Analysis of a Shunt Active Power Filter for mitigation of harmonics caused by Compact Fluorescent Lamps

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Abstract: - Compact Fluorescent Lamps (CFLs) are being used in energy efficient lighting and illumination applications. These lamps draw a non-sinusoidal current waveform that is rich in harmonics. While the detrimental effect of any individual unit on the power system is very small, harmonic distortion created by a large number of CFL units is measureable. Active Power Filters (APF) are seen as an effective means of dealing with harmonic distortion problems. APFs have seen much usage in industry where nonlinear devices as Variable Speed Drives (VSD) and six pulse rectifiers are used. Estimating the harmonic part of current to be compensated for is fundamental to the effectiveness of any APF scheme. Current estimation methods produce different results under different conditions. While most of these harmonic estimation methods are used for larger industrial loads, their actual performance with smaller loads as Compact Fluorescent Lamps (CFLs) varies. This work evaluates the performance of a d-q theory based APF when compensating for an unbalanced three phase CFL load under distorted AC mains voltage.

Key-Words: -Compact Fluorescent Lamps, Active Power Filter, Power Quality

1 Introduction

Compact Fluorescent Lamps (CFLs) tend to be a more efficient means of illuminating spaces. CFLs work on the same principle as other fluorescent lamps. Energized electrons in inert gas atoms return to their previous states and emit energy in the ulta-violet (UV) spectrum. UV rays interact with phosphor coating inside the fluorescent tube to produce fluorescence.

A steady flow of current is required through the inert gas to maintain the above described process. Previously inductors were used to maintain such current flow. The inductor size is large due to low power frequency. Figure-1 shows the schematic diagram of the CFL drive. CFL power supplies rectify AC mains voltage to charge capacitors (C1 and C2), the capacitors then feed a switch mode power supply (S1 and S2) that creates high frequency output. This ignites an arc inside the fluorescent tube and a steady flow of current is maintained by using very small inductor L1. The inductor size required is small due to high frequency.

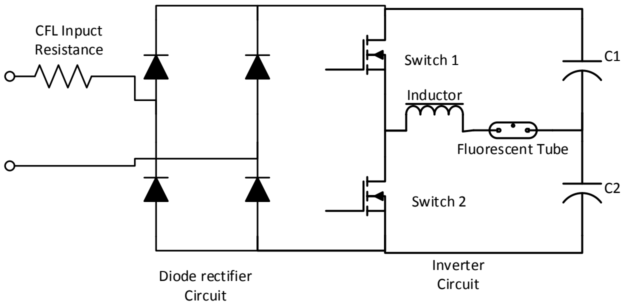

Fig. 1: CFL complete model showing Inverter circuit and fluorescent tube

The DC link capacitors (C1 and C2) charge during each half cycle near the peak voltage causing the power supply to draw current in narrow pulse like waveform. In the Fourier domain, such current waveforms can be seen to have a large harmonic content.

The power quality deterioration created by individual CFL is small when used with large conventional loads. Wide spread use of CFL units with relatively small conventional loads, cause considerable harmonic distortion. Especially larger numbers of low rating CFL units (< 25watt) produce a large amount of harmonic content.[1][2]

Shunt Active Power Filters (SAPF) are a popular method of reducing harmonic distortion. The idea behind SAPF is to inject harmonic part of non-linear load current into the grid and create a sinusoidal current waveform at the Point of Common Coupling (PCC).[3]

Mostly SAPFs are implemented to compensate for larger industrial loads as Variable Speed Drives (VSD), six pulse rectifiers and arc furnaces. However, the performance of SAPF in mitigating harmonics generated by smaller loads as CFLs, may vary because the magnitude of current being drawn is small. Furthermore, the effectiveness of harmonic current estimation and compensation methods vary with amount of harmonic distortion in grid voltage.[4]

This paper presents the results of compensating for harmonics created by CFLs through a d-q theory based SAPF.

