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UNIFIED ZERO SEQUENCE ELECTROMAGNETIC FILTER

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ABSTRACT – This paper aims at presenting the operation principle, modelling, computational implementation and performance studies of an electromagnetic zero sequence harmonic filter. This proposal considers a combined shunt and series filter units so as to reach a better overall performance. Besides theoretical and computational concepts, a prototype experimental performance is also included into the studies.

KEYWORDS – Harmonic distortion, zero sequence harmonic currents, electromagnetic filter.

I. INTRODUCTION

Nowadays the majority of commercial and residential three phase installations show a high level of neutral current [1, 2]. This is, in part, attributed to the increasing use of nonlinear loads. Therefore, it is quite usual to measure heavy neutral currents containing zero-sequence-fundamental current and a large amount of zero sequence harmonic. Amongst the undesirable effects, emerge the increase of neutral to ground voltage, cable heating, and transformer overheating. As most of these problems are associated to the operation of power electronics devices one should expect the problems to increase greatly with the coming years. Typical nonlinear phase-to-neutral loads are: rectification circuits, switched, and linear power supplies, fluorescent lights using conventional or electronic ballasts, variable speed drivers, etc. Some of them are quite rich at producing zero sequence harmonics, being the third one the most important component. This harmonic current can easily reach around 100% of the fundamental component and, under these circumstances, high neutral-harmonic-current circulation can occur.

In order to reduce the circulation of zero-sequence-harmonic currents throughout the mains (phase and neutral cables, transformers, etc) and to avoid the undesirable consequences, the classical solutions are: transformers derating procedures, independent neutral to nonlinear loads, harmonic filters, etc. The use of filters for harmonic compensation constitutes common techniques and different solutions are found on this principle. Reference [3] describes an active filter based on the reduction/elimination of harmonic components through the generation of equal and opposing frequencies to those produced by loads. Another methodology uses an electromagnetic filter composed by entirely electromagnetic arrangements so as to achieve a high (blockade) or low (passing) impedance performance. References [4, 5] have shown that shunt filter efficiency depends on the zero sequence filter impedance, which could be low enough to compare with the supply and an appreciable level of current is deviated from being inject into the mains.

II. ZERO SEQUENCE ELECTROMAGNETIC FILTER

Fig. 1 shows a three-phase supply connected with a nonlinear load and the zero sequence shunt filter.

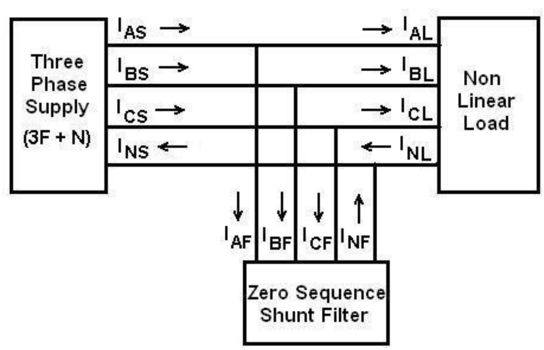


Fig. 1. The electromagnetic shunt zero sequence filter concept.

Where:

I_{AS}, I_{BS}, I_{CS} e I_{NS} -	A, B, C and neutral currents related to the mains;
I_{AL}, I_{BL}, I_{CL} e I_{NL} -	A, B, C and neutral currents

	associated to the nonlinear load;
I_{AF}, I_{BF}, I_{CF} e I_{NF} -	A, B, C and neutral currents throughout the zero sequence filter.

In a simplified way, Fig. 2 shows the zero sequence single-phase equivalent circuit for the previous three-phase arrangement.

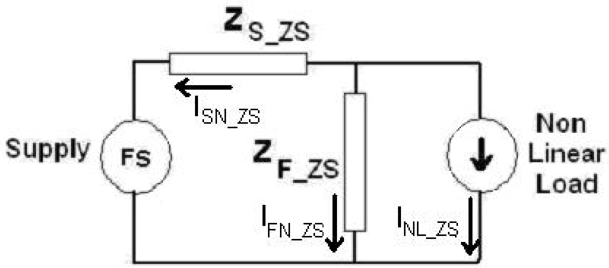


Fig. 2. Zero sequence single-phase equivalent circuit.

From the above figure it follows that, if the supply contains only fundamental frequency, the zero-sequence current driven by the shunt filter is:

$$I_{FN\_ZS} = \frac{Z_{S\_ZS}}{Z_{S\_ZS} + Z_{F\_ZS}} . I_{NL\_ZS} \qquad (1)$$

Being:

I_{NL_ZS} -	Zero sequence current produced by the nonlinear load;
I_{FN_ZS} -	Zero sequence current through the shunt filter;
Z_{S_ZS} -	Zero sequence supply impedance;
Z_{F_ZS} -	Zero sequence shunt filter impedance.

