



# PROPAGATION AND SINGLE-TUNED FILTER BASED MITIGATION OF HARMONICS IN DISTRIBUTION NETWORKS

J. Dragovic\*, J.V. Milanovic\*, V.A. Katic\*\*, M.T. Au\*

\*The University of Manchester, School of Electrical and Electronic Engineering, Manchester, UK  
[jelena.dragovic-2@manchester.ac.uk](mailto:jelena.dragovic-2@manchester.ac.uk), [milanovic@manchester.ac.uk](mailto:milanovic@manchester.ac.uk), [m.au@postgrad.manchester.ac.uk](mailto:m.au@postgrad.manchester.ac.uk)

\*\*University of Novi Sad, Faculty of Technical Sciences, Novi Sad, S & M, [katav@uns.ns.ac.yu](mailto:katav@uns.ns.ac.yu)

**Abstract:** *The paper analyses harmonic propagation and mitigation in realistic, large distribution network under different operating conditions. Total voltage harmonic distortion ( $THD_V$ ) levels are established for different loading and operating conditions and different network topologies. Once the range of  $THD_V$  variation for different scenarios is established, single tuned passive filters are designed to improve the overall network harmonic performance. A large number of simulations were performed taking into account different filter size, tuning frequency, operating conditions, network topologies and load composition in order to optimise the size, the number and the location of the filters in the network. The optimal filtering solution for the test network resulting in significantly reduced harmonic levels is proposed. A generic distribution network, based on typical UK distribution network is used in all simulations. Harmonic analysis was performed using commercially available software package, SuperHarm.*

**Key Words:** *Power quality, harmonics, single tuned filters*

## 1. INTRODUCTION

One of the main purposes of a power system is to deliver electric power to customers at specified quantity and quality. If the supply is constant, i.e. the quantity requirement is satisfied, the focus turns towards the quality of delivered energy. The quality of the electricity supply generally refers to voltage having constant frequency, amplitude, symmetry and sinusoidal waveform [1]. Depending on the sensitivity of the equipment connected to the network, variation in power quality may result in substantial financial consequences.

One of the important factors contributing to the quality of electricity supply is harmonics. They are defined as sinusoidal component of a periodic waveform having a frequency which is an integer multiple of the fundamental frequency [2].

The presence of harmonics have a negative impact on power systems. They may lead to harmonic resonance, increased losses, degradation of dielectric characteristics of cables and capacitors, malfunction of equipment, interference with communication circuits and power measurement, etc. [1],[2],[3],[4]. Ultimately this may

result in reduction of the lifespan of devices, increased maintenance cost and the need to oversize the equipment.

There is a need therefore, to consider appropriate mitigation techniques to reduce the level and propagation of harmonics in the network. In spite of natural and forced harmonic cancellation (due to different phase angles, supply via transformers having different winding connection, etc.) it is often necessary to include appropriately designed passive harmonic filters in distribution networks.

Before any harmonic mitigation measure is considered however, it is necessary to assess the overall harmonic characteristics and propagation of harmonics in distribution network.

In the analysis of harmonic propagation and mitigation presented in this paper, SuperHarm, a commercial grade harmonic simulation software is used in all simulations. A generic distribution network, based on typical UK distribution network, is modeled. Total harmonic voltage distortion levels ( $THD_V$ ) are established for different loading and operating conditions and network topologies. Frequency scan is performed to determine resonant conditions in the network.

Once the range of  $THD_V$  and the resonant conditions of the network are established for different load scenarios, single tuned passive filters are designed and tuned to improve the overall network harmonic performance. Several simulations taking into account different filter size, tuned frequency, operating conditions, network topologies and load compositions are performed to determine the optimum size, number and location of the filters in the network

## 2. MODELLING OF THE TEST NETWORK

### 2.1. Network model

A realistic distribution network shown in Fig.1 is fed from the transmission system at two high voltage substations at 400kV and 275kV. It consists of 289 buses, of which 24 are 132kV, 25 are 33kV, 233 are

11kV, and 4 are 3kV buses. 21 step-down transformers are also modelled. There are 300 lines, of which majority are 11kV underground cables, and the rest are 33kV overhead lines. (The 33kV network is predominantly meshed, whereas the 11kV network is of predominantly radial configuration.) Topology of the generic network is changed in simulations from predominantly meshed to predominantly radial by switching on/off some of the 24 available circuit breakers and switches.

