DATA CENTER COOLING HARMONICS – HOW TO GET THE 'GOOD' WITHOUT THE 'BAD'

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Abstract – With continual focus on improving PUE (Power Usage Effectiveness) in Data Center operations, cooling system efficiencies have been steadily increasing. Much of these efficiency gains can be attributed to more effective ventilation and 'free cooling' made possible by the use of electronically commutated (EC) fans. By utilizing rectifier and inverter technology, brushless permanent magnet motors and integrated intelligent electronics, EC fans have been able to achieve tremendous energy savings of 30% on average versus conventional AC fan operation. EC fans also allow for increased speeds and control flexibility with a wide voltage input range, allowing for universal use throughout most parts of the world.

However, one significant factor that needs to be considered in EC fan applications is the distorted AC current waveform that they draw. Their integrated rectifier/inverter package makes EC fans an example of a nonlinear load. Without proper harmonic mitigation, nonlinear loads will distort the AC power distribution upstream and can cause significant issues within a facility, such as overheating electrical distribution equipment and the failure of sensitive equipment connected to the same electrical bus.

In order to take advantage of the significant energy saving potential of EC fans, users of this technology must take into consideration the effects of harmonics. To reduce these negative effects, a passive harmonic filter specifically designed for the low DC bus capacitance of these devices can be easily applied such that the considerable 'good' in energy efficiency can be achieved without the 'bad' of poor power quality.

Index Terms — Electronically commutated (EC), permanent magnet, brushless DC, pulse width modulated (PWM), rectifier, inverter, adjustable speed drive (ASD), harmonics, nonlinear load, power usage effectiveness, PUE, air handling unit, AHU, heating ventilation and air conditioning, HVAC.

I. INTRODUCTION

Electronically commutated (EC) fans are frequently considered in many new and retrofit HVAC fan applications due to their energy savings potential, longer lifespan, ease of control and smaller footprint [1][2]. High system efficiency is important in applications such as air handling units (AHUs) and various other cooling systems, as these fan systems are a significant load in most buildings. This is particularly true in Data Centers where energy conservation efforts have led to the introduction of Power Usage Effectiveness or PUE.

PUE is calculated by dividing the total power entering a Data Center by the power used to run the required infrastructure. As the value decreases towards 1, a Data Center is considered to be more energy efficient. Since cooling systems account for much of the energy needed to support computer equipment operation, lower PUEs can be achieved by making them more efficient.

In this regard, EC fans are an attractive alternative to the use of traditional AC induction motors equipped with adjustable speed drives (ASDs) [3]. Although ASDs offer significant energy savings by optimizing the speed of an induction motor, the combination still pales in comparison to the EC fan's potential. EC fans can offer typical average energy savings of 30% but savings can reach as high as 70% [1][2]. And the integrated packaging of controls, motor and fan blades substantially reduces their footprint (Fig. 1).

However, much like ASDs, the power electronics of an EC fan consumes current in a non-sinusoidal manner. With the rapid growth in implementation of EC fans in AHU/HVAC applications, these distorted currents are resulting in high levels of both current and voltage harmonics. Left untreated, this harmonic distortion can lead to equipment failure, additional cable and transformer losses and failure to meet the recommended harmonic limits of IEEE Std 519 [4], IEC61000-3-2 [5], IEC61000-3-12 [6] and other international power quality standards.

II. PERMANENT MAGNET MOTORS AND EC FAN TECHNOLOGY

A. EC Fan Description

EC fans designed for operation on 3-phase AC supply, include an integrated circuit board with built-in rectifier, EMC protection, DC link capacitor(s), and the inverter module with IGBTs to control the commutation to a brushless DC (BLDC) motor. This type of synchronous BLDC motor includes permanent magnets on its rotor. Rare earth permanent magnets have allowed manufacturers to design EC fans with a smaller footprint than fans utilizing traditional AC induction squirrel cage motor type construction. The permanent magnet motors induce the required rotor flux without requiring current to be induced in separate rotor windings. This eliminates I^2R losses in the rotor, which is a major reason for the improved efficiency of EC fans compared to ASD controlled AC induction motors.

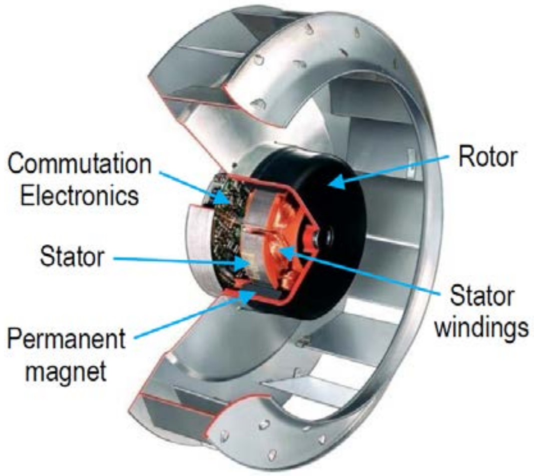


Fig. 1 Typical EC Fan Configuration [3]

B. Rectifier/Inverter Pulse Width Modulated (PWM) Topology

The built-in rectifier/inverter package of an EC fan operates in a similar manner as that of a standard ASD (Fig. 2). The 3-phase rectifier converts incoming AC voltage to DC. The inverter then creates a simulated AC variable voltage and frequency by systematically switching the DC voltage to the output phases through six IGBT power switches. The inverter output line-to-line voltage is a series of pulses with constant amplitude at varying widths as shown in Fig. 3.

