c)
From eq. (3) and (4)
iua + iub + iuc = - iN – (iLa1 + iLb1 + iLc1) (6)
With active filter, source current are given as –
isa = iLa - iaf,a
isb = iLb - iaf,b (7)
isc = iLc - iaf,c
On substituting iLa, iLb, iLc from equation (2) in (7)
isa = iLa1 + iLah - iaf,a
isb = iLb1 + iLbh - iaf,b
isa = iLc1 + iLch - iaf,c
From eq. (5)
isa = iLa1 + iua,
isb = iLb1 + iub (8)
isa = iLc1 + iuc
Neutral current with three-wire active filter is given as –i1N = - (isa + isb + isc)
Substituting isa, isb, isc from eq. (8)
i1N = - (iLa1 + iLb1 + iLc1 + iua + iub + iuc)
On substituting iua, iub, iuc from eq. (1.5)
i1N = - {iLa + iLb + iLc – (iaf,a + iaf,b + iaf,c)}
From eq. (4)
i1N = - (iLa + iLb + iLc) = IN (9)

In a 3-Ø, 4-wire system with a 3-Ø, 3-wire SAPF, the source current contains both the primary load current and an uncompensated portion, as seen in equations (8) and (9). Furthermore, the amplitude of the harmonics in the neutral current remains uncompensated. It is important to note that the SAPF cannot fully compensate for the line current when balanced single-phase nonlinear loads are present, as it lacks the ability to provide the necessary triplen components.

(b) Analysis with Four-wire Active Filter:

By establishing a connection between the neutral wire and the fourth wire of the active power filter (APF) using the Four-leg topology, it becomes possible to implement a per-phase current regulator, resulting in complete independence and decoupling of the individual phases.

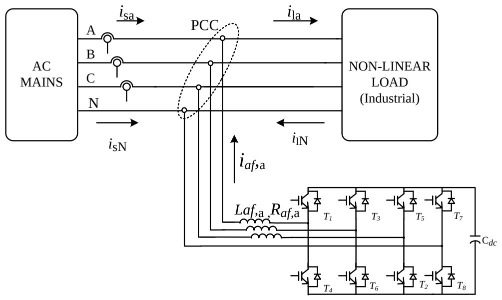

Fig. 2: 3-Ø APF connected to 3-Ø, 4-wire system

If APF compensate all the harmonics currents of nonlinear industrial load, the currents produced by the APF can be known as –

iaf,a = iLah
iaf,b = iLbh (10)
iaf,c = iLch

From eq. (7) and (10), the supply currents can be obtained as –

isa = iLa - iaf,a = iLa - iua
isb = iLb - iaf,b = iLb - iub
isc = iLc - iaf,c = iLc - iuc

i.e.

isa = iLa1
isb = iLb1 (11)
isa = iLc1

With four –wire active filter, current in the neutral wire can be given as –

isN = - (isa + isb + isc) (12)

Combining eq. (11) and (12)

isN = - (iLa1 + iLb1 + iLc1) (13)

From eq. (3), the neutral current without active filter can be given as –

iN = - (iLa + iLb + iLc)

$$\frac{i_{sN}}{i_N} = \frac{(i_{La1} + i_{Lb1} + i_{Lc1})}{(i_{La} + i_{Lb} + i_{Lc})} \quad (14)$$

Where, isN - neutral current with four-wire active filter, and iN - neutral current without active filter

If, fundamental component of the load currents are pure sinusoidal and balanced, then

iLa1 + iLb1 + iLc1 = 0

Hence,

isN = 0 (15)

And, if fundamental component of the load currents are not balanced –

$$\frac{i_{sN}}{i_N} < 1 \quad (16)$$

Hence, it is clear from eq. (11), (15), and (16) that in three-phase, four-wire system, with a four-wire active filter - Source current are fully compensated, and contain only fundamental component. Amplitude of the neutral current becomes zero or reduced significantly.

III. CONFIGURATION AND CONTROL SCHEME:

The control scheme for the three-phase, 4-wire SAPF (Fig. 3) utilizes a four-leg converter as the PWM converter.