The system is modeled as single-phase model using per unit values. Overhead lines and underground cables are modelled by their  $\pi$  equivalent circuit, linear loads as frequency dependent resistance in parallel with inductance, and nonlinear loads as harmonic current sources [5] (only the 5<sup>th</sup>, 7<sup>th</sup> and 11<sup>th</sup> harmonic are included in harmonic spectra of nonlinear loads).

### 2.2. Load/Consumer classes

Aggregate loads are categorized based on three typical consumer classes:

- a) Residential loads, where nonlinear loads are typically television sets, personal computers, low power home appliances with electronic converters, and discharge lamps;
- b) Commercial loads, where fluorescent lighting, computers and their peripherals form the majority of nonlinear load;
- c) Industrial loads, where nonlinear loads are mainly adjustable speed drivers and converters.

Aggregate nonlinear loads are connected at 146 out of 289 buses in the network. Ten of those are industrial loads, 30 are commercial and 106 are residential. (See Fig. 1)

## 3. CASE STUDIES

Nine different cases (combination of three network topologies and three characteristic loading scenarios) are considered in order to establish boundaries and levels of harmonic distortion and propagation in the network.

### 3.1. Network topologies

The following three network topologies are considered:

T1 - predominantly meshed topology where all breakers and switches are closed (See Fig. 1). This topology is considered to be the base case network.

T2 - predominantly radial topology obtained by opening 22 characteristic breakers and switches.

T3 - split network topology, obtained by opening 4 characteristic lines. In this case the network is practically divided into two almost equal parts, with connection at 132kV level (right and left part).

### 3.2. Loading scenarios

Taking into account different composition of linear and nonlinear loads in each consumer sector and variation of load demand with time of day and day of week, three loading scenarios are considered:

L1 - day peak load, i.e., from 10:30 - 11:30 am of a weekday,

L2 - night peak load, i.e., from 7:30 - 8:30 pm of a weekday,

L3 - off peak load period, i.e., from 10:30 - 11:30am of a weekend.

