Special Issue Article

Institution of MECHANICAL ENGINEERS

Journal of AEROSPACE ENGINEERING

Proc IMechE Part G:
J Aerospace Engineering
227(4) 599–607

DOI: 10.1177/0954410012473695
uk.sagepub.com/jaero
SAGE

Integrated series active filter with reduced capacitance requirements for variable frequency aerospace systems

D Ganthony[1], **CM Bingham**[2] **and N Schofield**[3]

Abstract

This article considers the design and development of an integrated series active filter with a front-end consisting of a standard 6-pulse bridge rectifier to satisfy power supply harmonic standards for aerospace actuation and other dynamic and passive loads. Unlike previously reported fixed frequency solutions for enhancing power quality (typically based around 18- to 24-pulse TRUs for this application sector), the proposed converter reported here can be applied to non-ideal, non-stiff, frequency wild (380–800 Hz) supplies. Specifically, the proposed converter is shown to satisfy key harmonic limits over the full 380–800 Hz range of supply frequency variation, be robust to significant distortion in the input supply voltage waveform and have reduced capacitance requirements. Experimental results on a 2.5 kW converter are used to demonstrate the underlying harmonic attenuation provided by the prototype system, coupled with control robustness to significant input voltage distortion. The realisation of such power converter solutions that can accommodate variable frequency input supplies provides the opportunity to eliminate the complex hydraulic gearbox stages normally employed within aircraft generators to regulate electrical supply frequency when subject to engine speed variations.

Keywords
Active filters, power quality, aerospace variable frequency supplies

Date received: 15 May 2012; accepted: 6 December 2012

Introduction

The drive towards all/more-electric aircraft technologies has initiated significant research into the impact of on-board power quality requirements, with key emphasis on systems that must accommodate high power transient demands and noise/quality sensitive loads, such as those characteristic of aerospace flight control surface actuation systems, for instance. Moreover, voltage and current distortion increases network electrical stresses and reduces generation efficiency, requiring excessive peak-to-mean electrical ratings of components, and reduced overall mass density – a premium constraint for aerospace solutions.

To comply with normal industry standards, the commonly used specification (IEEE 519-1992) allows harmonic currents to be drawn in an attenuated 6-pulse shape.[1] That is, the 5th and 7th harmonics (at the respective fundamental) represent the largest magnitudes and the allowed magnitude decreases with increasing harmonic number. For the aerospace sector no single set of dominating specification exist, and specifications that do exist differ in how the maximum harmonic currents are defined. In Matheson and Karimi,[2] for instance, standard converters are expected to provide a 12-pulse waveshape for equipment with ratings below 5 kVA, and 18-pulse for equipment above 5 kVA. The harmonic current that can be drawn is defined with respect to the level of the fundamental. Hence, harmonic limits are defined as a relative percentage of the magnitude. In SAE Aerospace Standard,[3] the harmonics are defined with respect to the full load current. The difference between the studies in Matheson and Karimi[2] and SAE Aerospace Standard[3] is that the loads in SAE Aerospace Standard[3] can be variable whereas in Matheson and Karimi[2] the loads are expected to operate at constant power – there is therefore no requirement to use full load current in the definition. In MIL-STD-704E,[4] the load under which the

---

[1] EMD Group, University of Sheffield, Sheffield, UK
[2] School of Engineering, University of Lincoln, Lincoln, UK
[3] School of Electrical and Electronic Engineering, The University of Manchester, Manchester, UK

Corresponding author:
Chris M Bingham, School of Engineering, University of Lincoln, Brayford Pool, Lincoln, UK.
Email: cbingham@lincoln.ac.uk; cmbingam@yahoo.co.uk

benchmark specifications are applied is defined in terms of the voltage distortion that it will produce. The maximum harmonic currents for a load will therefore be dependent on the supply impedance and will vary with load position on the AC bus-bar, with the state of the power network and the number and size of connected loads. The degrees of freedom available with this standard are therefore not considered appropriate for the single connected loads that are developed here.

The situation is further complicated by the potential future deployment of alternative supply networks on-board aircraft. Conventionally, the supply (phase) voltage on a standard aircraft is $115V_{rms}$ with a nominal 400 Hz supply frequency. However, for future all/more-electric aircraft, other networks that are being considered include alternative fixed frequency, variable frequency, DC, or a combination of AC and DC.[5] Currently favoured alternative choices are biased towards a $115V_{rms}$ variable frequency three-phase supply and a 270 V DC supply. The frequency range is expected to be bounded to between 380 Hz (minimum) and 800 Hz (maximum).[6] Termed 'frequency wild' operation, such solutions have been considered in preference to fixed frequency counterparts due to reductions in cost, weight, and increased reliability.[7]