The simplest configuration is the six-pulse diode bridge rectifier with a large capacitor across the DC bus terminals. In this circuit, the capacitor is charged by three short current pulses every half-cycle of the supply frequency (six per complete cycle). Fig. 4 shows the current on one phase with a pulse between that phase and each of the other two phases. The third pulse that occurs each half cycle is between the other two phases so does not appear on the phase shown.

For six-pulse diode bridge rectifiers:

$$h = n \cdot 6 \pm 1 \qquad (1)$$

Where: h = harmonic number, and
n is any integer (1, 2, 3, etc.)

For a six-pulse rectifier, the predominant current harmonics are h = 5, 7, 11 and 13 as shown in Fig 5. The corresponding harmonic content can reach levels of up to 90% (5th), 80% (7th), 75% (11th), and 70% (13th). Triplen harmonics (3rd, 9th, 15th, etc.) typically are not present. The addition of an AC line reactor or DC choke provides some reduction in the harmonic current levels and is often used with ASD applications. [8]

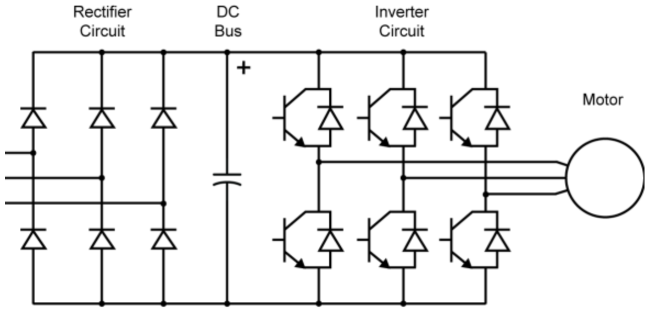


Fig. 2 Schematic Diagram for Typical PWM ASD with Diode Bridge Rectifier

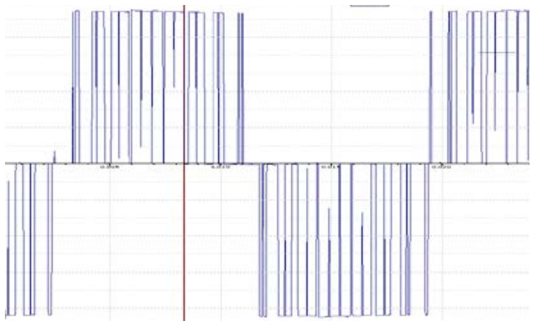


Fig. 3 Typical Output Voltage Waveform of PWM ASD

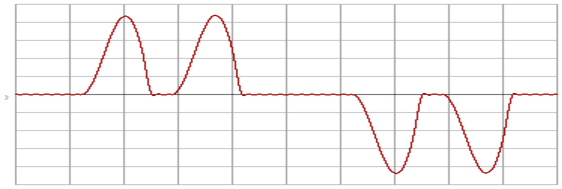


Fig. 4 Typical six-pulse rectifier input current waveform

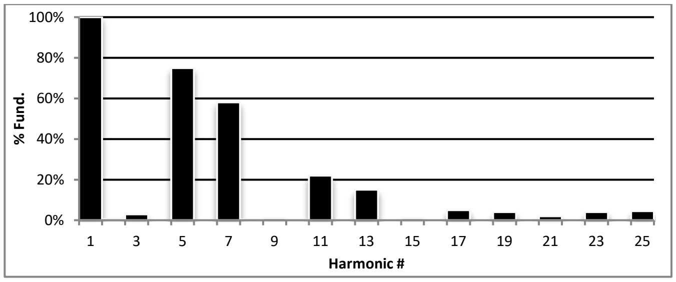


Fig. 5 Typical six-pulse rectifier input current spectrum

C. Lower DC Bus Capacitance in EC Fan Topology

To reduce size and cost, many EC Fan designs incorporate much lower DC bus capacitance than is typically found in standard ASDs. This results in some reduction in current harmonic distortion because the pulsed currents are broadened making the waveshape slightly more sinusoidal. The problem is that high levels of current harmonics remain and reducing them is now much more difficult because simply adding inductance, such as a line reactor, can cause the EC fan to become unstable due to electrical resonance with the power system as described in this paper. Conventional input passive harmonic filters will also cause instability and therefore, are not effective. In fact, any high impedance source, including synchronous generators, can cause instability. This must be taken into consideration when applying harmonic mitigation on EC fans and when using these fans in environments with emergency backup generators, such as Data Centers or Medical Facilities, with or without harmonic mitigation.