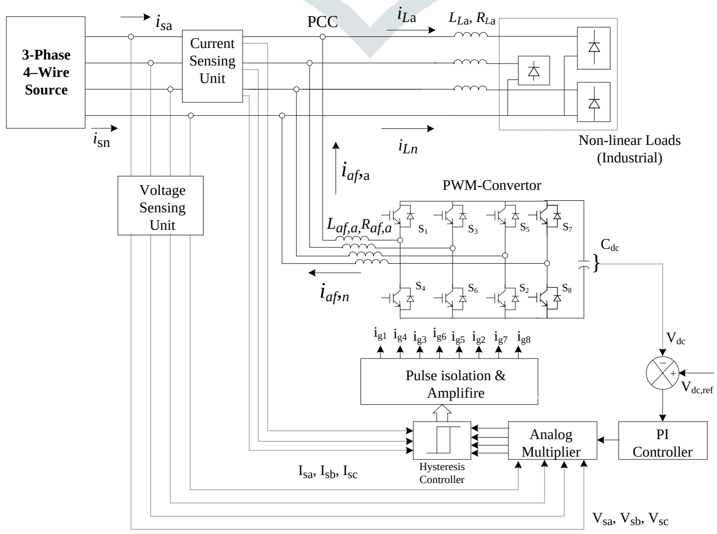

Fig. 3 Diagram illustrating the configuration of a 3-Ø, 4-wire SAPF

The peak value of the reference compensating currents (Imax) is estimated by regulating the DC link voltage. Reference current templates (isa*, isb*, and isc*) are derived from Imax and unit sine vectors (usa, usb, and usc). Three current sensors sense the line currents (isa, isb, and isc). The reference neutral current (isn*) is obtained as the negative sum of the three-phase reference currents.

A PI controller adjusts the reference value based on the capacitor voltage error signal. A hysteresis-based PWM current controller generates switching signals for the filter inductor Laf, compensating for harmonics, reactive power, and allowing active power from the source.

IV. CREATING MODELS AND CONDUCTING SIMULATIONS:

Simulations were conducted to evaluate the SAPF's effectiveness in compensating harmonics, reactive power, and neutral current in a 3-Ø, 4-wire system. Various scenarios, including uneven nonlinear industrial loads, were considered. The simulation model was developed using MATLAB and the Sim Power System tools. A compensation capacity of 5kVA was chosen for these simulations, with specific parameters selected for the study. These parameters include:

V_s = 230 volts, f = 50Hz
R_{af} = 0.4Ω,
L_{af} = 3.35 mH,
V_{dc} = 2000 µF,
$V_{dc,ref}$ = 680 volts.
K_p = 0.4, k_i = 9.38.

The proposed topology model is illustrated in Fig.3, representing a 3-Ø, 4-wire system with three balanced 1-Ø nonlinear industrial loads connected between each phase and neutral. These loads consist of 1-Ø diode rectifiers with R-L elements on their DC side. The load and neutral current depicted in Fig. 4 and frequency spectrums of the phase 'A' current and neutral current are depicted in Figure. 5(a), 5(b) respectively.

Upon examination, it is evident that the 1-Ø diode rectifier exhibits higher harmonic distortion in the line current compared to the three diode rectifiers. Despite balanced line currents, the neutral current lacks the fundamental component and contains triplen harmonics. This results in a significant flow of neutral current with a dominant presence of 3rd order harmonics, even under balanced load conditions.

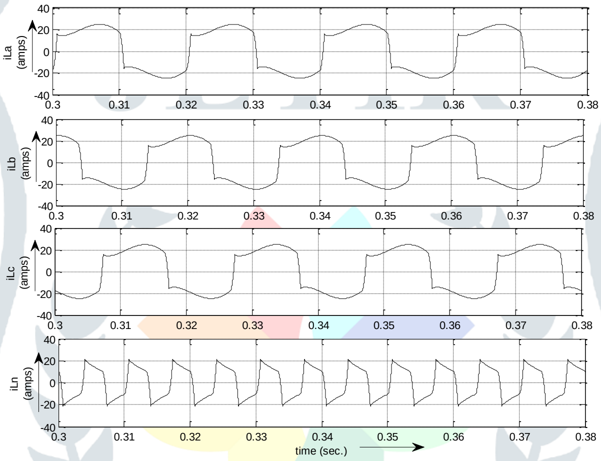

Fig. 4 Three-phase and neutral currents (i_{La}, i_{Lb}, i_{Lc}, i_{Ln}) of three-phase, Four-wire system with balanced 3×1-Ø nonlinear industrial loads.

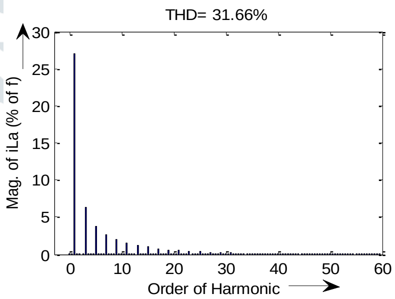

Fig. 5(a) Frequency spectrum of load current (i_{La}),THD:31.66%

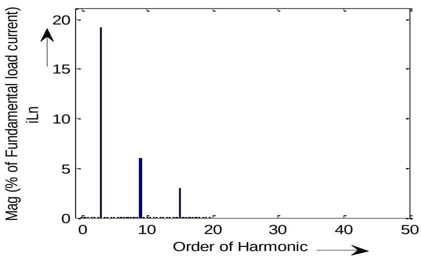

Fig. 5(b) Frequency spectrum of neutral current (i_{Ln})

In Fig. 6(a), simulation results for phase 'A' in a steady state after compensation are shown, displaying Vsa, iLa, isa, iaf, and Vdc. Fig. 6(b) illustrates the neutral current before and after compensation. Following compensation, phase currents become balanced, sinusoidal, and synchronized with phase voltages, improving power factor towards unity. The neutral current experiences a significant reduction from 20.20 A to nearly zero (0.48 A), resulting in a more balanced electrical system. Fig. 7

compares the frequency spectrums of phase A source current and neutral current before and after compensation, with the total harmonic distortion (THD) decreasing from 31.66% to 0.84%, surpassing the IEEE-519 recommended limit of 5%.