Existing solutions for the generation and distribution of power through the aircraft are extensively based on constant frequency systems, through the use of integrated drive generators (IDG). Such systems are based on mechanical/hydraulic gearing from the engines to provide a (relatively) constant shaft speed input to the electrical generator, thereby providing a constant frequency electrical output. Whilst being the most common technique, the system relies on the additional (system) mass of the mechanical/hydraulic gearbox and ancillary architecture, which is substantial, and requires regular maintenance to ensure reliable operation. This is, therefore, driving the need for alternative solutions that are more cost effective and reliable.[8] It should be noted that whilst electrical components generally have lower individual power densities when compared to their hydraulic counterparts, at a system level the benefits accrue due to lower losses (higher system conversion efficiency) and complexity for the electrical case. Of the solutions that have attracted the greatest attention, variable-speed generator input/constant frequency electrical output methods, through intermediate power electronic conversion, have found the most widespread deployment in both military and commercial aircraft – with cycloconverters often providing a preferred candidate technology,[9] although the emergence of matrix converter counterparts for fixed frequency output is attracting attention as the technology matures.[10] Such methods provide greater conversion reliability and efficiency than IDG-based systems, although power factor and harmonic issues have also to be accommodated, particularly for high power loads. A typical expectation for a non IDG system is to yield a 50% increase in reliability,[11] a major commercial factor that has driven the industry, for example Airbus, Thales and TRW Aeronautical Systems, to provide VF electrical power systems for the A380 and the Boeing 787 Dreamliner – see references[12,13] for more detail. The Boeing 787 uses VF starter/generator technology for the GE and Rolls-Royce engines, using a hybrid constant frequency/variable frequency solution to provide 1MW of power capability using a 360–720 Hz supply at $230V_{rms}$, and also a traditional $115V_{rms}$/400 Hz supply.[13] Nevertheless, the greatest projected system mass benefits, reliability, and cost savings at point-of-source can be obtained by full variable frequency electrical distribution. This requires the point of use equipment and conversion electronics to accommodate the variable frequency input whilst also allowing for harmonic regulation considerations. The preferred solution is then to distribute additional integrated power conversion and harmonic suppression solutions by judicious choice of converter and control architectures to accommodate the variable frequency input. It is converters falling into the latter of these solutions that is considered in this article. For a detailed background discussion of adopted solutions to-date, the reader is directed to Moir and Seabridge.[14]

All on-board power is generated from the aircraft engines whose rotational speed varies at take-off and landing, and at different times during the flight profile depending on instantaneous flight demands. The aircraft electrical generator is mechanically coupled to the engines, therefore, to provide a fixed frequency electrical supply network, hydraulic gearing is used to convert the variable speed output of the engine into a fixed mechanical speed (and hence frequency) input to the generator. A frequency wild system is simply coupled to the engine speed and whilst this arrangement can offer significant improvements to the generator system, a consequence is that all electrical loads must be capable of operating correctly over the complete variable frequency range, and during the specified frequency transients. The choice of rectification technology is, therefore, dependent on the ability to cope with a variable frequency supply, and the power quality specifications that are set for the system.

In the absence of benchmark specifications for such systems, this study will adopt the current harmonic specifications taken from Matheson and Karimi,[2] by virtue of them providing the most stringent low-frequency harmonic limits. Figure 1 illustrates these current harmonic limits with respect to the fundamental for loads <5 kVA (red bars) and for loads >5 kVA (dark bars), showing clearly that the 11th and 13th harmonic constraints are relaxed for loads <5 kVA.

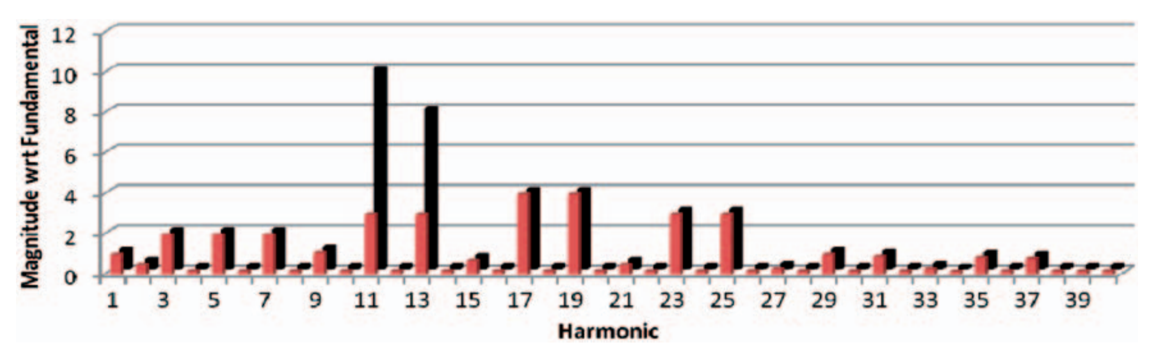

Figure 1. Benchmark current harmonic specification limits.[2]