On the other hand, the residual zero sequence current injected into the supply can be calculated by:

$$I_{SN\_ZS} = \frac{Z_{F\_ZS}}{Z_{F\_ZS} + Z_{S\_ZS}} . I_{NL\_ZS} \qquad (2)$$

Equation (2) shows that the bigger the supply impedance the smaller the level of zero sequence current through the mains. In addition, it must be understood that the relationship between the zero sequence supply impedance and the corresponding value for the filter is the major factor to define the shunt filter effectiveness.

It must be stressed that low voltage commercial and/or industrial installations is frequently fed by three-phase transformers delta connected at the high voltage side (13.8 and 34.5 kV) and star-grounded at the low voltage side. These equipment, normally present zero sequence impedance given by:

$$Z_{ZS\_T} = 0.85 . Z_{PS\_T} \qquad (3)$$

Where:

Z_{ZS_T} -	Transformer zero sequence impedance;
Z_{PS_T} -	Transformer positive sequence impedance.

Table 1 gives typical positive sequence impedances for distinct three-phase power transformers. The values are related to the low voltage side. Having in mind that the parallel filter will compete with such impedance; this device must be dimensioned so as to present a lower zero sequence impedance than the corresponding transformer impedance. By looking at the values shown it is quite clear this is a difficult task to be filled. This is the main reason to complement the filter arrangement with a series unit, as explained bellow.

Table 1. Impedances, resistances and maximum reactances for 13.8 kV/220-127V transformers.

Transformer Power (kVA)	Impedance Z_{TR} (Ω)	Resistance (Ω)	Leakage Reactance (Ω)
15	0.11294	0.07314	0.07313
30	0.09780	0.03065	0.09287
45	0.06520	0.01864	0.06247
75	0.03912	0.00981	0.03787
112.5	0.02608	0.00593	0.02539
150	0.01956	0.00411	0.01912
225	0.01676	0.00258	0.01656
300	0.01257	0.00180	0.01244
500	0.00922	0.00193	0.00901

By inserting a series unit to the arrangement given in Fig. 1, a combined solution characterised by a joined operation defined by the shunt and a series unit is achieved. The so called series filter has the purpose of blocking the zero sequence harmonic components and the shunt offers a low impedance path to the focused harmonics. Fig. 3 shows the complete three-phase arrangement.

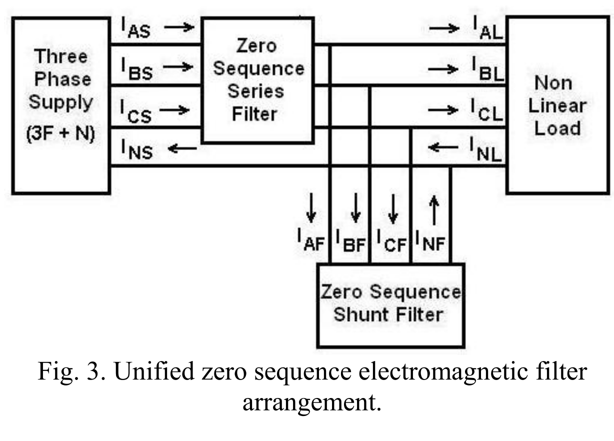


Fig. 3. Unified zero sequence electromagnetic filter arrangement.

The computational model to cope with the shunt unit has been fully described in references [4, 5]. Using the same approach, Fig. 4a shows the windings physical arrangement and Fig 4b illustrates the approach to include the device into the time domain simulator.

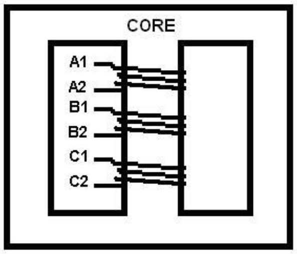


Fig. 4a. Shunt filter physical arrangement.

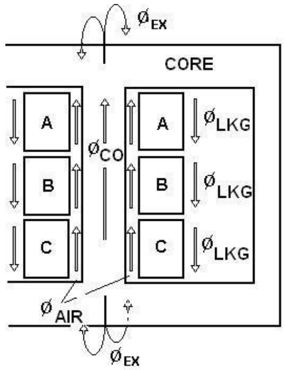


Fig. 4b. Magnetic flux distribution.

In Fig. 4b:

ϕ_{CO} - Main core flux;

ϕ_{AIR} - Flux through the air path between the core and windings;

ϕ_{LKG} - Winding leakage;

ϕ_{EX} - Flux between the upper and bottom yoke through air and/or tank.

