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Current Harmonics Mitigation of the Grid Connected Industrial Power Converter by using Optimized Passive Filters

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***Abstract*—The recent development in the power electronic devices leading to increasing use of power electronics converter in industrial and domestic applications. These power converters provide many advantages and flexibility in these applications, but at same time causes harmonic distortion in the power system. In various industrial applications, the DC choke are preferred harmonic mitigation solution due to less cost and smaller size. However, in many industrial plant small AC choke are used to improve the performance of power converter against grid disturbances like transients. Therefore, due to presence of AC choke, it is possible to optimize the size of DC choke in power converter, which can further reduce the cost and size of converter but still fulfill the harmonic requirements. In this paper, a mathematical model is developed to describe the relation between AC choke and DC choke inductances. The proposed model is analyzed by number of simulation studies and then verified by experimental results.**

***Index Terms*— Power Electronics Converter, Harmonic Mitigation, Distribution Grid, Power Quality, AC choke and DC choke.**

I. INTRODUCTION

Increasing use of non-linear industrial and commercial loads such as power converters and variable speed motor drives in various industrial pump, air-conditioning and compressor drives, is keeping high harmonic distortion in distribution network. This harmonic distortion causes unnecessary heat in the equipment connect to harmonic source, overloading of neutrals, overheating of transformers, nuisance tripping of circuit breakers and over-stressing of power factor correction capacitors and skin effect. Therefore, a strict harmonic requirement on supply side has been employed to limit the distortion at distribution network. The various harmonic standards like IEC 61000-3-12 and IEEE-519 describe the limit on individual non-linear loads. To comply with these standards while utilizing power converters, variable speed drives (VSDs) and other non-linear loads, the need of harmonic mitigation techniques became very important.

Therefore, a number of harmonic mitigation techniques have been developed for such applications using either: a) passive solutions (e.g., AC choke, DC choke and reduced DC-link capacitor) that are suitable in low power applications [1]-[4], b) multi-pulse transformer-based rectifiers as the front-ends (e.g., 12-pulse, 18-pulse or 24-pulse) that are suitable for high power applications [5], and c) active power filtering techniques [6]. These harmonic mitigation techniques are either increase the system overall volume or

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complicate the entire control system (or require auxiliary circuits), and thus leading to increased cost of the power converter system.

In various industrial power converters, the DC choke is an attractive harmonic mitigation solution due to its cost effective and mature technology. In industrial plants, the AC chokes are normally used to improve the power quality performance of system against grid disturbances like transient, phase jitter and unbalance. The DC choke in power converter are normally designed without considering the AC choke inductance and this could results overdesign of DC choke. This will result to increase the cost and volume of whole converter system. Therefore, in this paper a mathematical model has been developed to optimize the DC choke size based on existing AC choke inductor and still fulfil the harmonic standards requirements.

II. Passive Harmonic Mitigation Techniques

In many low power industrial applications, AC choke or DC choke is still much attractive solutions compare to other solutions discussed above. Therefore, this paper focused on the harmonic mitigation techniques based on passive components (AC choke and DC choke).

A. AC Choke

The AC choke electrically separate the DC bus voltage from the AC source as shown in Fig. 1(a), therefore the AC source is not clamped to the DC bus voltage during diode conduction in the rectifier. This feature helps to reduce the flat topping of AC voltage waveform caused by many VSDs when operate with a weak grid. At the same time line inductor helps to damp transient surges in the line due to lightning.

However, AC chokes inductor causes overlap in conduction between incoming diode and outgoing diode in a three-phase diode rectifier. This overlap phenomenon reduces the average DC link voltage (V_{dc}) and amount of reduction depend on the duration of the overlap (μ) as describe in following equations [1]:

$$\mu = \frac{2\times\sqrt{2}\times\omega L_{AC}\times I_{DC}}{\sqrt{3}\times V_{L-L}} \quad (1)$$

$$V_{dc} = \frac{3\times\sqrt{2}V_{L-L}\times cos(\mu)}{\pi} \quad (2)$$

Where, V_{L-L} is the line-to-line supply voltage, just before the three-phase rectifier.