2 Estimating harmonic current: stationary reference frame method

The stationary reference frame method (d-q method), relies upon Park's transformation of non-linear load currents. Three phase currents Ia, Ib, and Ic are transformed into d-q-0 reference frame current. The fundamental part appears as a near DC quantity. Whereas, the harmonic multiples appear as higher frequency alternating values. Equation (1) gives the Park transform. Whereas equation (2) gives the Inverse Park transform

$$\begin{bmatrix} Y_d \\ Y_q \\ Y_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix} \cdot \begin{bmatrix} y_a \\ y_b \\ y_c \end{bmatrix} \quad (1)$$

Inverse park transform

$$\begin{bmatrix} y_a \\ y_b \\ y_c \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} cos\theta & -sin\theta & \frac{\sqrt{2}}{2} \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) & \frac{\sqrt{2}}{2} \\ \cos\left(\theta + \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) & \frac{\sqrt{2}}{2} \end{bmatrix} \cdot \begin{bmatrix} Y_d \\ Y_q \\ Y_0 \end{bmatrix} \quad (2)$$

Harmonic part is filtered from the fundamental using Low pass filters in feed forward arrangement. These harmonic currents are then transformed back from d-q-0 to a-b-c using inverse park transform as in equation (2).[5]

3 CFL Model

For ease in simulation, a simpler CFL model has been proposed in [1]. Herein, the inverter circuit and fluorescent lamp have been modelled as an equivalent resistance (R_o). In comparison, a model that simulates CFL as harmonic current source does not interact with source voltage and maintains the same waveform even when source voltage is varied to include harmonic components. [2]

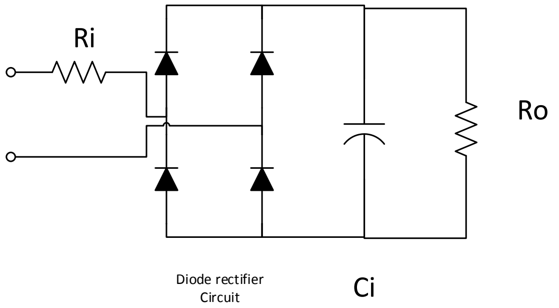

Fig. 2: CFL simplified equivalent circuit showing equivalent resistance for inverter circuit and fluorescent tube

4 Methodology

The current drawn by 23 watt CFL units has been simulated. THD and harmonic spectra have been presented for an unbalanced load composed of 10 to 28 CFL units per phase.

A d-q theory based active power filter has been implemented in Simulink ® to compensate for three phase unbalanced CFL load under distorted mains voltage

The THDi of resulting compensated current has been presented as a measure of the effectiveness of the method.

5 Simulation

This section presents details of the simulations implemented in Simulink ®

5.1 CFL Model

Figure-3 shows the CFL model used in simulation. A two-level diode bridge rectifier charges a capacitance. The inverter circuit and fluorescent tube have been modeled as an equivalent resistance.

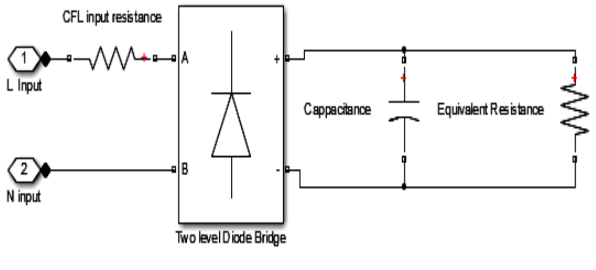

Fig. 3: 23 Watt CFL unit simulated in Simulink ®

Figure 4 shows three phase CFL load, each subsystem contain 10 to 30 CFLs per phase

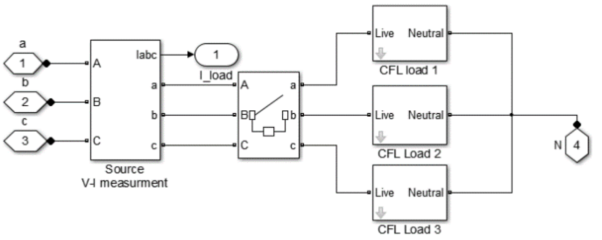

Fig. 4: Three phase CFL load

5.2 Shunt Active Power Filter

Figure 5 gives active power filter implemented as a two level IGBT-diode bridge. S1 to S6 are IGBTs being used as switches. L-filter reduces switching harmonics. The DC bus is composed of two capacitors grounded at neutral point.