Rectification stages with harmonic reduction

Passive rectifier bridges are the most common AC to DC front-end for power electronic converters. However, they induce non-linear current waveforms that substantially differ from the presented supply voltage, and are significantly load dependant. Owing to their prevalence, and the resulting harmonic distortion they induce, alternatives to replace the standard diode bridge rectifier have been widely investigated, namely, matrix converters (and derivatives),[15] active rectifiers (buck, boost and multilevel),[16] active filters (shunt, series, hybrid and Unified Power Quality Conditioners)[17] and passive solutions.[18] The most commonly employed solutions have classically been based on filter, transformer and rectifier stages, transformer rectifier units (TRUs). Although low-pass and tuned filters do not provide rectification they are included as the most common technique for improving power quality, and form part of other commonly encountered rectifier-based solutions, including high-pulse (>6) rectifier units.[1] The current harmonics drawn by such circuits are given by

$$n = pk \pm 1 \tag{1}$$

where n is the harmonic order with respect to the fundamental, p is the pulse number of the rectifier and k is a positive integer.

Therefore, by judicious choice of p, some control of harmonic content can be obtained. More generally, multi-pulse rectifiers consist of parallel 6-pulse rectifier units, each supplied by a phase-shifted supply – the pulse number of the system is therefore a multiple of six. The phase shift is designed through appropriate transformer connections (TRUs) such that particular harmonic currents are cancelled and not reflected at the supply. Common TRUs have $p = 12$, 18, 24, etc. With increasing p, the size and complexity of the TRU also increases, and this must be balanced against the benefits of the reduced harmonic content at the supply. In particular, the magnetic components have a relatively high VA rating, although some reduction can be made by using an autotransformer (at the expense of voltage isolation).[19–21] Moreover, if a significant difference exists in the impedance seen from the perspective of each rectifier, incomplete cancellation occurs and residual harmonic components will be present at the supply. Non-ideal input voltage waveforms and supplies that are not perfectly balanced also compound such effects as a result of core saturation, for instance.

A relatively recent study has shown that due to reduced voltage stresses on the active components, overall reliability of matrix converter solutions can compete with an 18-pulse transformer rectifier with inverter,[22] and a controlled rectifier and inverter.[23] However, the aerospace industry, at present, does not allow for regeneration on the supply bus and so precludes their use. Nevertheless, some unidirectional derivatives, for instance the dual bridge matrix converter and sparse derivatives, could be considered, but they are susceptible to supply side voltage distortions and limited voltage transfer ratios (see Wheeler et al.[22] for instance).

Other active filter circuits (shunt, series) can present robust solutions for cancelling harmonics, but combining with other passive topologies (to give a hybrid[24]) provides additional advantages, at the expense of increased component count. Firstly, the addition of passive components can increase the application range of the circuit – an example being the addition of a parallel passive path on the load side of a series active filter, allowing the traditional series active filter to attenuate harmonic currents drawn by a current-source load. Additionally, the passive filter components can also be used to provide direct harmonic attenuation (particularly low frequency) thereby reducing the required rating of the active filter, and consequently cost. Importantly, the combination of a TRU with a series active filter to increase the effective pulse number of the rectifier, from 6- to 12-pulse, for instance, can also be employed to remove particular harmonics from the supply current e.g. 5th and 12th,[25] allowing the rating of the active part of the filter to be reduced. The advantage of using an integrated circuit over standard topologies is that the component count can then be reduced. More generally, additional savings are made by only requiring a single dc-link, rather than the two required of more traditional circuits, and by the subsequent removal of extra charging circuitry for the active filter's DC link. This is of key strategic important to this application sector where the use of traditional electrolytic capacitors is prohibited based on reliability grounds, and counterparts with much greater m^3/F specifications (paper, foil or aluminium) have to be employed. Because of these benefits, to-date, integrated solutions have been considered for use in many applications sectors. However, a common factor has been that they are designed for operation with a single frequency input (i.e. 50, 60 or 400 Hz).

Nevertheless, the reduction in DC-link capacitance requirements, along with the robust attributes of the series active filter to voltage distortion, make the integrated series active filter a key candidate for variable frequency aerospace systems with non-stiff supplies. The remainder of this article therefore considers the application of an integrated series active filter for a variable frequency (380–800 Hz) aerospace supply that also has the potential for significant robustness to voltage distortion arising from other local harmonic loads. Although 18-pulse TRU-based filter solutions have been previously reported for single frequency (400 Hz) aerospace systems, with some demonstrable success,[20] here, only a standard 6-bridge diode rectifier is employed with the harmonic filtering provided by the 'active system' to accommodate the variable frequency range. The proposed circuit is illustrated schematically in Figure 2.