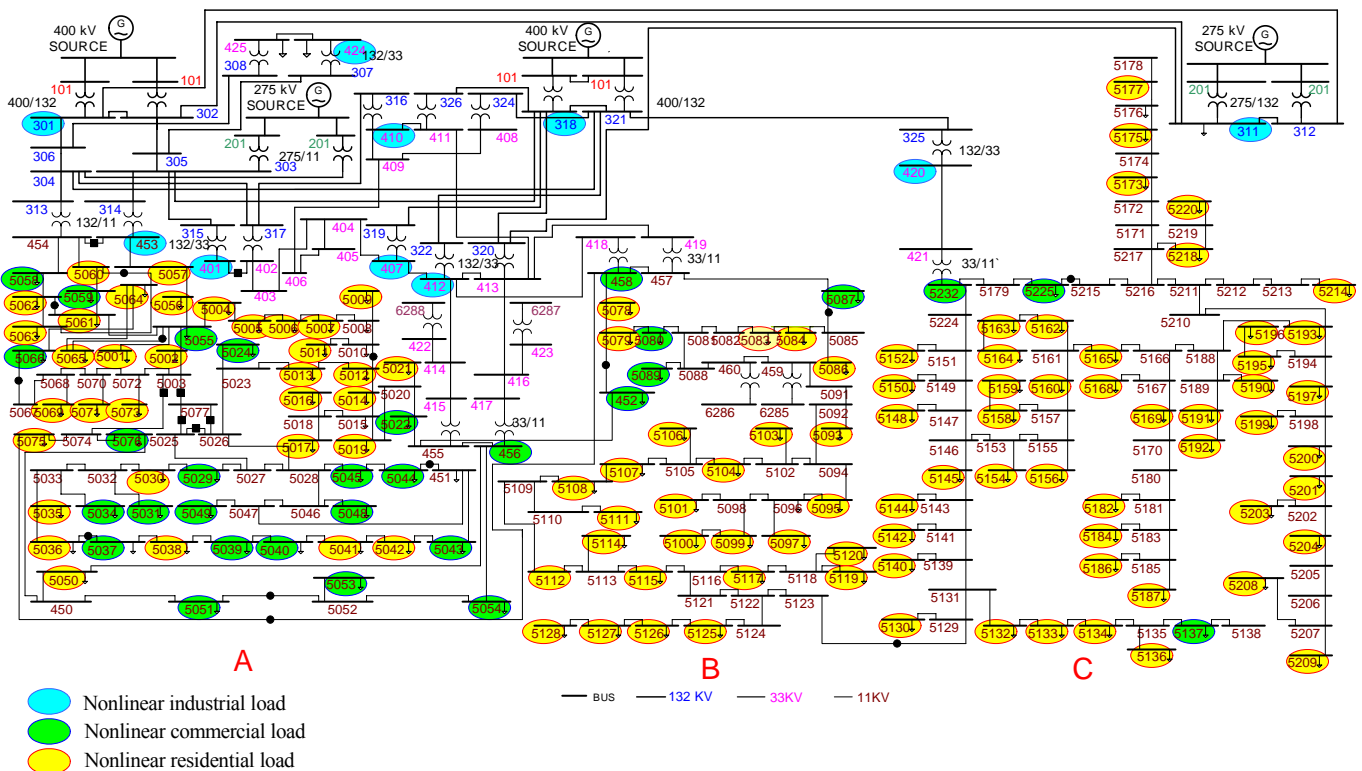


Fig. 1 - Generic Distribution Network.

## 4. HARMONIC CHARACTERISTIC OF THE NETWORK

### 4.1 The influence of network topology and loading conditions on THD<sub>v</sub>

In order to assess the influence of network topologies and load scenarios on harmonic voltage distortion, THD<sub>v</sub> is calculated for every bus and for every case study (Fig.2). According to IEEE 519-1992, THD<sub>v</sub> limit for 69kV and lower voltage level is 5%, and for 69kV < U<sub>N</sub> ≤ 161kV is 2,5%. None of the cases investigated exceeded the specified limits.

Higher values of THD<sub>v</sub> are noticed for buses at 11kV level. The maximum THD<sub>v</sub> is 4.18% at bus B5037 in the case of T2L2 combination. High THD<sub>v</sub> is also observed at all buses in the radial part of the network regardless of the operating condition.

The lowest THD<sub>v</sub> is observed during off peak (L3) period as usage of nonlinear devices is at its minimum. The maximum THD<sub>v</sub> for topology T3L3 is found to be only 0.905%.

The results obtained for the two characteristic cases are shown in the sequel.

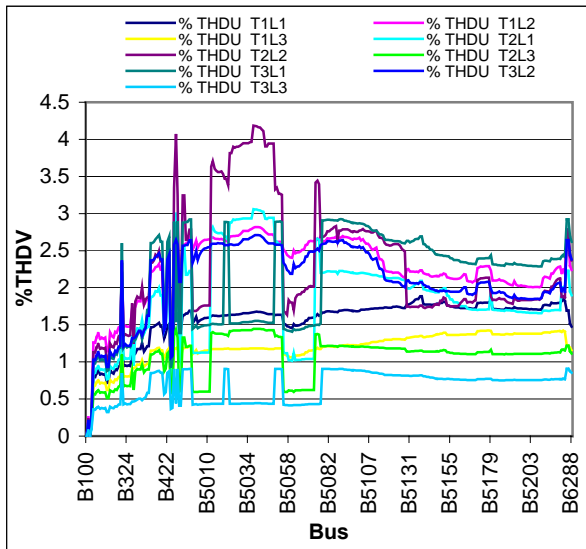


Fig.2 - THDV of all buses for all topologies and load scenarios.

### 4.2 The influence of network topology and loading conditions on voltage levels

Fundamental voltages at all buses in the network are determined for all cases of different network topologies and loading scenarios as shown in Fig. 3.

It can be observed that the largest magnitude occurs during the off peak period (L3), when the system is most lightly loaded. The region C (see Fig. 1) experienced significant voltage drop for all 9 cases primarily due to long lines effect.