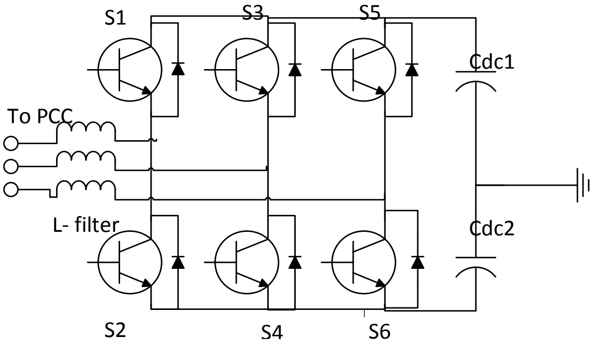

Fig. 5: Shunt Active Power Filter implemented through two level IGBT, diode bridge

5.3 Harmonic Current Estimation

Figure 6 shows harmonic current estimation algorithm. Non-linear load currents are transformed into d-q-0 co-ordinates and low pass filters are used to separate harmonic and fundamental parts. The harmonic components then form the basis for compensation currents injected through the SAPF. Figure-7 shows the application of a self-tuning filter (STF) to purify grid voltage reference where grid voltage contains harmonic distortion as demonstrated in[5] and [6].

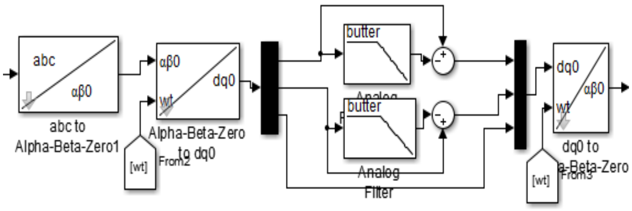

Fig. 6: Park transformation of load currents and current estimation using Low Pass Filters (LPF)

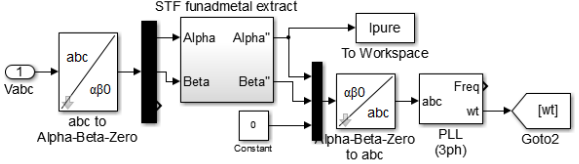

Fig. 7: Self tuning filter to purify grid voltage reference

6 Results

This section presents the experimental results obtained

6.1 D-Axis current

Figures 6 to 8 show the processing of load current in d-q-0 co-ordinates. Figure-6 shows d-axis current containing fundamental and harmonic components. Once this current has been passed through low pass filter, only the fundamental component remains as in figure-7. Whereas, the harmonic part has been shown in figure-8.

