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MITIGATION OF INTERHARMONICS DUE TO VOLTAGE SOURCE INVERTER FED ASDS BY USING COMBINED CONTROL OF PASSIVE FILTERS

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ABSTRACT
In this paper, solutions to mitigate interharmonics produced by voltage source inverter fed Adjustable Speed Drives are analyzed. A new scheme called combined control of passive filters to mitigate the interharmonics effectively is also proposed. Interharmonics are generated because of overmodulation of inverter or due to unbalanced load. The effect of load unbalance on rectifier input current is analyzed and simulation is carried out in PSIM software. First, the effect of dc link inductance on input current interharmonics is analyzed. Then the mitigation of interharmonics by using combination of two passive filters, One is at ac input side and another is at dc link are analyzed and simulated. The effective reduction of interharmonics is proved.

Keywords: interharmonics, combined control, dc link inductance, passive filter, load unbalance.

1. INTRODUCTION
Nonlinear loads such as power electronic converters distort the power system signals. [1] These loads inject not only harmonics but also interharmonics into the power system. [2] Voltage source inverter fed drives and cycloconverter fed drives are major sources of interharmonics. [3] In these two drives, the drive operating frequency is different from the supply frequency resulting in interharmonics in the supply system [4] and [5].

Interharmonics are components which are not integral multiple of the supply fundamental frequency [4]. Interharmonics result in temperature rise, communication interference, resonance and visual flicker even if their magnitudes are low [6].

The objective of this paper is to suggest methods to attenuate interharmonics. First the method of reducing interharmonics by changing the dc link inductance is presented and the rectifier current is analyzed using Fast Fourier Transform. Second a suitable passive filter is suggested to reduce interharmonics and its effectiveness is analyzed using PSIM software.

2. SYSTEM DESCRIPTION
The general block diagram of VSI-fed induction motor is shown in Figure-1. In case of the above shown AC-DC-AC conversion system, the dc voltage on either side of the inductor L is not smooth. Because of this, the current at the dc link is not smooth and has small ripple. This ripple appears on the grid. The ripple in the current of dc link depends both on supply frequency and motor operating frequency. When there is an unbalance in the motor side, this unbalance propagates into the dc link side. This is again reflected into the supply side as interharmonics. The level of interharmonic present in the source depends upon the reflected inverter harmonics to the dc link and the dc link's capability to block the inverter current propogation [7]. Interharmonics that are generated in the supply side are dependent on the motor speed which is dependent on the motor operating frequency [8].

3. ANALYSIS OF THE INTERHARMONIC COMPONENTS
In this section, to analyze motor current unbalance, an inductor is added in series with one phase. The effect of this unbalance in the input current is investigated in various stages.

3.1. Harmonic transfer from the inverter to the dc link
Pulse Width Modulation technique is used to synthesize the output voltage at the desired frequency from the constant dc link voltage. Only the low frequency components are considered. The inverter output voltages are given by:

$$V_{ui} = \frac{V_{dc}}{2}\left(1 + m_i \cos \omega t\right) = V_{dc}\, S_{ui} \qquad (1)$$

Where m_i = modulation index. Phase voltages V_{vi} and V_{wi} are shifted by 120˚ and 240˚, respectively. S_{ui} is inverter switching function.
The inverter switching function S_{ui} is given by:

$$S_{ui} = \frac{1}{2}\left(1 + m_i \cos\omega t\right) \qquad (2)$$

The swithching functions S_{vi} and S_{wi} are shifted by 120˚ and 240˚, respectively.

As the motor current is unbalanced, in addition to the positive sequence components, negative sequence components are also present in the motor currents [9]. The motor input current is given by:

$$i_{ui} = \sqrt{2}\left(I_p\right)\cos\left(\omega t + \varphi_p\right) + \sqrt{2}\left(I_n\right)\cos\left(\omega t + \varphi_n\right) \qquad (3)$$

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Where I_p = positive sequence component of current