III. THE EFFECT OF HIGH IMPEDANCE ON EC FANS WITH LOW DC BUS CAPACITANCE

A. Power System Resonance

Power systems and the loads they supply can have issues with resonance when harmonic distortion is high. Resonance occurs at a certain frequency, f_o, when the capacitive reactance and inductive reactance at that frequency are essentially equal (Fig. 6). If this occurs at a harmonic frequency that is prevalent in the power system, the harmonic can be amplified resulting in high levels of both current and voltage distortion. When the resonance is between the power system and a load, such as an EC fan, this can lead to instability, overheating, high DC bus voltage and even component failure.

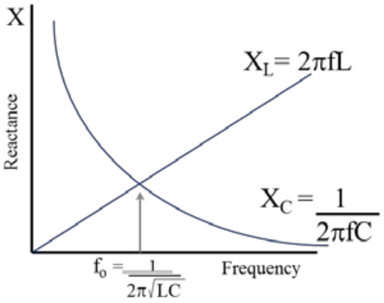


Fig. 6 Reactance curves and resonant frequency, f_o

$$f_o = \frac{1}{2\pi\sqrt{LC}} \qquad (2)$$

Where: f_o = resonant frequency in hertz
L = system inductance in henry
C = system capacitance in farad

B. DC Bus Capacitance and Source Impedance

Figs. 7 and 8 show a very simplified 1-Line diagram and the equivalent circuit of a distribution system with a rectifier/inverter load. Power systems are naturally inductive unless over-compensated by power factor correction capacitors which should always be avoided. Inverter loads are typically capacitive due to their DC bus capacitance. Conventional ASDs usually have very high levels of DC bus capacitance in order to reduce the DC bus ripple and provide stable operation regardless of the power system from which they are being supplied.

When inverter DC bus capacitance is high, it has a substantial influence on the resonant circuits with the power system. The high capacitance shifts the resonant point substantially below the characteristic harmonics on the power system, which would be 5th harmonic and above. From Fig. 6, when capacitance is high, the capacitive reactance curve shifts left, lowering the resonant frequency, f_o. Power system inductance will only shift this resonant point further left and further away from these harmonics. This means that when DC bus capacitance is high, the power system inductance has negligible effect on resonance even with a high impedance or ‘weak’ source, such as a synchronous generator.

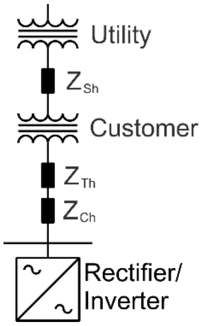


Fig. 7 Simple distribution system with nonlinear, rectifier/inverter load

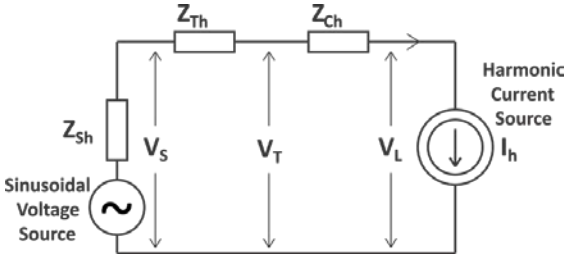


Fig. 8 Equivalent circuit with rectifier/inverter as a current source of harmonics

C. The Effect of Low DC Bus Capacitance

However, when DC bus capacitance is low, as is the case with many EC fans, the resonance point will be much higher and typically above the 5th and other prevalent harmonics. With low impedance or ‘stiff’ sources, the resonant frequency is usually substantially higher than the most common harmonics, so there is very little to amplify. However, on a high impedance source, the resonant frequency can shift into the range where harmonics are present. Their amplification can then lead to high levels of harmonics and the problems mentioned earlier.

IV. HARMONIC MITIGATION USING PASSIVE WIDE SPECTRUM HARMONIC FILTER

One of the most effective forms of passive harmonic mitigation for 3-phase rectifiers is the wide spectrum harmonic filter (WSHF). This approach is series connected and incorporates a combination of a blocking element and a tuned filtering element as shown in Fig. 9. [8]

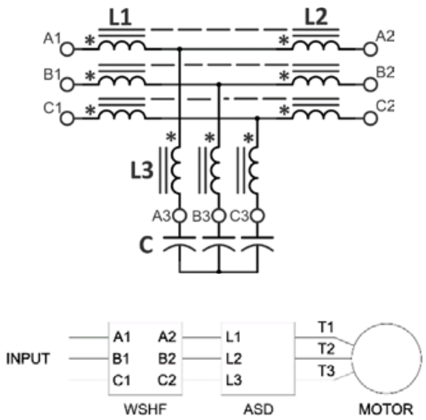


Fig. 9 Wide spectrum harmonic filter schematic and connection diagram

Important in the design of an effective filter is the prevention of harmonic importation from the line side of the filter. Without this ability, a filter could easily be overloaded when installed on a power system where other harmonic generating, nonlinear loads exist on the same bus. A wide spectrum filter consisting of a reactor with multiple windings on a common core and a relatively small capacitor bank can be a very effective solution since this design exploits the mutual coupling between the windings to improve performance. To prevent importation of upstream harmonics, the resonant frequency, as seen from the input terminals, is near the 4th harmonic, comfortably below the predominant harmonics of three-phase rectifiers.