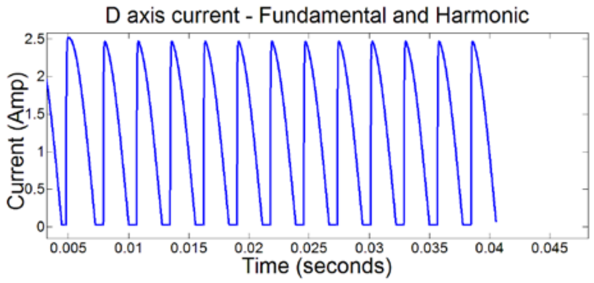

Fig. 8: d-q-0 transformed d-axis current showing harmonic and fundamental part

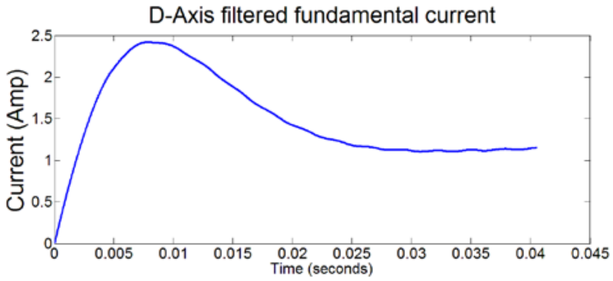

Fig. 9: Filtered d-axis current showing only fundamental part

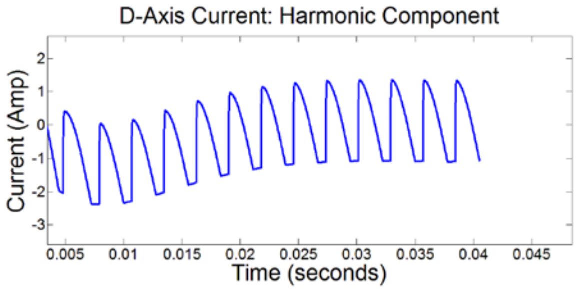

Fig. 10: d-axis current showing only harmonic part

6.2 Load Current

Figure-9 shows the three phase un-balanced CFL load current under distorted grid voltage. Figure-10 gives the THDi of load current of phase-A.

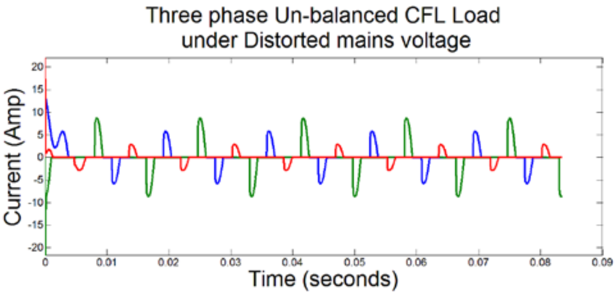

Fig. 11: three phase un-balanced CFL load current under distorted AC mains voltage

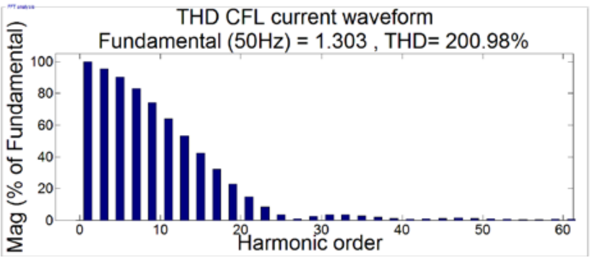

Fig. 12: THDi of phase A: CFL load current under distorted AC mains voltage

6.3 Effect of Line Impedance on Current spectrum

Figure-13 shows harmonic spectrum of load current drawn by 28 simulated CFL units, rated at 23 watts each. Figure-14 shows spectrum of the same current when a small line impedance is included in the simulation.

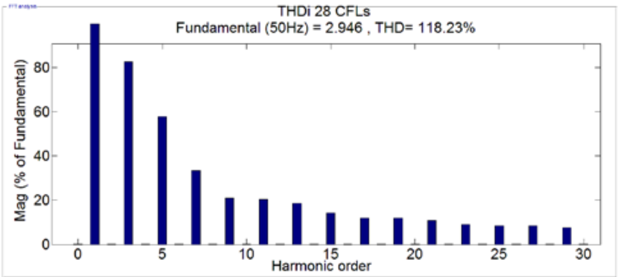

Fig. 13: Harmonic current spectrum and THDiof 28 CFLs 23 watt each. No system impedance considered

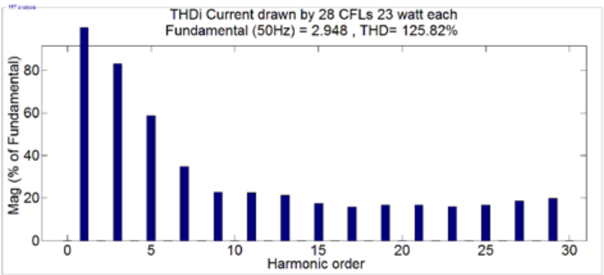

Fig. 14: Harmonic current spectrum and THDi of 28 CFLs 23 Watt each. Small line impedance included in simulation

6.4 Compensated Load Current

Figure-11 gives three phase current after compensation through load current. Figure 12 gives THDi of phase-A after compensation.