I_n = negative sequence component of current

These components of currents have phase shift of φ_p and φ_n

Similarly motor input current equations can be written for the remaining two phases.
The inverter input current is given by:

$$i_{inv} = \mathrm{S_{ui} i_{ui}} + \mathrm{S_{vi} i_{vi}} + \mathrm{S_{wi} i_{wi}} \quad (4)$$

$$S_{ui} i_{ui} = \frac{1}{2}(1 + m_i \cos\omega t)\begin{bmatrix} (\sqrt{2}(I_p)\cos(\omega t + \varphi_p)) + \\ (\sqrt{2}(I_n)\cos(\omega t + \varphi_n)) \end{bmatrix} \quad (5)$$

Similarly expressions for $S_{vi}i_{vi}$ and $S_{wi}i_{wi}$ can be obtained by proper substitution. Final substitution in equation (4) gives:

$$i_{inv} = \left(\frac{3}{4} m_i \sqrt{2} I_p \cos\varphi_p\right) + \left(\frac{3}{2\sqrt{2}} m_i I_n \cos(2\omega_{out} t + \varphi_n)\right) \quad (6)$$

$$i_{inv} = I_{dc} + I_{dist} \quad (7)$$

where

$$I_{dist} = \frac{3}{2\sqrt{2}} m_i I_n \cos(2\omega_{out} t + \varphi_n)$$

$$I_{dc} = \frac{3}{4} m_i \sqrt{2} I_p \cos\varphi_p \quad (8)$$

I_{dc} is related to the positive sequence component and is responsible for active power transfer. The component I_{dist} is related to the negative sequence component and is responsible for the disturbance in the inverter dc side current which fluctuates at two times the output frequency ($2\omega_{out}$) i.e., the operating frequency of the inverter.

3.2. Harmonic transfer through dc link

The disturbance in the inverter side dc link is transferred to the dc link of rectifier. Current magnification occurs at the dc link due to parallel resonance. The disturbed current at the dc link of the rectifier is given by:

$$i_{rect} = \mathrm{I_{dc}} + \sqrt{2}\, \mathrm{I_{rect}} \cos(2\omega_{\mathrm{out}} \mathrm{t} + \phi) \quad (9)$$

Where

$$I_{rect} = \mathrm{k_{dclink}} I_{dist} \quad (10)$$

$$\mathrm{k_{dclink}} = \left| \frac{\mathrm{R_c} + C_{dc}}{(\mathrm{R_c} + C_{dc}) + (\mathrm{R_L} + L_{dc})} \right| \quad (11)$$

$$\phi = \varphi_{\mathrm{n}} + \varphi_{\mathrm{z}} \quad (12)$$

Where

$\mathrm{k_{dclink}}$ = dc link current magnification factor
R_c, C_{dc} = resistance and capacitance of the capacitor at the dc link
R_L, L_{dc} = resistance and inductance of the inductor at the dc link
φ_z = phase shift due to dc link

As the motor output frequency is varied from 0 to f_{out} the rectifier side dc link current fluctuates with the frequency ranging from 0 to 2 $f_{out.}$

3.3. Harmonic transfer through the rectifier

For this analysis, the rectifier switching functions are considered. The rectifier is assumed to conduct continuously. The input currents of the rectifier considering the switching function are given by:

$$i_{ar} = \mathrm{S_{ar}} i_{rect} \quad (13)$$

Similarly current equations for b and c phases can be obtained by multiplying corresponding switching functions with rectifier dc link current.

The switching function of the rectifier is represented as follows:

$$S_{ar} = \mathrm{A_1} \cos(\omega_{in} t) \quad (14)$$

Where A_1 is the amplitude of the fundamental harmonic component and it is given by:

$$A_1 = \frac{2\sqrt{3}}{\pi} \quad (15)$$

Similarly S_{br} and S_{cr} are shifted by 120° and 240°, respectively.

Thus the input current of the rectifier for phase a is obtained by substituting equations (9) and (14) in equation (13). The final expression of the rectifier phase a input current is given in equation (16).

$$i_{ar} = A_1 \cos\omega_{in} t\left[I_{dc} + \sqrt{2} I_{rect} \cos(2\omega_{out} t + \phi)\right]$$

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$$i_{ar} = \sqrt{2}A_1 I_{dc} \cos(\omega_{in} t + \varphi_{in}) + \frac{1}{\sqrt{2}} A_1 I_{rect} \cos((2\omega_{out} t + \omega_{in})t + \phi) + \frac{1}{\sqrt{2}} A_1 I_{rect} \cos((2\omega_{out} t - \omega_{in})t + \phi) \quad (16)$$

Thus the unbalance in the motor current is propagated to the supply with two components which are symmetrical at $2f_{out} \pm f_{in}$.