This reactor design allows for the use of a significantly smaller capacitor bank (typically < 15% reactive power as a percent of full load rating). This reduces voltage boost and reactive power at no load to ensure compatibility with generators. The filter is connected in series between the main supply and the rectifier.

When applied to a conventional ASD, the ASD's relatively high level of DC bus capacitance allows for stable operation and very effective harmonic mitigation. Standard designs typically reduce current distortion to < 8% and premium models can reach levels of < 5%.

But when applying these filters to inverters with low DC bus capacitance, as is found in many EC fan designs, unstable operation can occur due to the inverter's capacitance and the filter or power system's inductance.

V. RESONANT CIRCUITS BETWEEN POWER SYSTEM, HARMONIC FILTER AND RECTIFIER/INVERTER

Fig. 10 shows a resonant circuit that exists between the harmonic filter and the rectifier/inverter.

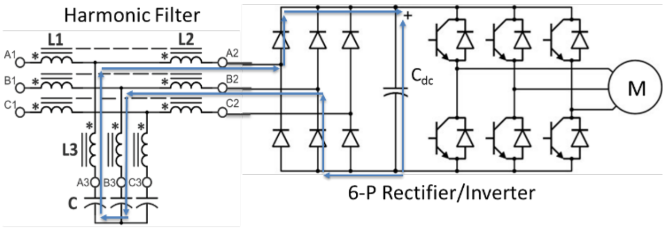


Fig. 10 Parallel resonant circuit between filter and rectifier/inverter

Using Equation 2, the resonant frequency is determined by the total capacitance of the inverter DC bus capacitors, C_{dc}, in series with two phases of the filter's capacitance, C, and the filter inductances of L2 and L3.

In a typical ASD circuit, the DC bus capacitance used will be in the mF range while the harmonic filter capacitance will be in the μF range. This means that the DC bus capacitance has significantly more influence on the resonant circuit than the filter capacitance. As mentioned earlier, the DC bus capacitance is usually high enough to result in a resonant frequency substantially below the 5th harmonic and therefore, there will not be any amplification of the characteristic harmonics generated by the 6-pulse rectifier. The result is a stable operation with the filter installed.

However, in most EC fan designs, DC bus capacitance is in the μF range, so the filter capacitors have an influence on the resonant circuit. The combined capacitance often increases the resonant frequency above the 5th harmonic and into the range where 6-pulse rectifier harmonics are present. This then means that these harmonics can be amplified leading to unstable operation, high DC bus voltages, poor harmonic mitigation and even component failures.

Fig. 11 shows a second resonant circuit that exists between the power system and the rectifier/inverter. The DC bus capacitance has a major influence on this series resonant circuit. As with the parallel resonant circuit, when DC bus capacitance is high, it usually results in a resonant circuit with the power system that is below the 5th harmonic. Power system inductance will simply move this resonant point further down and away from prevalent harmonics. However, with low DC bus capacitance, the resonance point can be above the 5th where the power system inductance will have influence. This is why many EC fan applications will have current oscillations in the resonant circuit when connected to 'weak' power sources, such as an AC reactor, small transformer or high impedance synchronous generator.