Considering an alternative physical construction for the windings, as given in Fig. 5a, the leakage flux can be minimized or even eliminated. Under these circumstances, the magnetic structure can be simplified and the final result is given by the magnetic arrangement indicated in Fig. 5b.

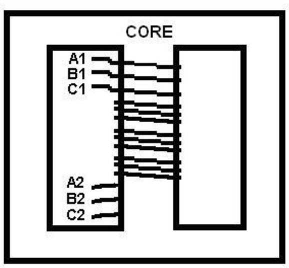


Fig. 5a. Zero sequence series filter with minimized leakage flux.

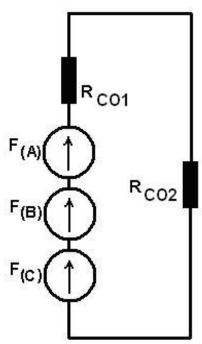


Fig. 5b. Magnetic equivalent model of the core and windings.

Where:

$F_{(A)}$, $F_{(B)}$ e $F_{(C)}$ - A, B and C windings MMF's;

R_{CO1} - Main core reluctance;

R_{CO2} - Lateral and yoke equivalent reluctances.

III. ELECTROMAGNETIC FILTER PROTOTYPE

In order to provide means to evaluate the filter performance, both computational and experimental studies were carried out using a typical non-linear zero sequence harmonic generator. The experimental evaluation was performed in laboratory and a filter prototype was need. Without going into details about the construction, tables 2 and 3 give the filter main characteristics for the shunt and series units.

Table 2. Shunt filter main characteristics.

Rated Voltage	220 V
Three-phase power	9000 VA
Winding turns	88
Core total area	41.19 cm^2
Stacking factor	0.95
Window height	13.6 cm
Core height	27.6 cm
Winding resistance	0.145 Ω
Leakage reactance	0.0895 Ω
Leakage impedance	0.1704 Ω

Table 3. Series filter main characteristics.

MW and AW winding turns	8
Core total area	64.0 cm^2
Stacking factor	0.96
Window height	13.6 cm
Core height	27.6 cm
Winding resistance (MW + AW)	0.01 Ω

Figs. 6a and 6b illustrate both the shunt and series units for the unified electromagnetic zero sequence filter prototype.

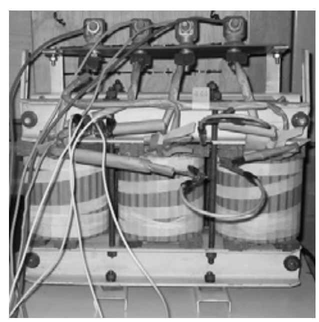


Fig. 6a. Zero sequence shunt filter.

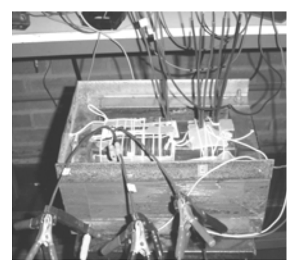


Fig. 6b. Zero sequence series filter.

IV. COMPUTATIONAL STUDIES

Fig. 7 shows the arrangement used to investigate the unified zero sequence filter operation. The harmonic current source is defined by a three-phase saturated core reactor with the common star connected to the supply neutral. This system was used for both computational and experimental analysis.

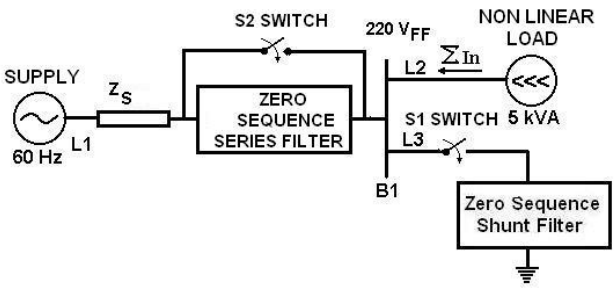
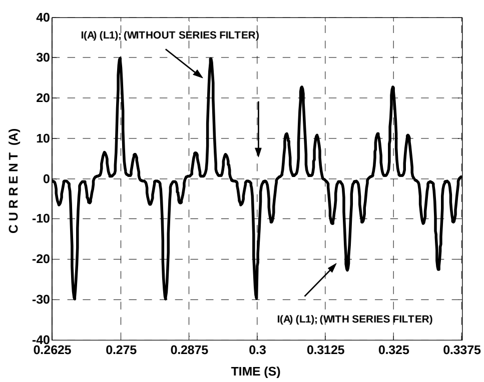


Fig. 7. Tested system.