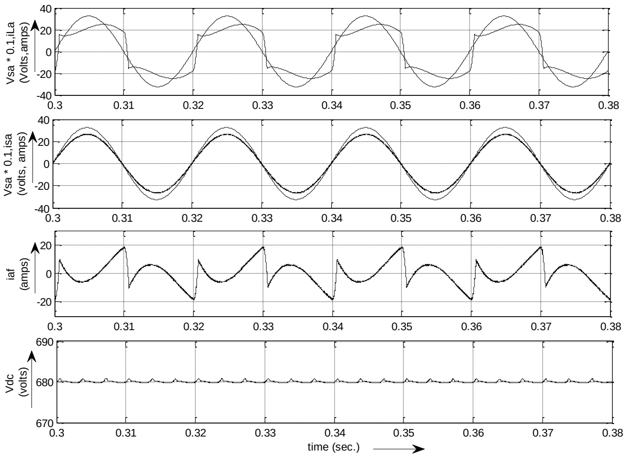

Fig.6(a) Simulation results after compensation in steady state of phase ‘A’ (3-Ø, 4-wire system supplying 3×1- Ø balanced nonlinear industrial loads)

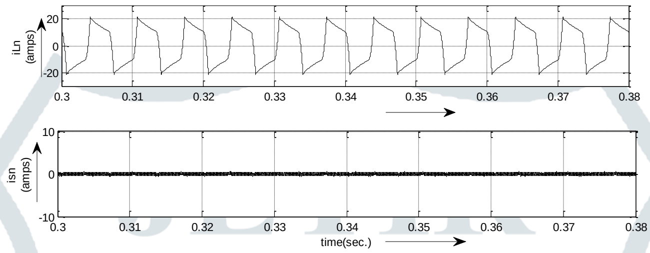

Fig. 6 (b) Neutral current before (i_{Ln}) and after (i_{sn}) compensation (3-Ø, 4-wire system supplying 3×1- Ø balanced nonlinear industrial loads)

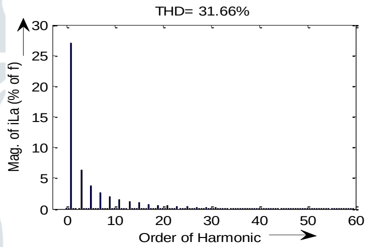

Fig. 7(a) Frequency spectrum of load current (i_{La}) THD: 31.66%

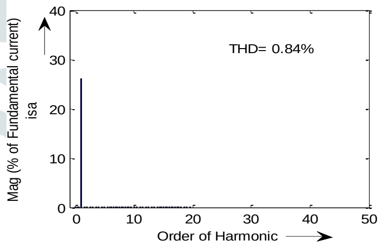

Fig 7(b) Frequency spectrum of load current (i_{sa}) THD: 0.84%

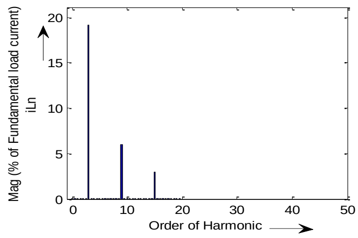

Fig. 7(c) Frequency spectrum of neutral Current (i_{Ln}) before compensation

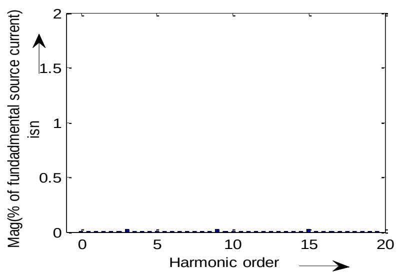

Fig 7(d) Frequency spectrum of neutral current (i_{sn}) after compensation

V. CONCLUSION

A four-leg SAPF's performance is studied in a 3-Ø, 4-wire system to compensate harmonics, reactive power, neutral current, and balance input current. Simulation results validate its effectiveness with various nonlinear industrial loads. The simple control scheme achieves balanced, sinusoidal, and unity power factor current, facilitating implementation. The SAPF successfully achieves harmonic compensation, neutral current reduction, reactive power correction, and improved power factor. The four-leg topology eliminates the need for double-value capacitors and provides better control of third harmonic current components, offering significant advantages over other approaches.

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