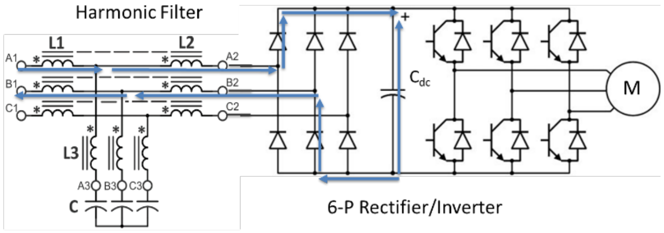
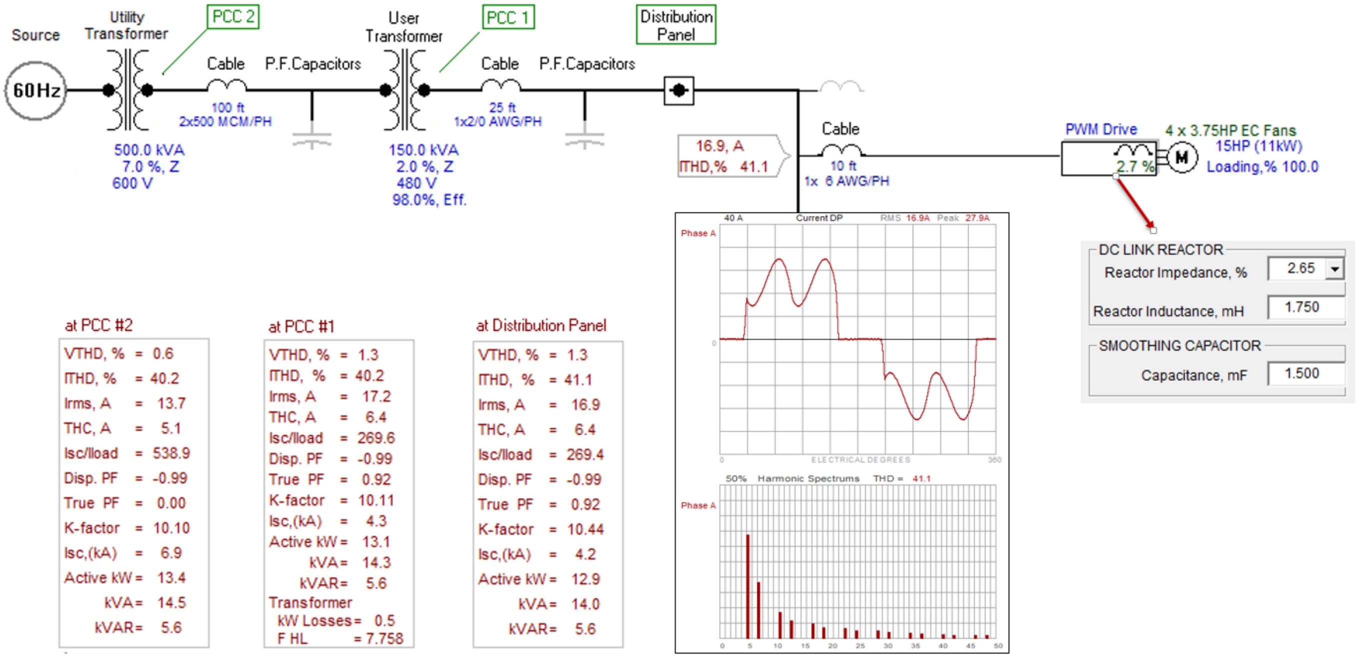


Fig. 11 Series resonant circuit between power system, filter and rectifier/inverter

VI. ANALYSIS THROUGH COMPUTER SIMULATION

For this paper, an array of four EC fans at 3.75 HP each were analyzed and tested both with and without harmonic mitigation. Computer simulation used Nodal Analysis by formulating a Nodal Matrix and solving the set of numerical ordinary differential equations using the backward Euler (second order and third order) method. The backward Euler method was chosen for its stability in resolving complex differential equations although it must solve iteratively requiring more demanding computation. The factory setup included a 150 kVA autotransformer to stepdown the voltage supplied by an upstream 500 kVA transformer.

Fig. 12 shows the computer simulation results without harmonic mitigation. Total harmonic current distortion was above 40% with predominant harmonics as expected being 5th, 7th, 11th and 13th. This was a relatively small load on the power system so total harmonic voltage distortion did not exceed 2%.