3.4. Simulation results

Simulation is done in PSIM for the circuit shown in Figure-2. The power rating of the motor considered is 75kW, 4 pole asynchronous motor. The motor is operated in constant torque region and the output frequency can be varied between 20Hz to 45Hz.

4. EFFECT OF CHANGING THE DC LINK INDUCTANCE

4.1. DC link inductance L_{dc} = 0.001H

First the effect of varying the inductance at the dc link is analyzed. The corresponding results are given in Figure-3(a) when the dc link inductance is 0.001H and f_{out} = 30Hz.When the spectrum is analyzed, it shows that interharmonics are present at frequencies between fundamental and third order harmonic and between third order and fifth order harmonics. The results are shown in Figure-4 for DC link inductance of 0.001H and f_{out} = 40Hz.

4.2. DC link inductance L_{dc} = 0.1H

Simulation is done with a dc link inductance of 0.1H for the circuit shown in Figure-2 for f_{out} = 30Hz and the corresponding results that are input current of the rectifier and its spectrum at L_{dc} = 0.1H and f_{out} = 30Hz are given in Figure 5(a) and (b).

The spectrum of input current of rectifier shows considerable reduction in interharmonics between fundamental and fifth order harmonic and between fifth and seventh order harmonics. This shows considerable improvement in the interharmonic attenuation.

Simulation is done with a dc link inductance of 0.1H and f_{out} = 40Hz and the results that are rectifier input current and its spectrum at L_{dc} = 0.1H and f_{out} = 40Hz. is given in Figure 6.a) and b).

4.3. Passive filter

A suitable passive filter is designed to attenuate harmonics and interharmonics. This passive filtering scheme has a notch filter tuned at 600Hz and a third order high pass filter that provides damping over wide high frequency ranges. Passive shunt filter is shown in Figure-7.

Simulation is carried out using the model shown in Figure-8 in PSIM. The parameters of the filter are

R_2 = 1.0632 Ω	C_1 = 40 µF	C_1' = 10 mF
L_2 = 10.6 mH	R_1 = 2.23 Ω	
C_2 = 40 µF	L_1 = 0.2H	

Simulated results are shown in Figure 9(a) and (b) for f_{out} = 30Hz with passive filters.

Improved current spectrum is obtained with the passive filter. There is considerable reduction in the fifth order harmonic component compared to the previous method of changing the dc link inductance.

Simulation results with f_{out} = 40Hz and the corresponding results are shown in Figure 10(a) and (b).

The percentage magnitude of the interharmonic components for the two output frequencies are compared for the methods discussed. For an output frequency of 30Hz, the input current has interharmonic frequencies of 10Hz and 110Hz. For an output frequency of 40Hz, the input current has interharmonic frequencies of 30Hz and 130Hz. The compared results are shown in Figure-11. This shows that the passive filter method gives comparatively better results.

5. CONCLUSIONS

Combined control of two passive filters for the reduction of interharmonics is suggested. The method is analyzed mathematically and simulated using PSIM in two stages. In first stage, by selecting proper values of inductance at the dc link, interharmonics in rectifier input current is reduced. In second stage, a suitable passive filter is incorporated. The simulated result shows improvement in interharmonic mitigation.

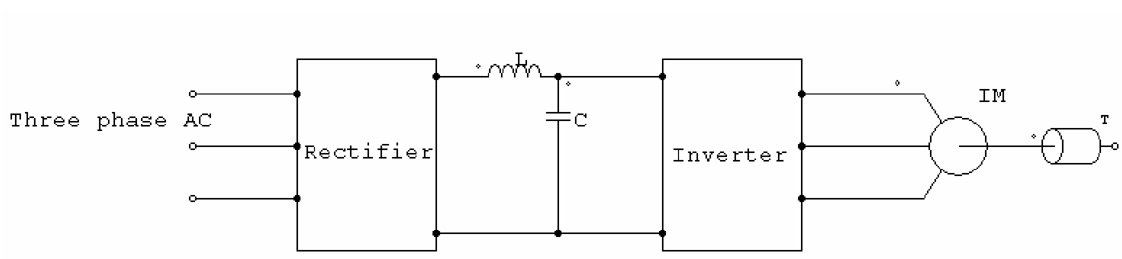

Figure-1. Block diagram of VSI-fed induction motor.