Harmonic description

A three-phase variable frequency, variable magnitude power supply is used to test the prototype circuit. Results are taken in response to the application of discrete supply frequencies between 400 Hz and 800 Hz, in 100 Hz increments. The power supply also allows the shape of the output voltage to be programmed, enabling results to be obtained with a non-sinusoidal supply voltage.

The 6-pulse diode rectifier is a commercial off-the-shelf three-phase bridge module, rated at 800 V and 60 A. The DC link capacitance, CDC, has a value of 14.6 mF. Each of the active filter's three H-bridge inverters are formed using two Semikron SKM50GB063D modules. Each module contains a top and a bottom Insulated Gate Bipolar Transistor (IGBT) with freewheeling diodes. The modules are rated at 600 V and 50 A,[26] and are switched at 30 kHz. The inverter modules are driven by six Skyper 32 modules.[27] These are two channel drivers produced by Semikron, and are recommended to drive the SKM50GB063D modules. With minimal additional circuitry the driver modules receive 15 V switching signals from the control circuitry, and produce isolated IGBT gate drive voltages. The Skyper 32 board allows different gate resistors to be used to turn the IGBT on and off. Here, the turn on resistance is 90Ω, and the turn off resistance is 2.9Ω. The modules introduce 3 μs of dead time.

The integrated DC link is formed from two copper buss-bars, separated by a thin sheet of insulator. The thickness of the insulator is minimised to reduce the DC link parasitic inductance. The various components are bolted directly to the buss-bars, again to minimise the effects of parasitic inductances, as shown in Figure 3(a).

Matching transformers are used to add the active filter voltages, V_{af}, to the supply (Figure 2). The transformer ferrite cores are commercial off-the-shelf items of mid-grade material. Each core is made up of U and I sections having a minimum cross sectional area of $8.4 \times 10^{-4} m^2$. The transformer is wound with 180 primary turns and 225 secondary turns. To minimise the leakage inductance, the transformers are bifilar wound, resulting in an average value of 9.7 μH. An example transformer is illustrated in Figure 3(b). The series line inductors, Lac, are made of air-cored Brooks coils to maximise the achievable inductance for a given wire length. An example Brooks coil is shown in Figure 3(c); each coil has 90 turns and a mean radius of 36 mm, giving 0.5 mH.

Control algorithms for the prototype circuit are realised using a TMS320F2812 eZdsp development board (Figure 3(d)). System phase currents and voltages are measured and input to the digital signal

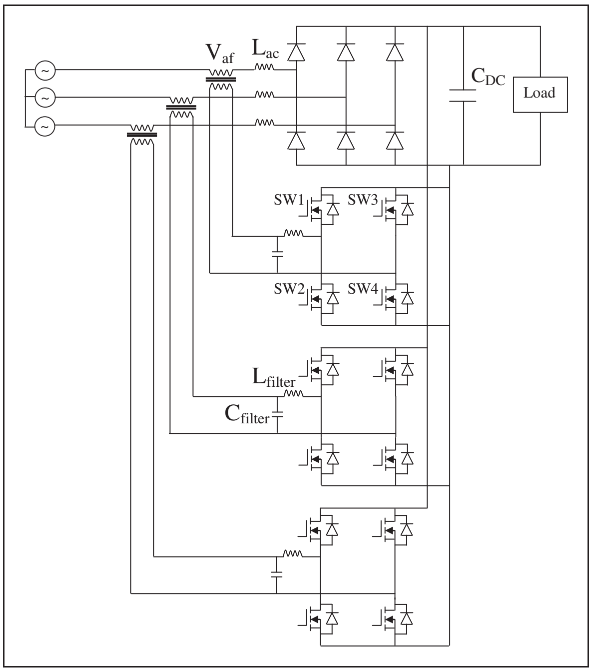

Figure 2. Proposed integrated series active filter with 6-pulse bridge rectifier and L_{ac} to facilitate improved stability characteristics.

processor (DSP) after isolation and protection. The DSP board measures two of the supply currents and one-phase voltage signal, each at 120 kHz. After the DSP has processed the input data, 12-pulse width modulation (PWM) switching signals are obtained, one for each switch of the active filter; the PWM switching frequency is set at 30 kHz. A simplified block diagram of the filter control scheme is shown in Figure 4. In practice a soft-start circuit is also included to allow the DC link to be pre-charged before the active filter is activated.