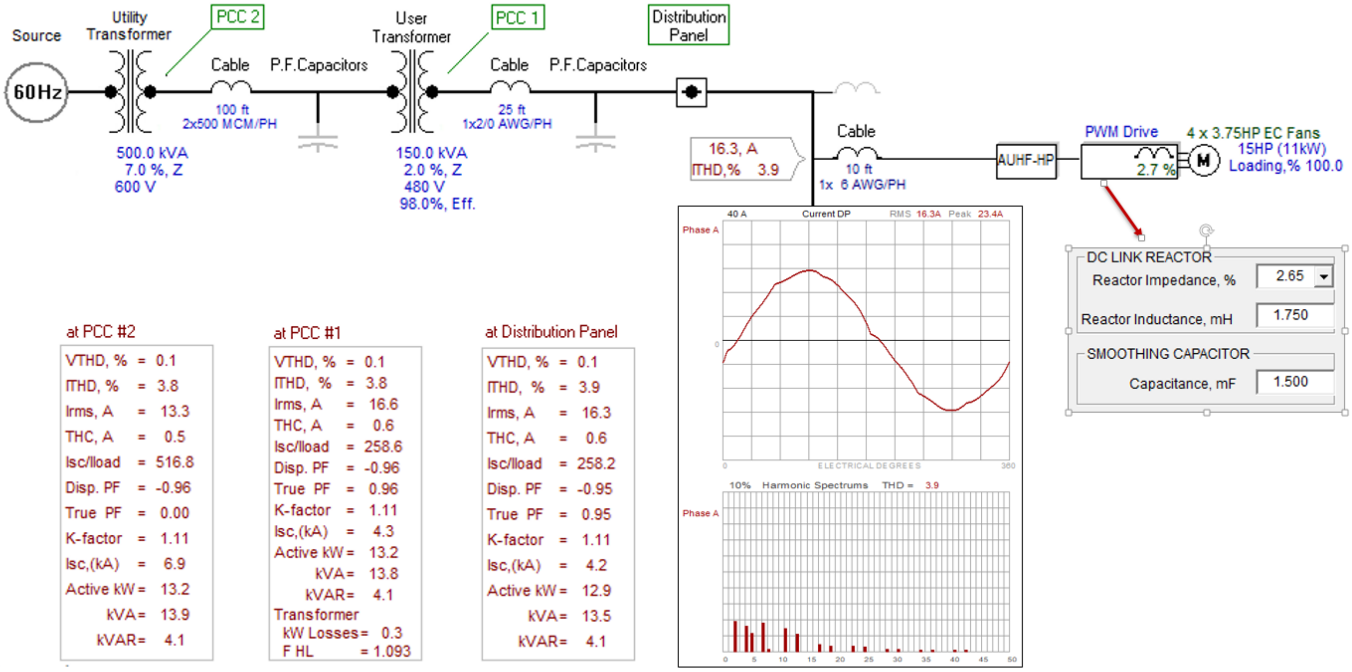
```
DC LINK REACTOR
  Reactor Impedance, %     2.65
  Reactor Inductance, mH   1.750
SMOOTHING CAPACITOR
  Capacitance, mF          1.500
```

```
at PCC #2
VTHD, %  =  0.6
ITHD, %  =  40.2
Irms, A   =  13.7
THC, A    =  5.1
Isc/Iload  =  538.9
Disp. PF   =  -0.99
True PF    =  0.00
K-factor   =  10.10
Isc,(kA)   =  6.9
Active kW =  13.4
       kVA=  14.5
      kVAR=  5.6
```

```
at PCC #1
VTHD, %  =  1.3
ITHD, %  =  40.2
Irms, A   =  17.2
THC, A    =  6.4
Isc/Iload  =  269.6
Disp. PF   =  -0.99
True PF    =  0.92
K-factor   =  10.11
Isc,(kA)   =  4.3
Active kW =  13.1
       kVA=  14.3
      kVAR=  5.6
Transformer
 kW Losses=  0.5
 F HL        = 7.758
```

```
at Distribution Panel
VTHD, %  =  1.3
ITHD, %  =  41.1
Irms, A   =  16.9
THC, A    =  6.4
Isc/Iload  =  269.4
Disp. PF   =  -0.99
True PF    =  0.92
K-factor   =  10.44
Isc,(kA)   =  4.2
Active kW =  12.9
       kVA=  14.0
      kVAR=  5.6
```

Fig. 12 Computer simulation of a 4 EC fan array without harmonic mitigation



```
DC LINK REACTOR
  Reactor Impedance, %     2.65
  Reactor Inductance, mH   1.750
SMOOTHING CAPACITOR
  Capacitance, mF          1.500
```

```
at PCC #2
VTHD, %  =  0.1
ITHD, %  =  3.8
Irms, A   =  13.3
THC, A    =  0.5
Isc/Iload  =  516.8
Disp. PF   =  -0.96
True PF    =  0.00
K-factor   =  1.11
Isc,(kA)   =  6.9
Active kW =  13.2
       kVA=  13.9
      kVAR=  4.1
```

```
at PCC #1
VTHD, %  =  0.1
ITHD, %  =  3.8
Irms, A   =  16.6
THC, A    =  0.6
Isc/Iload  =  258.6
Disp. PF   =  -0.96
True PF    =  0.96
K-factor   =  1.11
Isc,(kA)   =  4.3
Active kW =  13.2
       kVA=  13.8
      kVAR=  4.1
Transformer
 kW Losses=  0.3
 F HL        = 1.093
```

```
at Distribution Panel
VTHD, %  =  0.1
ITHD, %  =  3.9
Irms, A   =  16.3
THC, A    =  0.6
Isc/Iload  =  258.2
Disp. PF   =  -0.95
True PF    =  0.95
K-factor   =  1.11
Isc,(kA)   =  4.2
Active kW =  12.9
       kVA=  13.5
      kVAR=  4.1
```

Fig. 13 Computer simulation of a 4 EC fan array with harmonic mitigation

Fig. 13 shows the computer simulation results with a wide spectrum harmonic filter designed specifically for a rectifier/inverter circuit with low DC bus capacitance. Various iterations were run with different configurations of inductance and capacitance values in order to eliminate resonance points that would amplify harmonics and create unstable conditions. Total harmonic current distortion was reduced to < 4% which satisfies even the most stringent requirements of IEEE Std 519. With these extremely low levels of current harmonics, their contribution to voltage harmonic distortion was virtually eliminated.

VII. FACTORY TESTING

Based on the computer simulations, a 15 HP, 480 V, 60 Hz harmonic filter was built and tested on an array of 4 x 3.75 HP EC fans (Fig. 14). The fans were run over their full operating range and measurements taken at 100 rpm speed intervals (Table 1). Current harmonic distortion at full load was well below the targeted level of 5% and the critical DC-Link voltage level of the fans remained well within acceptable operating levels. Also, there were no signs of instability at any speed point.