From equation (2) it is clear that the overlap angle contributes to the reduction in the average DC voltage and which in turn depends on the value of AC choke inductance. Therefore, a care should be considered while selecting the AC choke inductor in order to avoid the low voltage situation at the input terminal of drive.

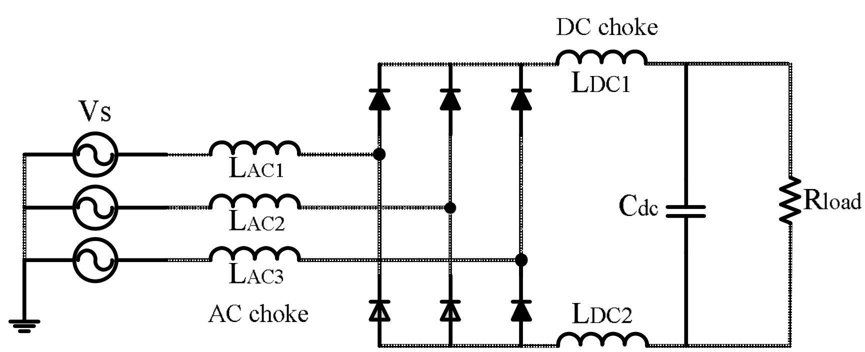


Figure 1: A diode rectifier with AC and DC choke

B. DC Choke

DC choke electrically present after the diode rectifier as shown in Fig. 1(a) and therefore will not contribute anyway to the overlap in diode commutation as AC choke inductor does discussed above. Therefore, there is no voltage drop in average DC voltage due to DC choke compare to that in the AC choke.

The DC choke increases the diode conduction duration in rectifier system. There is a critical DC choke inductance value, which result to complete 60-degree conduction of a diode pair in three-phase diode rectifier. So any value of DC choke higher than this critical value will not give any significant benefits. However, a large DC choke inductor will help to reduce the DC bus ripple but at same time will result in extra voltage drop due to the higher winding resistance. Therefore, a care should be considered while selecting a critical DC choke inductor to achieve complete 60-degree conduction.
The critical value of the DC choke inductance can be described by equation (3) [1]:

$$L_{DC} = \frac{(\pi-3)}{\pi} \times V_m \times \frac{T/_6}{I_{DC}} \quad (3)$$

From equation (3) it is clear that the critical inductance of the DC choke depends on the peak line-to-line voltage (V_{m}), load condition and frequency of input AC supply.

III. Relationship Between AC and DC Choke Inductance

In order to optimize the DC choke inductance by considering the presence of AC choke in the system, it is important to first find the relation between AC and DC choke inductance.
In a three-phase diode rectifier, during a commutation period any two phases are in operation at a time as shown in Fig. 1(b).

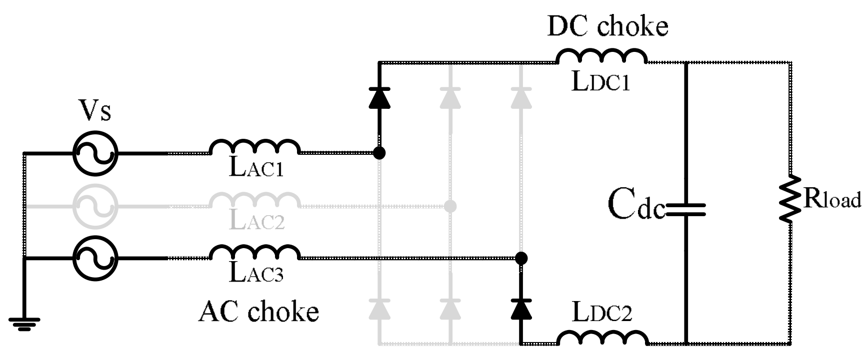


Fig. 2: Total inductance during a commutation period

The total impedance during a commutation period is: L_{AC1}+L_{DC1}++L_{DC2}+L_{AC3}. The total inductance in AC and DC side is calculated by using the grid/supply current (I_s). For three-phase motor drive system, the supply current depends on main line-to-line voltage (V_{L-L}), motor shaft power (P_s), motor efficiency (η_m) and drive efficiency (η_c) as given in equation (4):

$$I_s = \frac{P_s}{\sqrt{3} \times V_{L-L} \times \eta_m \times \eta_c} \quad (4)$$