The most significant drop in fundamental voltage occurs during the night peak, in particular at 11kV buses where there are a large number of residential consumers. Case T2L2 is the most problematic as the voltage at bus B5209 dropped to 0.62 p.u., which is attributed to the radial network topology. The under voltage problem

observed in these cases can be successfully resolved by installing switched capacitors at appropriate buses in the network.

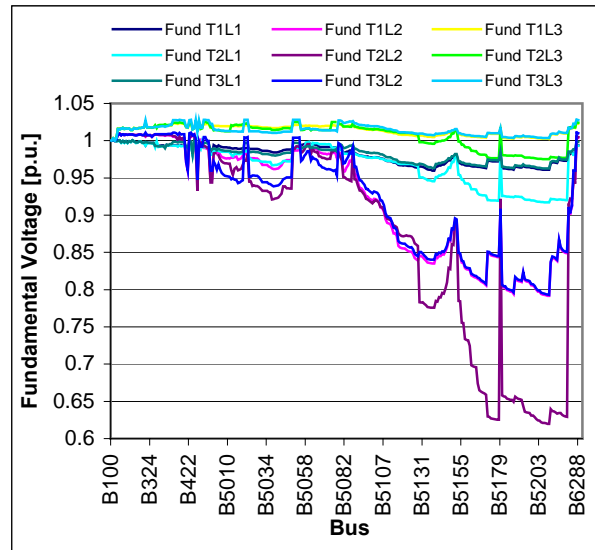


Fig.3 - Fundamental voltage profile for all buses.

### 4.3 Frequency response of the characteristic cases

Resonant conditions in the network are assessed by performing frequency scan for characteristic cases, T2L2 (Fig.4) and T3L3 (Fig.5). Frequency scan is performed by injecting  $1\angle 0^\circ$  p.u. harmonic currents (within frequency range of 50 (h=1) and 1500 Hz (h=30)) at buses of interest (B412, B450 and B5106). In frequency scan mode, voltage sources are short circuited and harmonic current sources representative of nonlinear loads are open circuited. Based on  $Y_f \times v_f = i_f$ , (where  $Y_f$  is admittance matrix and  $i_f$  harmonic current), the nodal voltage vector  $v_f$  is calculated at every frequency of interest. A parallel resonance in the network is indicated by a sharp rise in voltage. The frequency at which it occurs is dependent on the ratio of the equivalent network capacitance and inductance [4].

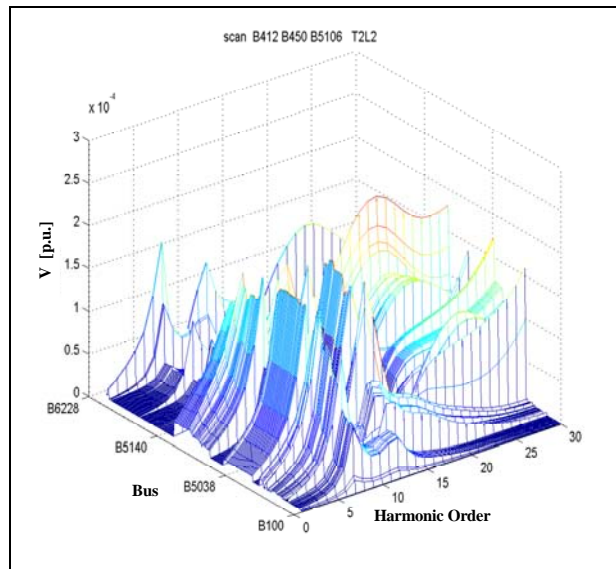


Fig.4 - Voltage frequency response for case T2L2.

For the case T2L2, it is observed that parallel resonance occurs at the 7<sup>th</sup> and 12<sup>th</sup> harmonic at 132kV buses. At the 33kV buses, parallel resonance occurs at the 7<sup>th</sup> harmonic with significantly higher peak voltage. At the 11 kV buses of the region A of the network, parallel resonance occurs at the 7<sup>th</sup> and 12<sup>th</sup> harmonic with the peak voltage which is about 25% higher than that at the 33kV buses. Similar frequency response is observed in regions B and C of the network, as well as at the 3 kV buses.