The phase locked loop (Figure 4), uses the measured supply phase voltage to generate 3 unit amplitude sine waves having a balanced relative phase shift of 120°. These are stored and subtracted from the PWM reference signals, Figure 4 (V_{dc} control), through the action of a gain control block these signals can be used to control the fundamental voltage at the rectifier terminals. The phase locked loop is also used to obtain a unit amplitude sine wave and a cosine wave, which are used in the d-q transform and its inverse. The d-q axis supply currents are low-pass filtered to obtain the fundamental component, the fundamental component is converted back into the ABC domain and stored. The stored fundamental current components are subtracted from the next set of measured phase currents, resulting in the current harmonic components. These signals, through the action of a gain control block, are used to generate the PWM reference signals. The d-q transform is the critical part of the control since it is this that allows the integrated series active filter to function over a range of supply frequencies with minimal changes to the control circuit. The voltage that the active filter adds to the supply, V_{af}, will have a small fundamental component with harmonic voltages forming the majority. This means that the integrated series active filter will attenuate the harmonic current components, but have minimal effect on the fundamental, effectively making the integrated series active filter appear as an impedance to the harmonic currents but not to the fundamental current, thereby giving a net reduction in the harmonic magnitudes. The passive low-pass filters are required to attenuate switching distortion in the active filter voltages. The filter corner frequency is selected as a trade-off between switching distortion attenuation and adversely affecting the compensation voltages. This becomes increasingly difficult as the supply frequency, or the load power, increases. In this case, the corner frequency is fixed at 8 kHz.

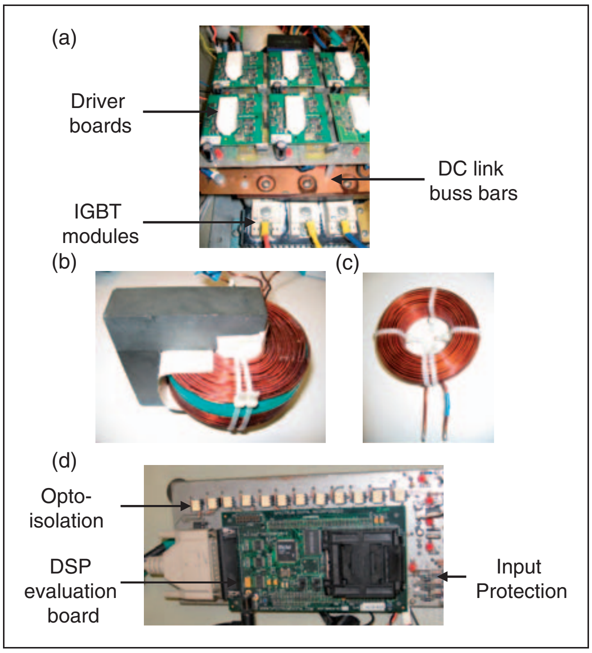

Figure 3. Integrated series active filter hardware: (a) IGBT modules, DC link Buss-bar and Skyper 32 driver modules; (b) matching transformer; (c) line inductors; (d) control system. IGBT: insulated gate bipolar transistor.

Experimental results

It can be seen in Figure 5(a), that the supply phase current and voltage have a near unity displacement factor, and the measured power factor from the power supply is 0.99. From the frequency spectrum,

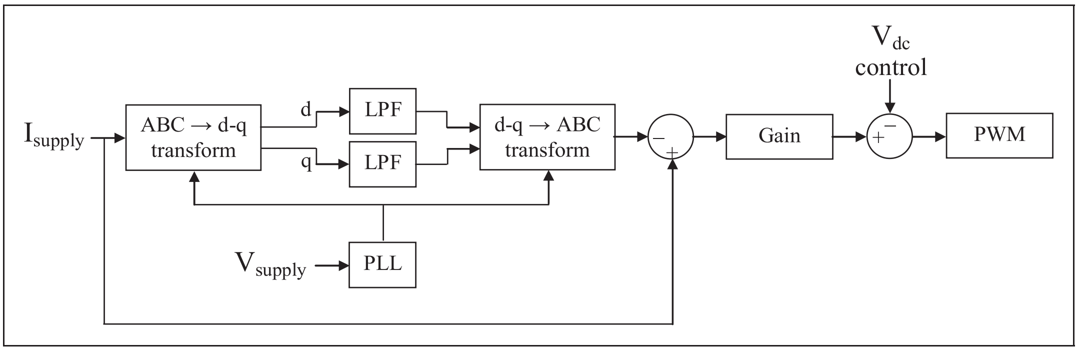

Figure 4. Block diagram control circuit description. PWM: pulse width modulation.