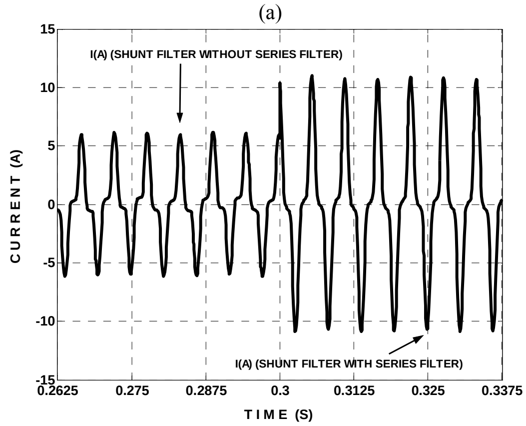
The simulations are related to two operating conditions. At t=0 the operation starts with the shunt unit connected (S1 closed) without the series unit (S2 closed). Then, at t=0.3 s, switch S2 is opened and the series filter is inserted. This sequence allows for a fully understanding of the complete filter effectiveness.

a. Line Current

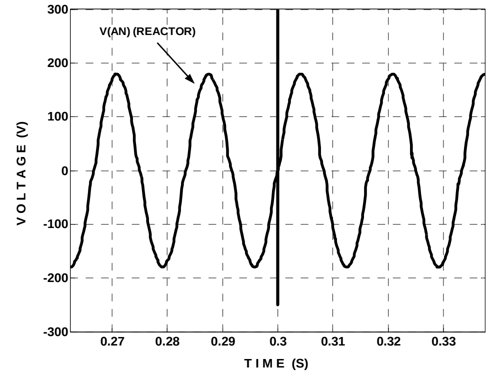
Fig. 8a shows the line "a" current at L1 feeder. It is possible to see that, at 0.3 s the current waveform has been changed so as to reduce its peak and rms value. Further, Fig. 8b illustrates the shunt filter current during the same period. Again, the result is clear enough to highlight the shunt filter performance. The increase in the current is an indicative that a higher zero sequence harmonic is driven by this unit. The supply voltage was assumed as balanced, as well the nonlinear load. Fig 8c shows the phase-to-neutral reactor voltage.



(a)



(b)



(c)

Fig. 8. (a) Feeder current (phase a); (b) Filter current (phase a); (c) Reactor voltage (phase a).

Table 4 summarizes the L1 feeder harmonic current components (phase a), with and without the series unit insertion. As expected, a significant reduction on the third and ninth harmonics can be noticed. This proves the unified filter arrangement has a better performance when compared to the use of the shunt unit only. As shown, the zero sequence harmonics are largely reduced and the positive and negative ones are not greatly affected.

Table 4. Main feeder harmonic current components (phase a).

t(s)	Fund	3rd	5th	7th	9^{th}
<0.3	9.61	4.12	6.85	5.19	1.70
>0.3	9.05	0.20	6.38	4.82	0.07

b. Neutral Current

Fig. 9 gives the supply neutral current and the shunt filter neutral current waveforms under the stated operating conditions. The series unit insertion effect is to drive a larger amount of the total load zero sequence current through the shunt filter. This is in total agreement with physical expected performance.

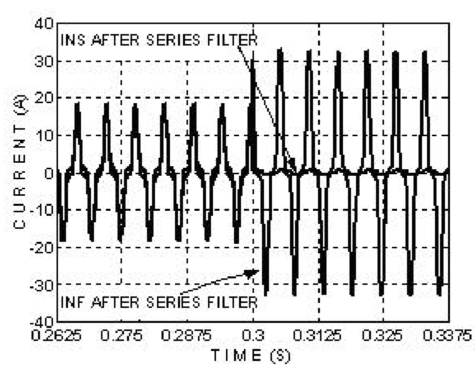


Fig. 9. Supply neutral current and shunt filter neutral current - series unit insertion at t=0.3 s.

V. LABORATORY STUDIES

By setting the laboratory arrangement given in Fig. 8, experimental results were obtained so as to validate the unified filter performance and the computational model approach. The waveforms to highlight the filter effectiveness are discussed in the sequence.

a. Line Current

Fig. 10 shows the three-phase line current waveforms at the supply without the zero sequence filter unit. It can be seen the current shape is associate to a saturated magnetic device and the corresponding harmonic spectrum is quite rich on 3rd component.