Fig. 15 plots the harmonic distortion levels over the full operating range. Total Current Harmonic Distortion (THDi) was below 4% at full load and only slightly exceeded 8% at any load level. When plotted as Current Total Demand Distortion (TDDi), the value remained well under 5% over the full operating range. TDDi is defined in IEEE Std 519 and calculated to be THDi x Measured Current / Maximum Current. The full load values closely matched those predicted by the computer simulations.

Fig. 14 Array of 4 x 3.75 HP EC fans during factory testing

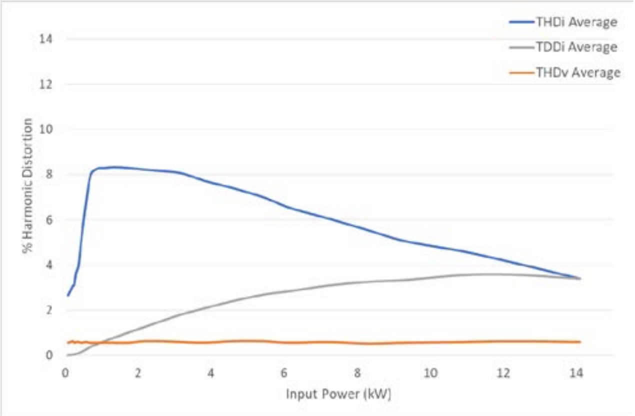


Fig. 15 Harmonic distortion levels of current and voltage on 4 x 3.75 HP EC fans with WSHF

TABLE 1
FACTORY TEST RESULTS ON FOUR 3.75 HP EC FANS WITH A WSHF DESIGNED FOR LOW DC BUS CAPACITANCE

Speed (RPM)	Vrms at Filter Input (V)			Irms at Filter Input (V)			THDv at Filter Input (%)				THDi at Filter Input (%)				TDDi	P at Filter Input (kW)	Vrms at Filter Output (V)				DC-Link Voltage of Fan
	A	B	C	A	B	C	A	B	C	Avg	A	B	C	Avg	Avg		A	B	C	Avg	
0	480	479	483	4.7	4.7	4.7	0.6	0.6	0.5	0.6	2.5	3.6	1.9	2.7	0.0	0.08	513	514	516	514	730
100	480	480	482	4.7	4.7	4.7	0.7	0.7	0.5	0.6	2.6	3.8	2.9	3.1	0.0	0.21	512	515	517	515	723
200	480	480	482	4.7	4.7	4.7	0.6	0.6	0.5	0.6	2.6	3.8	2.9	3.1	0.1	0.24	515	516	518	516	723
300	480	481	483	4.7	4.7	4.7	0.6	0.6	0.6	0.6	3.1	4.1	3.8	3.7	0.1	0.3	515	516	518	516	720
400	481	481	483	4.7	4.7	4.7	0.6	0.6	0.6	0.6	3.6	4.4	3.9	4.0	0.1	0.36	515	516	518	516	720
500	481	481	484	4.7	4.7	4.7	0.6	0.6	0.5	0.6	4.4	5.9	5.5	5.3	0.2	0.45	515	516	518	516	720
600	481	481	483	4.7	4.7	4.7	0.7	0.6	0.5	0.6	5.5	7.8	6.3	6.5	0.3	0.55	515	516	517	516	716
700	481	481	484	4.7	4.7	4.7	0.6	0.6	0.5	0.6	7.1	9.2	7.6	8.0	0.4	0.69	515	516	517	516	709
800	482	482	484	4.7	4.7	4.7	0.6	0.6	0.5	0.6	7.8	9.1	7.9	8.3	0.5	0.87	515	516	517	516	702
900	482	481	484	4.7	4.8	4.8	0.5	0.6	0.6	0.6	8.9	8	8	8.3	0.6	1.08	515	515	517	516	698
1000	481	481	484	4.8	4.9	4.9	0.6	0.6	0.5	0.6	8.9	8.2	7.9	8.3	0.8	1.35	515	516	517	516	695
1100	481	481	483	4.9	5	5	0.6	0.6	0.5	0.6	8.9	8.2	7.8	8.3	1.0	1.74	515	516	517	516	695
1200	482	481	483	5.1	5.2	5.2	0.6	0.7	0.6	0.6	8.7	8.2	7.8	8.2	1.2	2.13	515	516	517	516	695
1300	482	481	483	5.4	5.5	5.5	0.7	0.6	0.6	0.6	8.7	8	7.8	8.2	1.5	2.61	515	515	516	515	695
1400	482	481	484	5.8	5.9	695	0.7	0.6	0.5	0.6	8.5	8	7.7	8.1	1.8	3.18	515	515	516	515	695
1500	481	482	484	6.3	6.3	6.3	0.6	0.6	0.5	0.6	8.1	7.7	7.4	7.7	2.1	3.81	516	516	517	516	691
1600	481	481	483	6.8	6.9	6.9	0.7	0.6	0.6	0.6	7.7	7.5	7.1	7.4	2.4	4.53	516	516	517	516	691
1700	482	481	484	7.5	7.5	7.5	0.7	0.6	0.6	0.6	7.4	7	6.6	7.0	2.7	5.43	516	516	516	516	691
1800	482	481	484	8.2	8.3	8.2	0.6	0.6	0.5	0.6	6.9	6.5	6.2	6.5	2.8	6.15	515	515	515	515	688
1900	482	482	484	9.3	9.3	9.2	0.6	0.6	0.6	0.6	6.4	6.1	5.7	6.1	3.1	7.2	514	512	513	513	685
2000	482	481	484	10.2	10.2	10.1	0.6	0.5	0.5	0.5	5.8	5.5	5.4	5.6	3.3	8.25	510	508	509	509	678
2100	482	481	484	11.7	11.6	11.5	0.6	0.6	0.5	0.6	5.4	4.9	4.9	5.1	3.3	9.3	508	507	508	508	670
2200	481	481	484	13.2	13.1	13	0.7	0.6	0.5	0.6	4.8	4.4	4.6	4.6	3.6	10.92	502	499	500	500	660
2300	481	480	483	14.8	14.7	14.6	0.7	0.6	0.6	0.6	4.2	3.9	4.2	4.1	3.6	12.3	494	493	494	494	646
2400	482	481	484	17.1	16.9	16.7	0.7	0.5	0.6	0.6	3.5	3.1	3.6	3.4	3.4	14.1	484	482	482	483	632