The total AC choke inductance (L_{ACtot}) during a commutation period will be:

$$L_{ACtot} = L_{AC1} + L_{AC3} = 2 \times L_{AC1} \quad (5)$$

$$X_{ACtot} = 2 \times \pi \times f_s \times L_{ACtot} \quad (6)$$

Similarly the total DC chokes inductance (L_{DCtot}) during a commutation period will be:

$$L_{DCtot} = L_{DC1} + L_{DC2} = 2 \times L_{DC1} \quad (7)$$

$$X_{DCtot} = 2 \times \pi \times f_s \times L_{DCtot} \quad (8)$$

The value of AC and DC choke inductor calculated based base impedance (Z_{base}) of power converter. In order to fulfil the current harmonic requirement as per IEC 61000-3-12, the AC choke with 3% (per phase) of base impedance (Z_{base}) or the DC choke with 2% (per phase) of base impedance is sufficient. The AC and DC choke inductance in terms of the converter's base impedance is defined as below:

$$L_{ACtot} = 2 \times \left[\frac{(3\%) \times Z_{base}}{2 \times \pi \times f_s}\right] \quad (9)$$

$$L_{DCtot} = 2 \times \left[\frac{(2\%) \times Z_{base}}{2 \times \pi \times f_s}\right] \quad (10)$$

Where, $Z_{base} = \frac{V_{L-L}}{\sqrt{3} \times I_s}$

From equation (9) and (10):

$$\frac{L_{DCtot}}{L_{ACtot}} = \frac{2\%}{3\%} = 0.67 \quad (11)$$

$$L_{DCtot} = 0.67 \times L_{ACtot} \quad (12)$$

For 12kW motor drive, a 1.5mH/phase (or 3.0mH on two phase) AC choke or 1.0mH/phase (or 2.0mH on two phase) DC choke can fulfill the current harmonic distortion requirement as per IEC 61000-3-12. For example if 1/3rd of AC choke inductance is transferred to DC-link side, then L_{DCtot} will be:

$$L_{DCtot} = 0.67 \times \frac{L_{ACtot}}{3} = 0.67mH$$

In order to verify the above mathematical model in terms of harmonic performance, a number of simulations have been implemented by transferring the inductance from AC choke to DC choke based on equation (9). The simulation results in Table-1 show that current harmonic performance remains almost same while transferring the inductance between AC choke to DC choke and vice versa.
Therefore, the proposed mathematical model can be used to optimize the DC choke in motor drive by considering the size of AC choke inductance in the system used to improve the against grid disturbances.

TABLE I: HARMONIC PERFORMANCE AT DIFFERENT VALUE OF AC AND DC CHOKE INDUCTANCE

Case	AC choke (mH)	DC choke (mH)	Current Harmonics					THDI (%)
			I1 (A)	I5 (A)	I7 (A)	I11 (A)	I13 (A)	
1	3.0	0.000	16.5	6.1	2.1	1.1	0.5	39.6
2	2.8	0.134	16.5	6.1	2.1	1.2	0.5	40.0
3	2.6	0.268	16.5	6.1	2.1	1.2	0.6	40.0
4	2.4	0.402	16.5	6.0	2.2	1.2	0.6	40.1
5	2.2	0.536	16.5	6.0	2.2	1.2	0.6	40.0
6	2.0	0.670	16.5	6.0	2.2	1.2	0.6	40.0
7	1.8	0.804	16.5	6.0	2.2	1.2	0.6	40.1
8	1.6	0.938	16.5	6.0	2.3	1.2	0.6	40.2
9	1.4	1.072	16.5	6.0	2.4	1.3	0.7	40.3
10	1.2	1.206	16.5	5.9	2.4	1.3	0.7	40.1
11	1.0	1.340	16.5	5.9	2.4	1.3	0.7	40.1
12	0.8	1.474	16.5	5.8	2.5	1.3	0.7	40.1
13	0.6	1.608	16.5	5.8	2.6	1.3	0.8	40.3
14	0.4	1.742	16.5	5.7	2.7	1.3	0.8	40.0
15	0.2	1.876	16.5	5.6	2.8	1.4	0.9	40.0
16	0.0	2.010	16.5	5.5	3.0	1.4	1.0	40.5