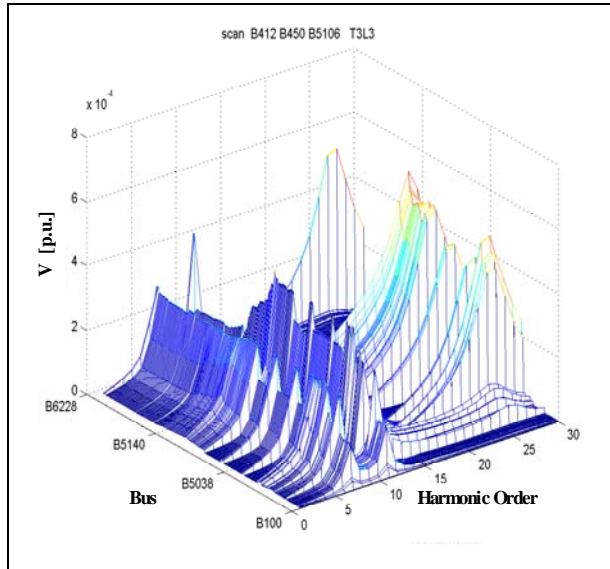


Fig.5 - Voltage frequency response for case T3L3

For case T3L3, parallel resonance is observed at the 7<sup>th</sup>, 11<sup>th</sup>, and 26<sup>th</sup> harmonic. The 7<sup>th</sup> and the 11<sup>th</sup> harmonic are characteristic for all the buses, whereas the 26<sup>th</sup> harmonic is mostly observed at buses from the region B (see Fig. 1) of the network.

In this study, harmonics of interest are 11<sup>th</sup> and below. Harmonic currents with frequencies higher than the 11<sup>th</sup> harmonic are considered to be negligible and therefore are not included in the nonlinear load model.

Comparing harmonic responses for cases T2L2 and T3L3, it can be seen that network topology and loading scenario have a significant impact on the peak voltage as well as on the resonant frequency. The peak voltage in case T3L3 is almost doubled compared to that observed in case T2L2. This is mainly due to the loading condition of the network which has a direct effect on damping of harmonic voltage. For all cases considered in this analysis the resonance at the 7<sup>th</sup> harmonic is the most dominant.

## 5. HARMONIC MITIGATION

Simulation results indicate that maximum THD<sub>V</sub> at the 11 kV buses is 4.18%, which is within typical limits of 5%. However, assuming constant growth in the usage of nonlinear loads in customer installations, overall increase in THD<sub>V</sub> is expected and hence harmonic mitigation should be considered.

Frequency scan indicates that the 7<sup>th</sup> harmonic is the common resonant frequency for all cases under investigation. Therefore, harmonic filters tuned to the 7<sup>th</sup> harmonic are considered for mitigating harmonic

propagation in the distribution network and to improve overall harmonic performance.

Single tuned passive filters are chosen, as they are simple to design, reliable and the least expensive.

Generally, the best location to place a filter is at the harmonic source. However, this is not feasible in the network with huge amount of nonlinear loads. Therefore, the aim is to place the minimum number of filters to improve the overall network harmonic characteristics.

Multiple simulations were performed taking into account filter sizes, tuned frequency, and location to establish optimum locations and number of filters required for the network.

### 5.1 The influence of tuning factor on frequency response

Dielectric materials of capacitors generally degrade over the time which results in decrease in capacitance. A consequence of this is the increase in resonant (tuned) frequency of the filter and it may become less effective. To compensate for this phenomenon, harmonic filters are tuned typically to a value slightly below the resonant frequency. The usual value of filter "tuning factor" is  $a=(3-10)\%$  [4].