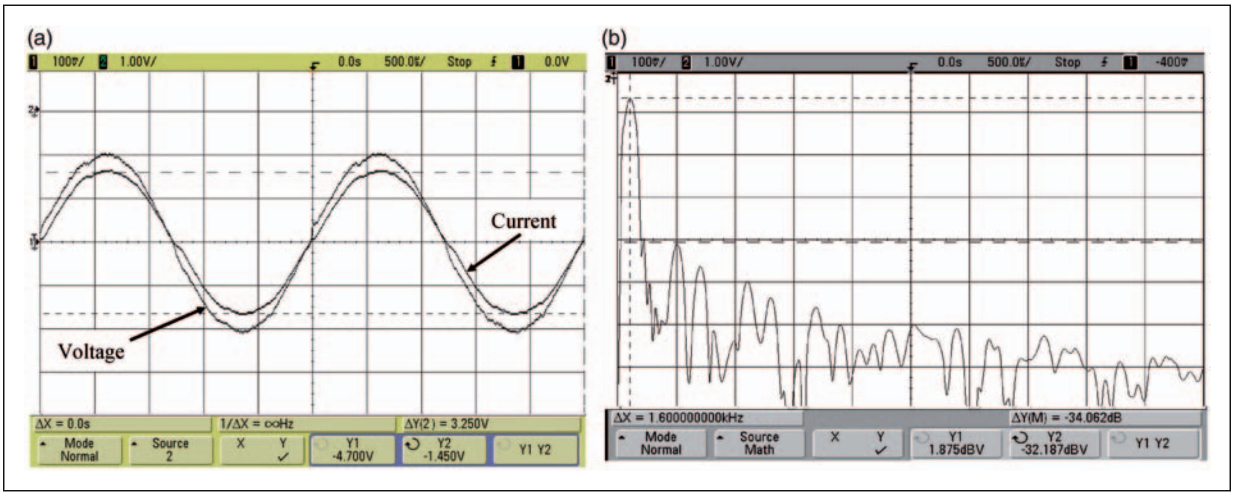

Figure 5. Results with 400 Hz sinusoidal voltage supply: (a) time domain supply current and phase voltage; (b) supply current frequency spectrum.

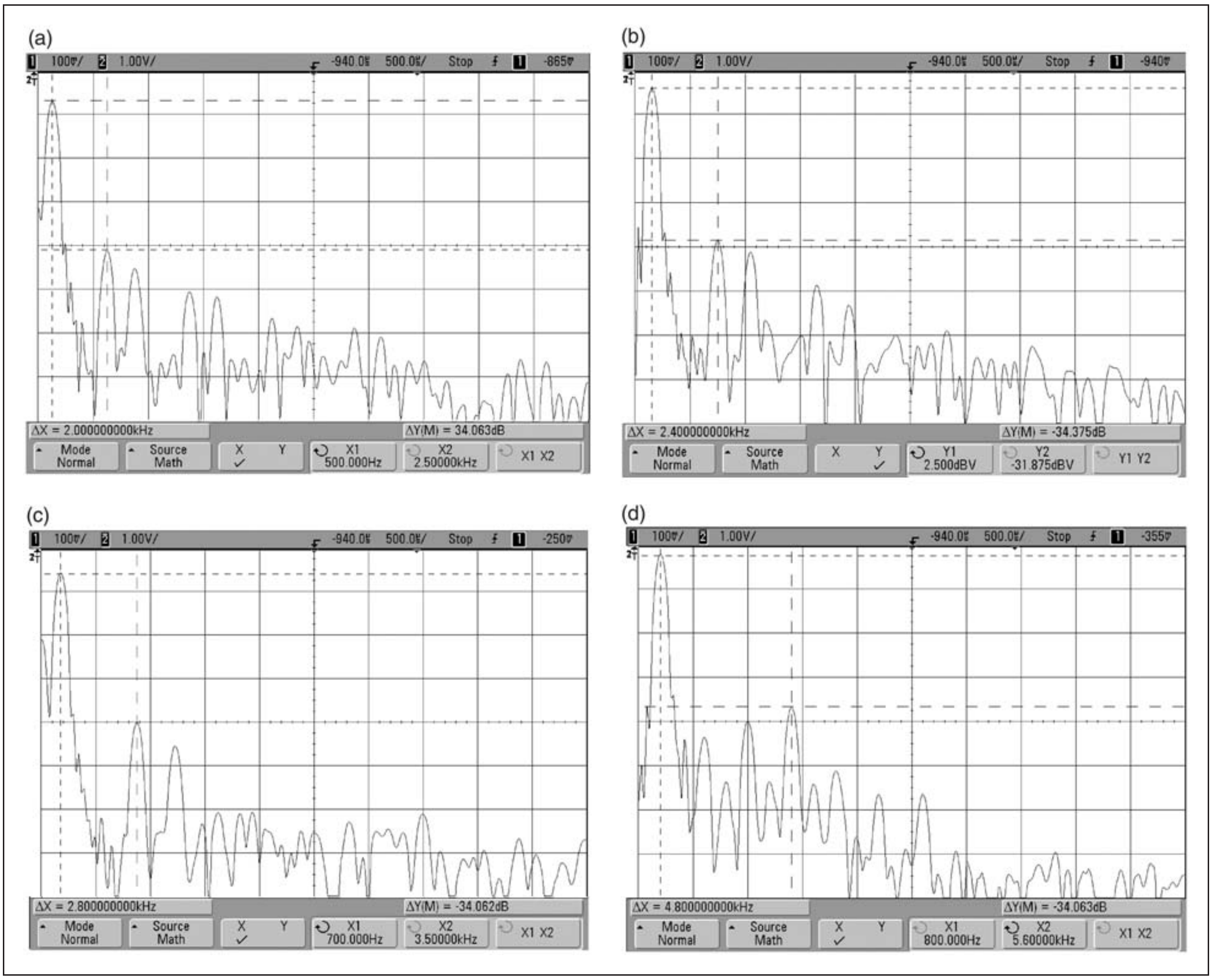

Figure 6. Current spectra as a result of excitation at a sinusoidal voltage input supply frequency of: (a) 500 Hz; (b) 600 Hz; (c) 700 Hz; (d) 800 Hz.