VIII. CONCLUSIONS

To reduce energy consumption and improve PUE, Air Handling Systems incorporating electronically commutated fans are becoming much more commonly used in Data Centers. If left untreated, these benefits come at the cost of higher harmonic distortion levels. The challenge of reducing harmonics generated by EC fans is a difficult one however, due to their very low DC bus capacitance. This low capacitance shifts the resonant point of the circuit between the filter and the rectifier/inverter to a value above the prevalent harmonics being generated by the rectifier. The impedance of standard harmonic filters will tend to shift this resonant point down and into a region where the harmonics will be amplified creating instability, overheating, high DC bus voltage levels and even component failure.

Through computer modelling, modified inductance and capacitance values of the wide spectrum harmonic filter were determined that provided excellent harmonic mitigation without introducing unstable operation of the fans. Factory testing confirmed the accuracy of the computer simulations resulting in a solution that will allow the use of EC fans in HVAC applications while meeting the requirements of IEEE Std 519 and other recognized harmonic standards.

IX. REFERENCES

[1] EBM Papst, *"GreenTech EC Technology"*, 37854-7-8811, 2016-04.

[2] EBM Papst, *"Reducing Energy Consumption in the Built Environment through EC Fan Technology"*, http://www.greensenseplus.com/sites/default/files/ebm-papst_CPD.pdf.

[3] Somasundaram B, Ashok Kumar L, Banu Rekha B, Hemanand R, "Study on Energy Efficiency and Harmonics Mitigation in a HVAC AHU Blower/Fan Application Using Electronically Commutated BLDC Motors", Journal of Electrical Engineering, Oct. 2016.

[4] IEEE Std 519-2014, *IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems,* New York, NY: IEEE.

[5] IEC 61000-3-2, *Limits for harmonic current emissions for equipment with input current <16A/phase single and 3 phase*.

[6] IEC 61000-3-12, *Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current >16A and < 75A per phase*.

[7] M. Farbis, A. H. Hoevenaars, J. L. Greenwald, "*Oil Field Retrofit of ESPs to Meet Harmonic Compliance*", IEEE Transactions on Industry Applications, Vol. 52, No. 1, January/February 2016, pg 718-728.

[8] A. H. Hoevenaars, M. Fahrney, M. James, M. McGraw, "*Design Considerations When Applying Various LV ASD Topologies to Meet Harmonic Compliance*", IEEE Transactions on Industry Applications, Vol. 47, No. 4, July/August 2011, pg 1578-1585.

[9] G. Nosek, M. Halczynski, A. Romanska, J. Szczepanik, *"The Effects of Growing Popularity of EC Motors on Building's Automatic Systems",* Department of Electrical and Computer Science, Cracow University of Technology, Krakow, Poland.

[10] P. Deshpande, S.S. Mopari, P.S. Swami, *Power factor correction and power quality improvement in BLDC motor drive using SEPIC converter",* Faculty of Electrical Engineering, Government College of Engineering, Aurangabad.

[11] V. Ghorbanian, D. A. Lowther, *"Magnetic and Electrical Design Challenges of Inverter-Fed Permanent Magnet Synchronous Motors",* IEEE Transactions on Magnetics, Vol. 53, No. 6, June 2017.

[12] X. Wang, W. Zhou, R. Dou, *"Analysis of Harmonic Current in Permanent Magnet Synchronous Motor and Its Effect on Motor Torque",* Journal of Electromagnetic Analysis and Applications, pp 15 to 20, 2012.

X. VITAE

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