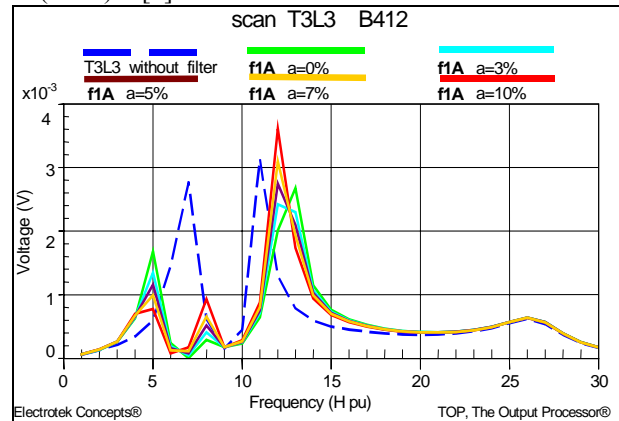


Fig.6 - Impact of tuning factor on frequency response of bus B412

Fig.6 shows the frequency response at bus B412 of case T3L3 with and without filter. Configuration **f1** refers to a filter (**f1A**) placed at bus B412 tuned to  $h=6.65$  ( $a=3\%$ ), rated capacity of 6.5 p.u., and a filter placed at bus B5165 tuned to  $h=10.45$ , rated capacity of 1p.u. In subsequent cases, filter tuning factor ( $a$ ) at bus B412 was changed from  $a=0\% \Rightarrow h=7$ ,  $a=3\%$ ,  $a=5\%$ ,  $a=7\%$ , up to  $a=10\% \Rightarrow h=6.3$ .

It can be seen from Fig. 6 that filter completely damps tuned harmonic. Reduction in tuning factor  $a$  (from the original value, say 5%) leads to voltage increase (reduced damping effect) at lower harmonics and decrease at higher harmonics. Therefore, as capacitor units grow old ( $a$  reduces) lower harmonics become less damped and higher slightly more.

### 5.2 The influence of filter size on frequency response

Case T3L3 with filter configuration **f1** is used to investigate the influence of filter size on frequency response. Frequency response curve at bus B412 is

shown in Fig. 7. Filter size at bus B412 is varied from 50%, 100% and 150% of base value. The results are compared with the case without the filter in Fig.7.

It can be seen that as the filter size increases the frequency response of harmonics close to the tuned harmonic reduces. Also, higher filter size moves resonant frequencies away from tuned frequency: the 50% sized filter causes results in peaks (harmonic resonance) at the 5<sup>th</sup>, 8<sup>th</sup> and the 12<sup>th</sup> harmonics; for 100% sized filter, the peak is at the 12<sup>th</sup> harmonic, while the peaks at 5<sup>th</sup> and 8<sup>th</sup> are much smaller; for 150% sized filter, the dominant resonant frequency is moved to the 4<sup>th</sup> and the 13<sup>th</sup> harmonic.

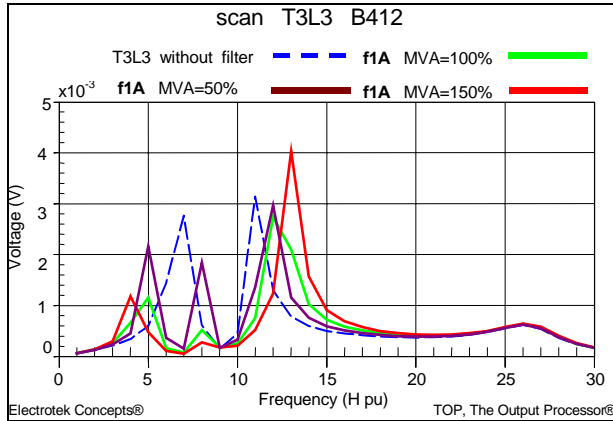


Fig.7 - Impact of filter size on frequency response of bus B412.

## 6. OPTIMAL FILTER PLACEMENT

A large number of simulations were performed with filters placed at nodes with high THD<sub>V</sub> which are nodes with large harmonic sources. As there are many cases of different network topologies and load scenarios, it is difficult to find the right combination that will satisfy all cases. One of the major problems was with filter placement that caused a reduction in THD<sub>V</sub> in all cases, but the fundamental voltage exceeded permitted limit of 105%. There are other cases where filter combinations resulted in optimal fundamental voltage regulation but no significant reduction in THD<sub>V</sub>. Further course of investigation led to placement of filters closer to sources of supply, as the impact on all topologies would be more equalized.