the largest harmonic is the 5th. It can be seen that the harmonic is 34.062 dB below the level of the fundamental, or 1.98% of the fundamental, and so below the required specification limit.

As the supply frequency is increased towards 800 Hz (Figure 6), the fundamental voltage components added by the active filter must be allowed to increase in magnitude in order to compensate for

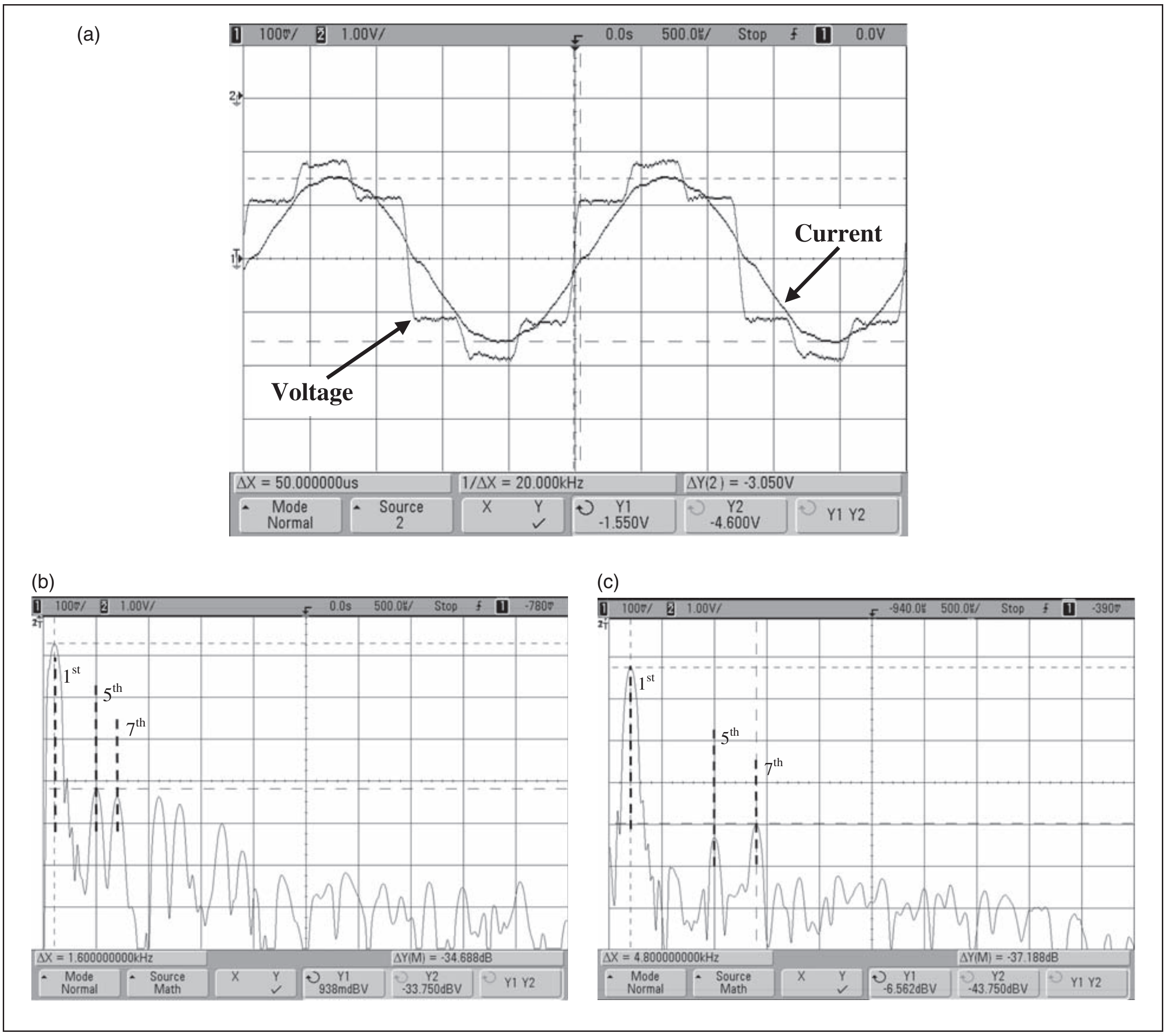

Figure 7. Response to distorted input voltage excitation waveforms: (a) 400 Hz supply time domain response; (b) 400 Hz supply harmonic characteristics; (c) 800 Hz supply harmonic response.