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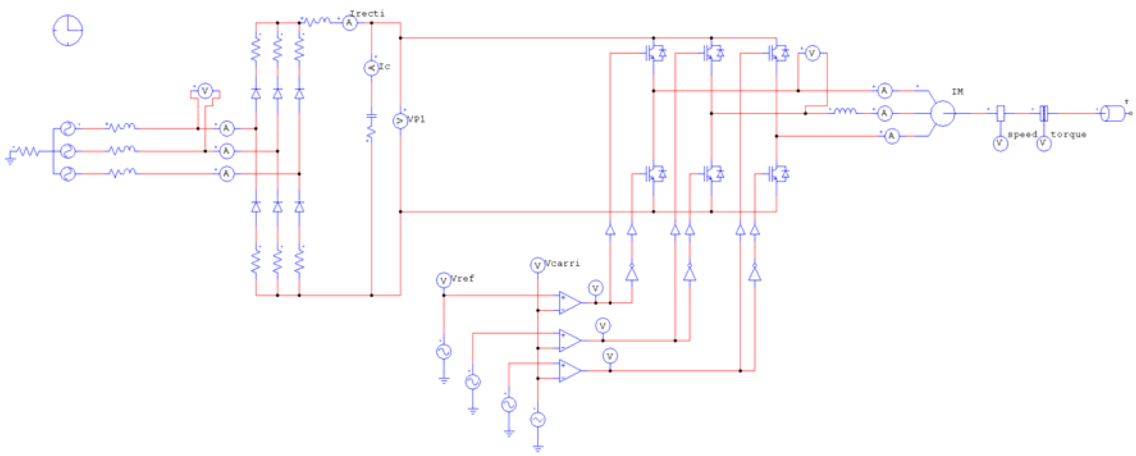
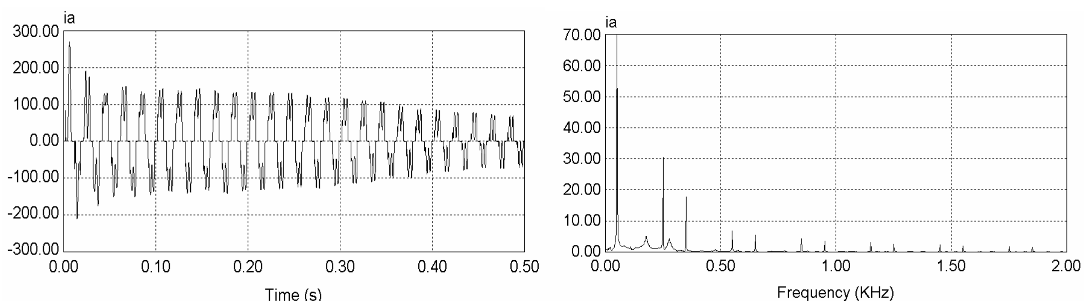
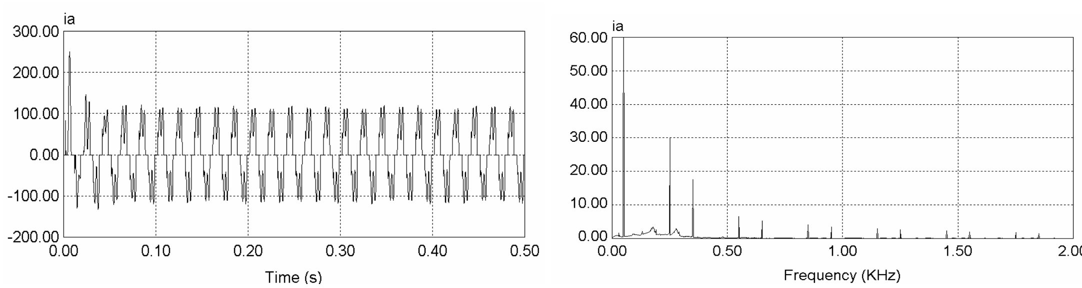


Figure-2. Power circuit diagram in PSIM software.