IV. EXPERIMENTAL VERIFICATION

In order to verify the simulation results based on proposed mathematical model to optimize the DC choke inductance based on AC choke, a lab prototype has been developed as shown in Fig. 3. In order to limit the number of lab measurement due to unavailability of different choke's inductance, the performance of simulation model has been verified with lab measurement results. It has been considered that if the performance of simulation model matches with lab prototype with single set of AC and DC choke, then the conclusion can be generalized for other case too. In this study a 12kW motors drive with 1.5mH/phase AC choke and 600uH (in total) DC chokes has been simulated and tested at 9.3kW operating power. The line current waveform in time domain with simulation and lab measurements are shown in Fig. 4. The current harmonics performance of simulation model matches very well with lab measurements as shown in Fig. 5. Therefore, the analysis performed by simulation model can be generalized and expect similar conclusion with lab measurements.

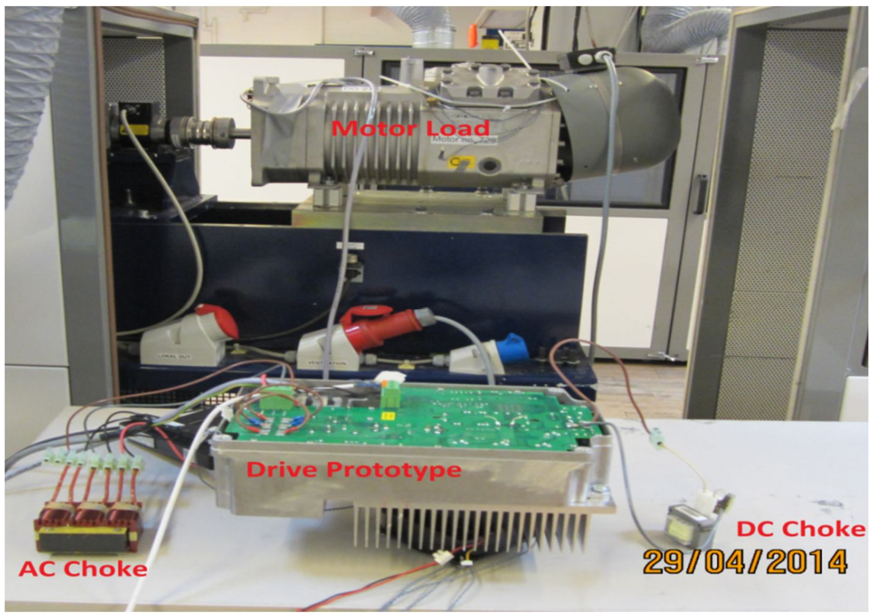
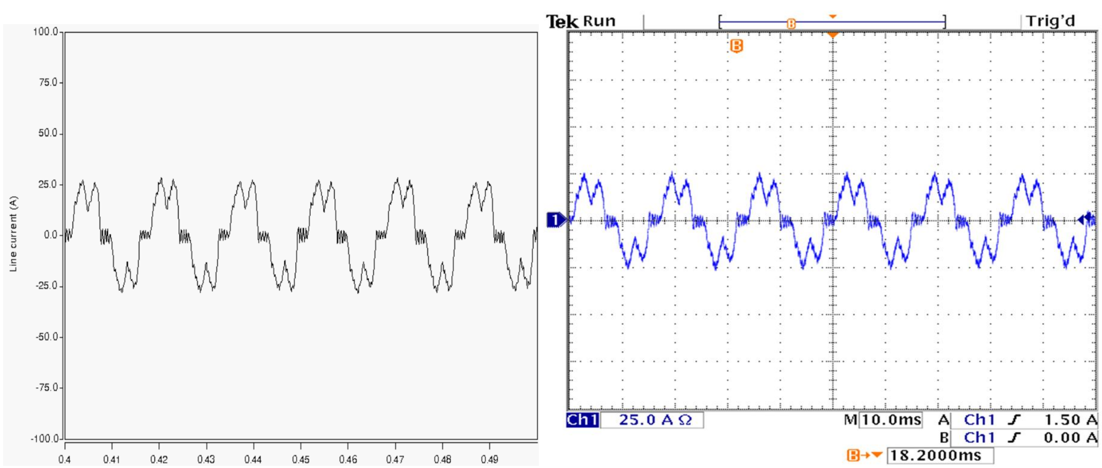