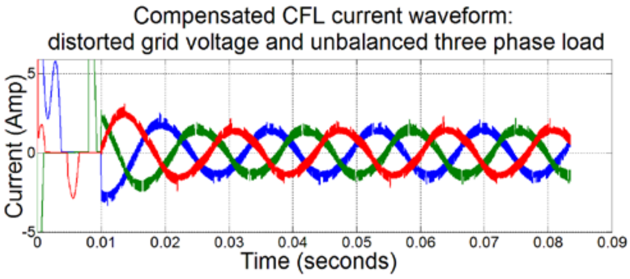

Fig. 15: CFL load current after compensation through SAPF

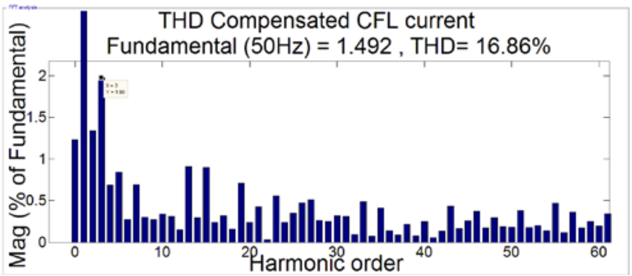

Fig. 16: THDi of phase A: compensated CFL Load currrent

6.5 Injected current

Figure-12 compares the compensation current reference with current injected by SAPF into the system.

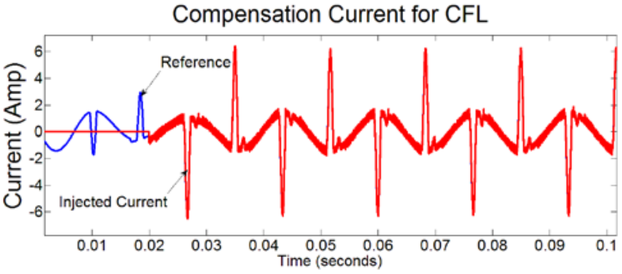

Fig. 17: SAPF current: reference vs Actual

7 Discussion

Section-6.1 of results shows plots of d-q-0 transformed load current. Waveform in Figure-8 contains both harmonic and fundamental components. Waveform in figure-9 is obtained by passing these values through a low pass filter (LPF), thus obtaining the fundamental component. Figure-10 shows the remaining purely harmonic content.

Section-6.2, figure 11 shows plot of three phase load current. Figure-13 shows the harmonic spectrum of current of phase-A. The THDi is around 200%, this is due to distortion in grid voltage

Section-6.3 compares harmonic spectra of 28 identical simulated CFL units each rated at 23 watt. Figure-13 shows THDi and harmonic spectrum when no line impedance has been considered. Whereas, figure-14 shows THDi and spectrum when a small line impedance has been included. Comparing the two, it can be seen that line impedance causes an increase in THDi by causing higher order harmonics to increase.

Section-6.4 shows results of compensating the distorted load current through a d-q theory based SAPF. Figure-15 shows a compensated three phase current waveform. It can be seen that the current is nearer to a sine wave. Figure-16 shows harmonic spectrum of compensated current where THDi has reduced to 17%.

Section-6.5, figure-17 compares SAPF injected current with the reference generated by current estimation block. It can be seen that injected current (in red) closely follows reference current (in blue).

8 Conclusion

The results presented show a d-q theory based current estimation SAPF scheme, where an STF is used to process grid voltages and LPF to process load current. The THDi of load current has reduced from 200% to 17%. Thus, it can be said the proposed scheme adopted here is successful in reducing harmonic distortion in current.

From the comparison of 28 CFL load current spectra where a line impedance is simulated, it can be concluded that line impedance adds to harmonic distortion in current.

9 Acknowledgments

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10 References

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