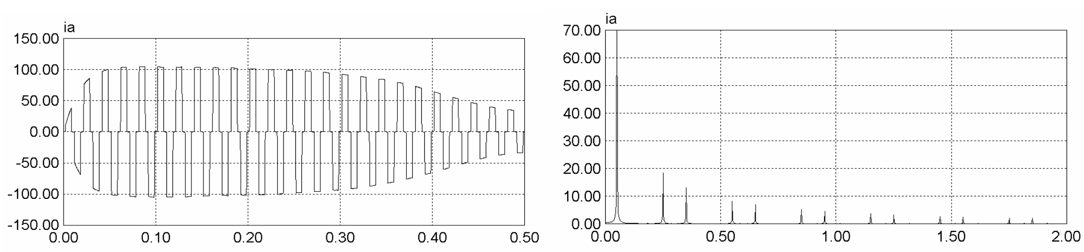
(a) (b)

Figure-3. a). Rectifier input current with dc link inductance is 0.001H and f_{out} = 30Hz: b) Rectifier input current spectrum.



(a) (b)

Figure-4. a) Rectifier input current with DC link inductance of 0.001H and f_{out} = 40Hz: b) Rectifier input current spectrum.



(a) (b)

Figure -5. a). Rectifier input current with DC link inductance of 0.1H and f_{out} = 30Hz: b) Rectifier input current spectrum.

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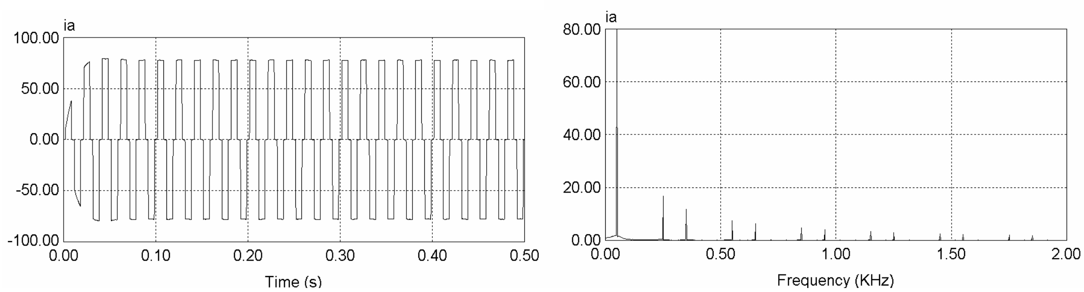

Figure-6. a). Rectifier input current with DC link inductance of 0.1H and $f_{out} = 40$Hz: b) Rectifier input current spectrum.

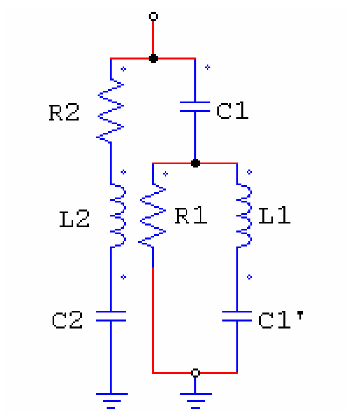

Figure-7. Passive shunt filter.