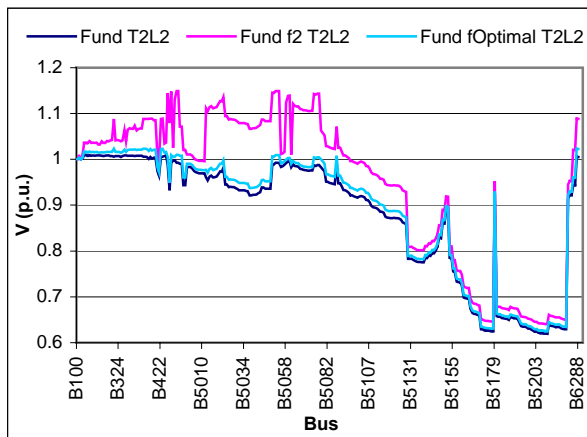


Fig.8 - Fundamental voltage profile for situation without filters, with *f2* and with *fOptimal* for case T2L2.

Fig.8 and 10 show fundamental voltage profile of the network for cases T2L2 and T3L3 respectively.

Fig. 9 and 11 show THD<sub>V</sub> of the network for cases T2L2 and T3L3, respectively. In the case of *f2*, three filters are tuned to frequency 6.65x50Hz (a=5%), with rating equal to 20 p.u. and placed at the bus having the largest nonlinear load in each consumer sector, i.e, bus B412, B456 and B5060.

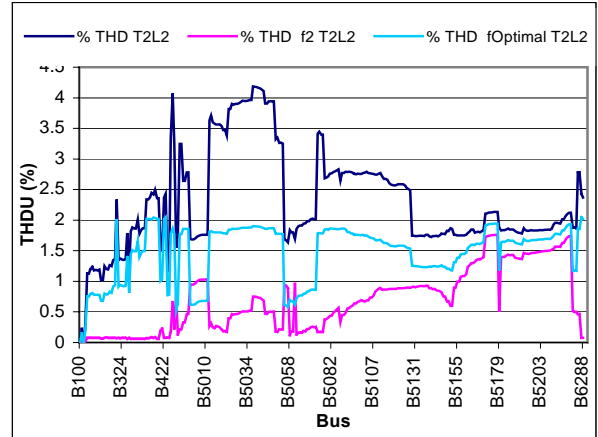


Fig.9 - THDV profile for situation without filters, with *f2* and with *fOptimal* for T2L2.

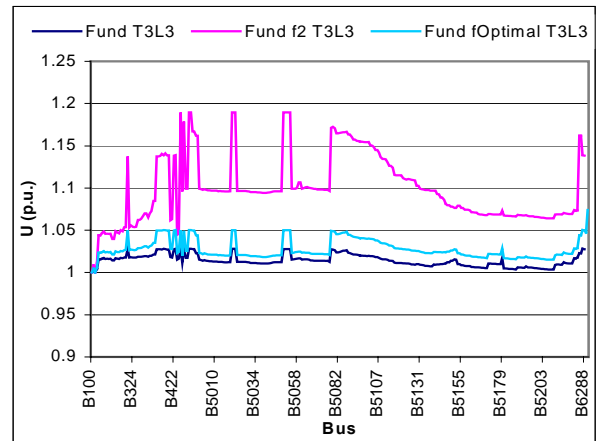


Fig.10 - Fundamental voltage profile for situation without filters, with *f2* and with *fOptimal* for T3L3.

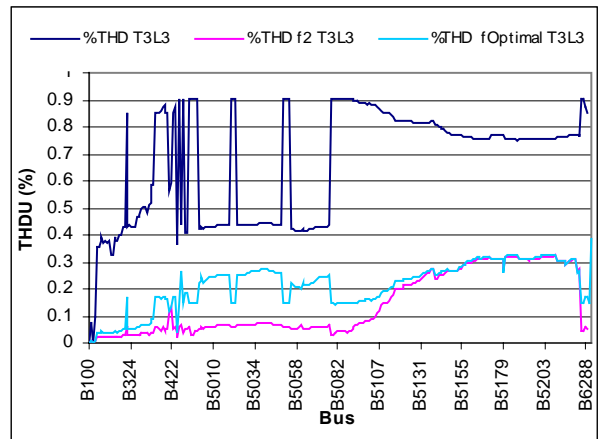


Fig.11 - THDV profile for situation without filters, with *f2* and with *fOptimal* for T3L3.