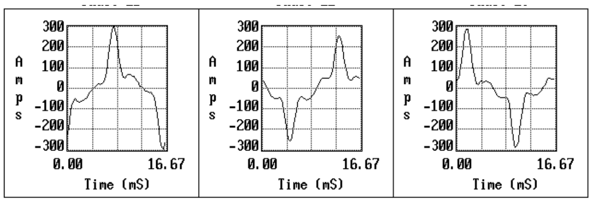


Fig. 10. Supply three-phase line currents without the series and shunt units. Scale factor (SF) = 0.1.

The fundamental and harmonic components for the line current waveforms are given in Table 5.

Table 5. Supply three-phase line currents without the filter units.

	Fund.	3rd	5th	7th	9th	I_{RMS}
I(a)	10.917	5.017	3.967	1.583	0.367	12.760
I(b)	10.100	3.540	3.563	1.278	0.352	11.359
I(c)	10.800	5.017	4.217	1.700	0.433	12.760

By connecting the shunt filter unit, Table 6 quantifies the new line current harmonics. The results evidence a significant reduction on the third, ninth, and fifteenth harmonic currents. These are the well known zero sequence components.

Table 6. Supply three-phase line currents with the shunt filter connection.

	Fund.	3rd	5th	7th	9th	I_{rms}
I(a)	11.637	0.827	4.230	1.785	0.100	12.541
I(b)	10.428	0.788	4.038	1.522	0.077	11.317
I(c)	11.667	0.900	4.680	1.917	0.110	12.753

With the series unit insertion, the unified filter performance has largely increased the filtering effectiveness. This is shown in Table 7. The 9th harmonic has been practically eliminated and a lower level of third harmonic was found.

Table 7. Supply three-phase line currents with both shunt and series units.

	Fund.	3rd	5th	7th	9th	I_{rms}
I(a)	11.637	0.160	4.332	1.800	0.042	12.548
I(b)	10.862	0.221	4.212	1.567	0.000	11.757
I(c)	11.684	0.151	4.570	1.885	0.097	12.689

The final line currents at the mains are illustrated by Fig 11.

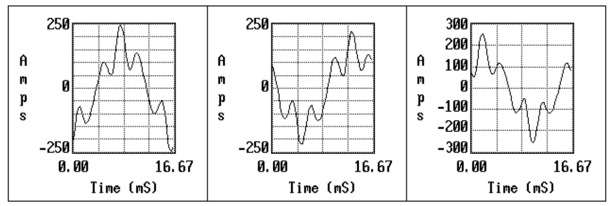


Fig. 11. Line current waveforms with the unified filter operation.

b. Neutral Current

Table 8 summarises the harmonic components for both supply and load neutral currents, without the presence of the zero sequence electromagnetic filter.

Table 8. Supply neutral current without the shunt and series units.

	Fund.	3rd	5th	7th	9th	I_{rms}(A)
I_{NS}	0.808	14.404	0.368	0.126	1.202	14.487
I_{NNL}	0.814	14.402	0.37	0.124	1.198	14.485

Once the shunt unit has been connected, the new neutral current harmonic components are given in Table 9. Three neutral currents as shown: at the supply, at the load and at the filter. Again, it is possible to identify a harmonic circulation improvement as a result of the shunt filter insertion.

Table 9. Supply neutral currents with only the shunt unit.

	Fund.	3rd	5th	7th	9th	I_{rms}(A)
I_{NS}	0.857	2.358	0.518	0.156	0.278	2.586
I_{NNL}	1.473	14.610	0.432	0.008	1.503	14.784
I_{NF}	2.315	11.901	0.132	0.130	1.317	12.202

Finally, the results shown in Table 10 are related to the same currents considering unified zero sequence filter operation. The values are clear enough to highlight the filter operation improvement.

Table 10. Supply neutral currents with both shunt and series units.

	Fund.	3rd	5th	7th	9th	I_{rms}(A)
I_{NS}	0.069	0.136	0.0	0.0	0.0	0.152
I_{NNL}	1.553	14.633	0.390	0.0	1.480	14.804
I_{NF}	1.610	14.367	0.363	0.0	1.463	14.545

The experimental studies had also shown that, with the serial unit operation; there are no modifications in the voltage harmonic distortion of the nonlinear load.

VI. CONCLUSION

This paper target was to carry out computational and experimental analysis of a proposed unified zero sequence electromagnetic filter operation. Equipment basic principles, computational modeling strategy, theoretical and practical performance investigations, amongst other aspects, were focused on this approach to cope with the undesirable zero sequence harmonics found in many electrical systems. Both computational and experimental studies have highlighted the proposal effectiveness at reducing the level of harmonic currents through the neutrals. The combination of a shunt and series unit was shown to largely improve the filter performance. Commercial sized filters have been produced and installed into real systems and the results are in close agreement with the results here described.

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