Mitigating EC Fan Harmonics to Achieve Energy Savings without Sacrificing Power Quality

Electronically Commutated (EC) fans are frequently considered in many new and retrofit HVAC fan applications due to their energy savings potential and small footprint. 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. By utilizing rectifier and inverter technology, brushless permanent magnet motors and integrated electronics, EC fans can achieve energy savings of 30% or more versus conventional AC induction motor fan operation.

One significant factor that needs to be considered in EC fan applications however, is the distorted AC current waveform they draw making them an example of a non-linear load. Without proper harmonic mitigation, non-linear 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.

The energy saving benefit of EC fan technology does come with a disadvantage – the circuit topology means that traditional harmonic mitigation strategies are often ineffective and instability can result. Mirus has developed a version of the Lineator AUHF technology however, that allows for the considerable energy savings to be realized without sacrificing good power quality.

Permanent Magnet Motors and EC Fan Technology

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 an inverter module with IGBTs to control the commutation to a brushless DC (BLDC) motor. Also referred to as a synchronous motor, the 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 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 Adjustable Speed Drive (ASD) controlled AC induction motors.

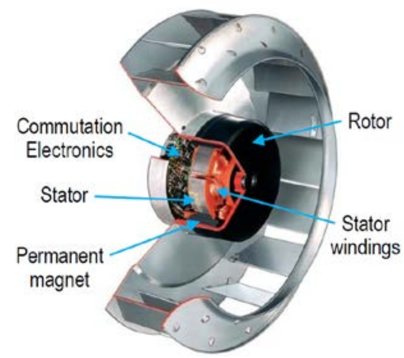

Fig. 1: Typical EC Fan Configuration (referenced from EBM Papst)

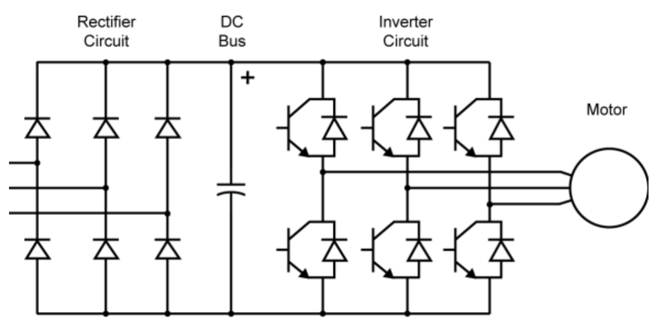

Fig. 2: Schematic Diagram for Typical PWM ASD with Diode Bridge Rectifier

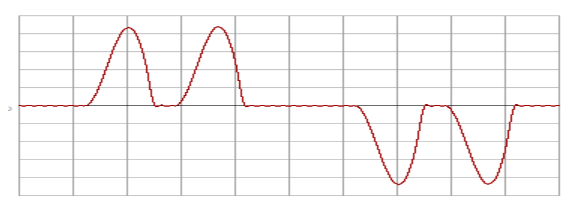

Fig. 3: Typical six-pulse rectifier input current waveform

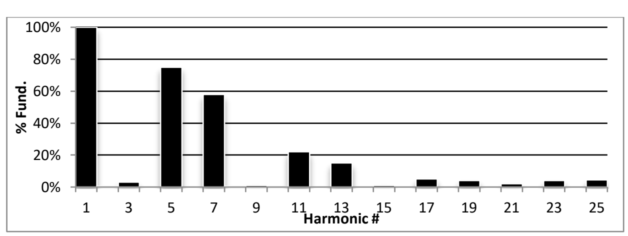

Fig. 4: Typical six-pulse rectifier input current spectrum

The built-in rectifier/inverter package of an EC fan operates in a similar manner as that of a standard 6-Pulse 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 rectifier draws current in pulses as shown in Fig. 3 which contain harmonic frequencies (Fig. 4).

To reduce size and cost, many EC Fan designs incorporate much lower DC bus capacitance than is typically found in a standard ASD. 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.

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.

Harmonic Mitigation using Lineator AUHF Passive Wide Spectrum Harmonic Filters

One of the most effective forms of passive harmonic mitigation for 3-phase rectifiers is the Lineator AUHF 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. 5.

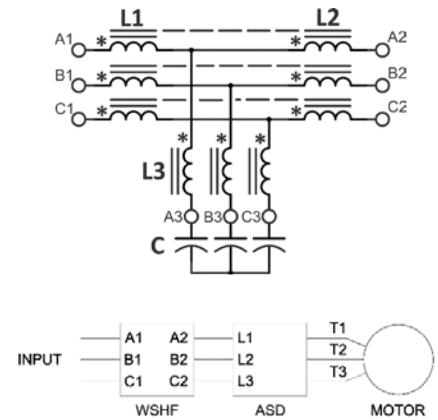

Fig. 5: Lineator AUHF schematic and connection diagram

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, non-linear loads exist on the same bus. The Lineator AUHF achieves this by tuning the filter, as seen from the input terminals, to near the 4^{th} harmonic, comfortably below the predominant harmonics of 3-phase rectifiers.

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 most EC fan designs, unstable operation can occur due to the inverter's capacitance and the filter or power system's inductance.

Resonant Circuits between Power System, Harmonic Filter and EC Fan

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

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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.