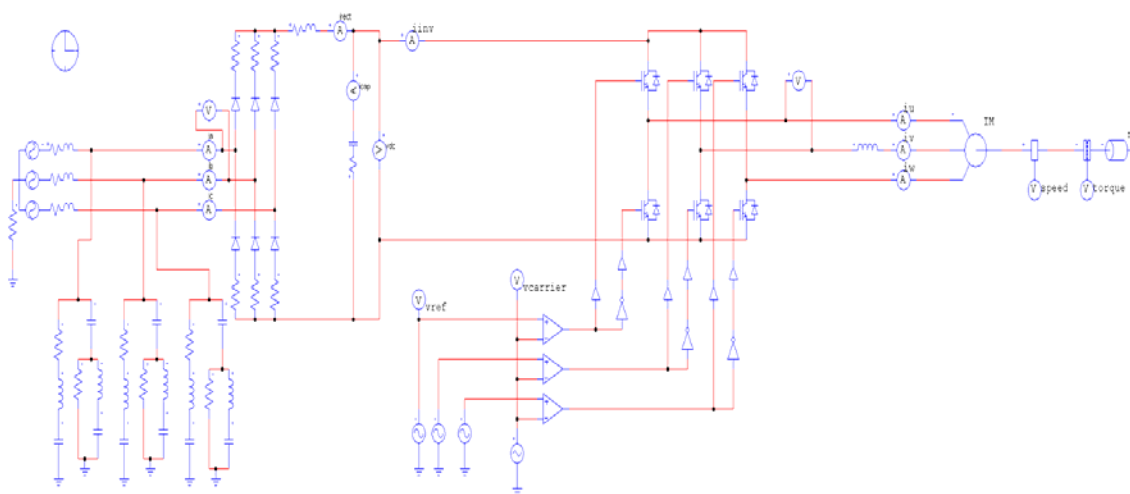

Figure-8. Power circuit diagram with combined passive filters.

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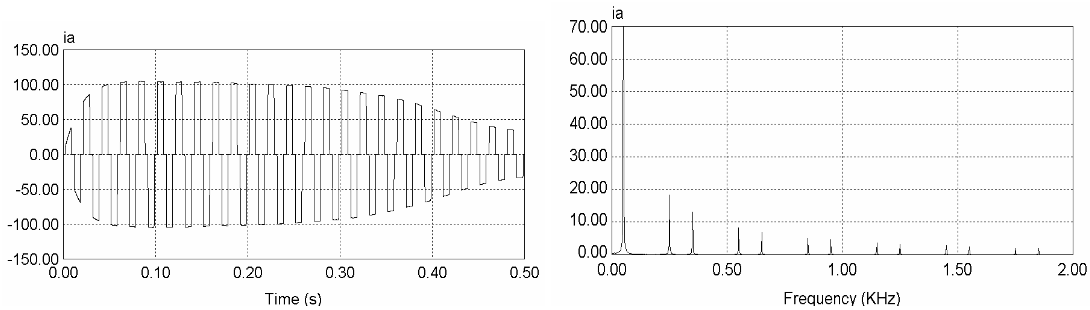
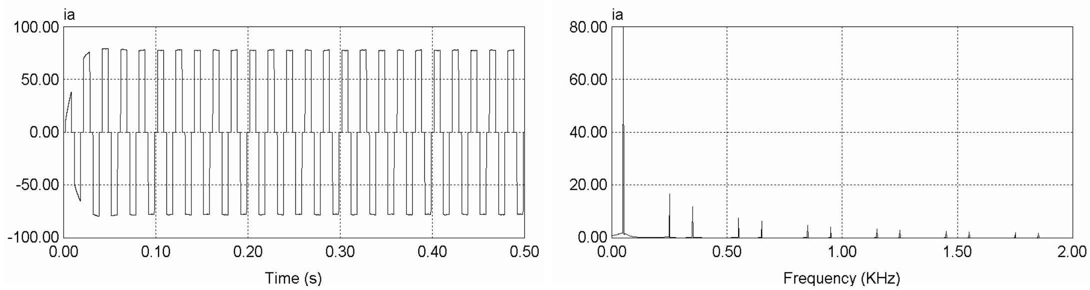


(a) (b)

Figure-9. Rectifier input current and its spectrum for f_{out} = 30Hz with passive filter.



(a) (b)

Figure-10. Rectifier input current and its spectrum for f_{out} = 40Hz with passive filter.

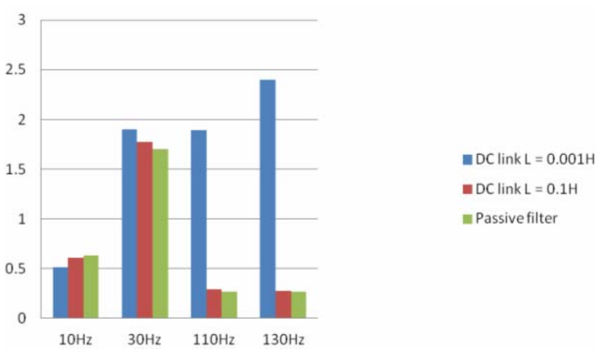


Figure-11. Comparison of results.

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