Fig. 3: Laboratory prototype with AC and DC choke



(a) (b)

Fig. 4: Line current waveform in time domain at 9.3kW operating power: (a) from simulation model, and (b) from lab prototype

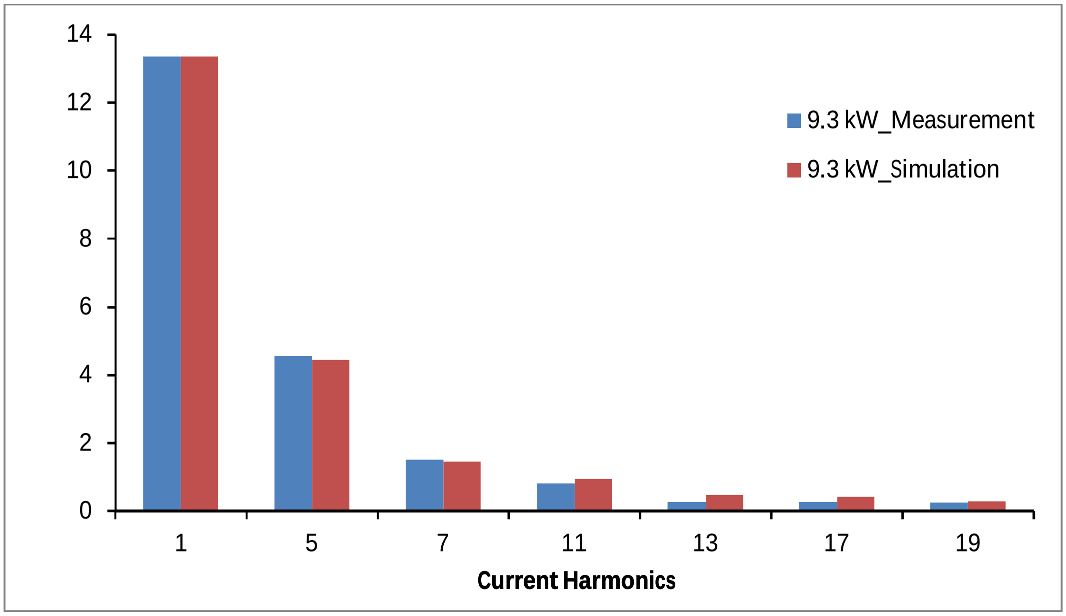


Fig. 5: Comparison of simulated current harmonics with laboratory measurement at 9.3 kW operating power

V. CONCLUSIONS

In various industrial power converters, the DC choke is an attractive harmonic mitigation solution due to its cost effective and mature technology. Also in various industrial plants, the AC chokes are used to improve the power quality performance of system against grid disturbances. Normally the DC choke design in the power converter have been designed without considering the AC choke inductance, therefore this could results overdesign of DC choke. This will result to increase the cost and volume of whole converter system. Therefore, in this paper a mathematical model has been developed to optimize the DC choke size based on existing AC choke inductor in the system. The developed model has been analyzed with simulation results and then verified with lab measurements. The analysis showed that proposed mathematical model can be practically use to optimize the DC choke size to have compact design of power converter at reduced cost without scarifying harmonic performances.

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