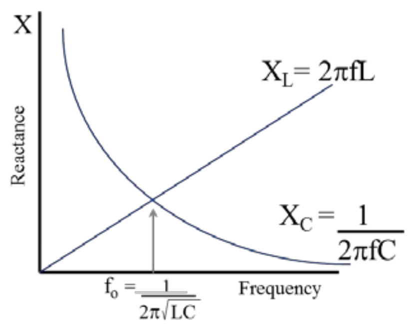

Fig. 6: Reactance curves and resonant frequency, f_o

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

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

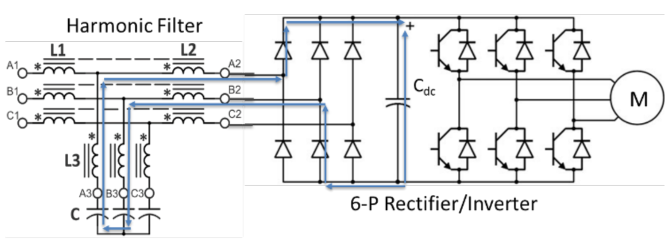

Fig. 7: Parallel resonant circuit between filter and rectifier/inverter

Fig. 7 shows a resonant circuit that exists between the harmonic filter and the rectifier/inverter. 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. The DC bus capacitance is usually high enough to result in a resonant frequency substantially below the 5^{th} 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 5^{th} harmonic and into the range where 6-pulse rectifier harmonics are present. This then results in amplified harmonics leading to unstable operation, high DC bus voltages, poor harmonic mitigation and even component failures.

Fig. 8 shows a second resonant circuit that exists between the power system and the rectifier/inverter. Again, 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 5^{th} harmonic. Power system inductance will simply move this resonant point further down and away from prevalent harmonics.

However, with low DC bus capacitance, the resonant point can be above the 5^{th} where the power system inductance will have influence. This is why many EC fan applications will have instability issues when connected to 'weak' power sources, such as an AC reactor, small transformer or high impedance synchronous generator.

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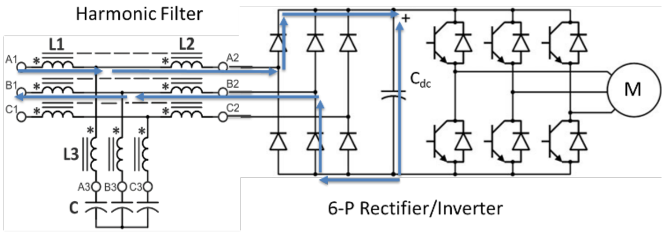

Fig. 8: Series resonant circuit between power system, filter and rectifier/inverter

For application on EC Fans, the harmonic filter must be designed to move the resonant point back below the 5th harmonic to eliminate instability.

Factory Testing of a Lineator AUHF-HP2 Harmonic Filter Designed for EC Fan Application

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. 9). 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. 10 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.

Fig. 9: Array of 4 x 3.75 HP EC fans during factory testing

TABLE 1

FACTORY TEST RESULTS ON FOUR 3.75 HP EC FANS WITH A LINEATOR AUHF-HP2 DESIGNED FOR LOW DC BUS CAPACITANCE

Speed (RPM)	Vrms at Filter Input (V)			Irms at Filter Input (A)			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

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MITIGATING EC FAN HARMONICS TO ACHIEVE ENERGY SAVINGS WITHOUT SACRIFICING POWER QUALITY

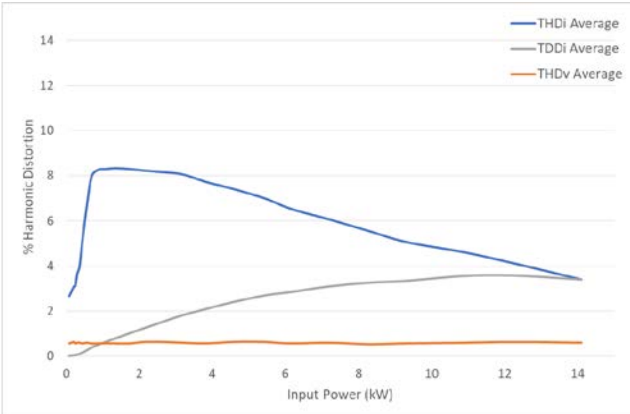

Fig. 10: Harmonic distortion levels of current and voltage on 4 x 3.75 HP EC fans with WSHF

Summary and Conclusion

To reduce energy consumption in today's modern buildings, Air Handling Systems incorporating electronically commutated fans are becoming much more commonly used. If left untreated when large quantities of these fans are employed, the benefits come at the cost of high 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.

A wide spectrum harmonic filter designed specifically for this low DC bus capacitance, the Lineator AUHF-HP2, can provide excellent harmonic mitigation without introducing unstable operation of the fans. Factory testing confirmed that this solution will allow the use of EC fans in HVAC applications while meeting the requirements of IEEE Std 519 and other recognized harmonic standards. Although, compatibility with all EC Fan manufacturer's equipment is still to be determined.

About the Author

Anthony (Tony) Hoevenaars (BESc'79) is President and CEO of Mirus International, Brampton, ON, Canada, a company specializing in the treatment of power system harmonics. With over 35 years of direct experience in resolving electrical power system problems, beginning in the 1980s as Chief Facilities Electrical Engineer at an IBM manufacturing facility in Toronto, Tony has earned an international reputation as a power quality and harmonics expert. As a Professional Engineer, Tony has published various papers on power quality. He is an active member of the IEEE having presented papers at several IAS conferences since 2003.

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