The case **fOptimal** refers to filters placed at 2 buses with the largest nonlinear loads disregarding consumer sector. At bus B412, the filter is sized at 8 p.u., whereas at bus B301 it is 10 p.u. Both filters are tuned to  $6.65 \times 50\text{Hz}$  ( $a=5\%$ ).

Combination **f2** is found to perform better in terms of  $\text{THD}_V$ , than combination **fOptimal**. However, combination **f2** resulted in voltages higher than statutory limits in both of cases (T2L2 and T3L3).

Amongst all the filter combinations, only **fOptimal** satisfied fundamental voltage limits and desired  $\text{THD}_V$  for all cases of network topologies and loading scenarios. For case T2L2,  $\text{THD}_V$  decreased from maximal value of 4.18% to 2.02%, and for case T3L3 from 0.9% to 0.33%.

A three-dimensional representation of frequency response for case T2L2 with optimal filter configuration **fOptimal**, based on  $1\angle 0^\circ$  p.u current injection at buses B412, B450 and B5106 is shown in Fig.12.

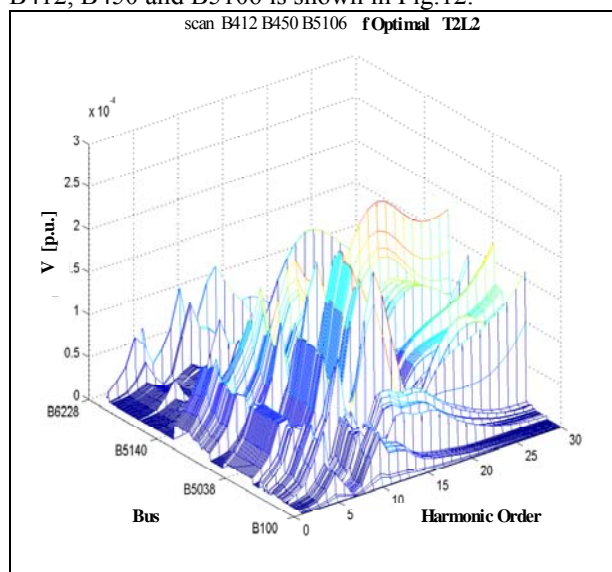


Fig.12 - Voltage frequency response for case T2L2 with optimal filter configuration **fOptimal** and  $1\angle 0^\circ$  p.u current injection at buses B412, B450 and B5106.

Significant damping is observed at the 7<sup>th</sup> harmonic for buses in regions A and B, while at the same time new set of resonant frequencies is at the 4<sup>th</sup>, 5<sup>th</sup>, 9<sup>th</sup> and 13<sup>th</sup> harmonic. In the region C of the network (see Fig. 1), the 7<sup>th</sup> harmonic voltage is almost completely damped, but new set of resonant frequencies (5<sup>th</sup> and 9<sup>th</sup>) is observed. The filters have no significant impact on harmonics greater than the 21<sup>st</sup>.

## 6. CONCLUSION

Presented analysis showed that network topology and loading scenario have a significant impact on harmonic

performance of distribution network in terms of  $\text{THD}_V$  and fundamental voltage.

The influence of harmonic filter tuning on network harmonic performance is also investigated. The level of harmonic voltage reduction for the respective frequencies is dependent on the frequency at which harmonic filters are tuned. Similarly, the size of harmonic filters affects the range of frequencies at which the filter is effective in damping harmonic voltages.

After detailed analysis of different influences on frequency characteristics of the network, determining characteristic cases according to maximum  $\text{THD}_V$  and establishing critical conditions for resonance, the single tuned passive filters are designed to improve the overall network harmonic performance.

A large number of simulations was performed taking into account different filter sizes, tuning frequencies, operating conditions, network topologies and load compositions in order to optimise the size, number and location of the filters in the network. It is shown that the proposed optimal filtering solution (with only two 7<sup>th</sup> harmonic filters) results in significant reduction in harmonic voltage levels.

Finally, it is observed that placing filters for damping particular harmonics in the network, results in new resonant conditions in the network. Depending on the severity of new resonances, new filters might need to be placed in the network.

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