the increased line impedance. The gain term that acts upon the unit magnitude sine waves is therefore altered to regulate the DC link voltage. Here, the gain term is reduced by a factor of 51 between the 400 Hz case and the 800 Hz case. This effectively constitutes the most dominant control based action to accommodate the wide supply frequency range. Results at 500, 600, 700 and 800 Hz, are also shown in Figure 6, where it can be seen that the harmonic currents are within the specified limits with respect to their fundamental in each case, thereby demonstrating that the proposed topology of converter has the capability of providing harmonic control over a wide input frequency range. It should be noted that the results are taken in steady state. It has been found that, transiently, the harmonic limits can be exceeded when the converter is subject to rapid changes in frequency or load, primarily as a result of the limited PLL dynamic characteristics in this instance. However, such transients have yet to be accommodated in any of the formal specifications.

Experimental results with non-ideal supply

To test the performance robustness of the circuit under non-ideal operating conditions, a 400 Hz square wave voltage supply excitation is applied to the system. The resulting supply phase voltage (which has a quasi 6-step characteristic) and current are shown in Figure 7(a), from where it can be seen that although the voltage is significantly distorted, the current is predominantly sinusoidal. This is confirmed in Figure 7(b) by the 5^{th} and 7^{th} harmonic spectra, which have magnitudes >34 dB below that of the fundamental. For completeness, excitation with a 800 Hz square wave supply has also been considered. The resulting harmonic spectra are also shown in Figure 7(c), where it can again be seen that the harmonic limits are also met.

Conclusions

The article has considered pertinent issues regarding power converter current harmonic reduction when loads are supplied from a variable frequency AC generator, commensurate with those considered for use in future all/more electric aircraft. Whilst the use of variable frequency supplies precludes the use of traditional passive component filter solutions, and active counterparts 'tuned' to accommodate only the normal 400 Hz supply, a solution based on an integrated series active filter that can satisfy harmonic standards over a wide input frequency range (380–800 Hz), is presented. The design methodology and details of component selection and manufacture are included. It is shown through the use of measurements taken from a prototype converter that current harmonic limits are adhered to over the full operating frequency range and, additionally, that the proposed converter topology is robust to substantial distortion of the input supply voltage. The realisation of this type of power converter solution to facilitate the use of variable frequency supplies provides the opportunity to eliminate the complex hydraulic gearbox stages normally present in aircraft engine schemes in order to regulate generator supply frequency, and thereby significantly reduce in-flight mass.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Acknowledgements

The authors acknowledge the UK Engineering and Physical Research Council (EPSRC) for provision of a PhD research studentship in support of this work.

References

1. Paice DA. *Power electronic converter harmonics: methods for clean power*. New York: Wiley, 1999.
2. Matheson E and Karimi K. Power quality specification development for more electric airplane architectures. SAE Technical Paper 2002-01-3206, 2002.
3. SAE Aerospace Standard, AS4361A. Minimum performance standards for aerospace electric power converters, July 2011.
4. MIL-STD-704E. Aircraft electrical power characteristics. Department of Defence Interface Standard, 1991.
5. Cross AM, Forsyth AJ, Trainer DR, et al. Simulation of power quality issues in more-electric aircraft actuator supplies. In: *10th European conference on power electronics and applications (EPE'03)*, Toulouse, France, 2–4 September 2003, Paper 183.
6. UK Department of Defence Interface Standard MIL-STD-704F. Aircraft electrical power characteristics, October 2000.
7. Olaiya M and Buchan N. High power variable frequency generator for large civil aircraft. In: *IEE colloquium on electrical machines and systems for the more-electric aircraft*, UK, 9 November 1999, pp.3/1–3/4.
8. AbdElhafez AA and Forsyth AJ. A review of more-electric aircraft. In: *13th international conference on aerospace science and and aviation technology*, Paper ASAT-13-EP-01, Cairo, Egypt, 26–28 May 2009.
9. Corcau JI and Dinca L. On using PEMFC for electrical power generation on more electric aircraft. *World Acad Sci Eng Technol* 2012; 62: 246–249.
10. Kobravi K, Irawani R and Kojori HA. A review and implementation of matrix-converter for aerospace application. In: *Energy conversion congress and exposition (ECCE2012)*, Raleigh, North Carolina, 15–20 September 2012, pp.698–705.
11. http://www.aviationtoday.com/av/commercial/A380-More-Electric-Aircraft_12874.html#.ULjzz83kI68 (accessed 30 November 2012).
12. http://www.boeing.com/commercial/aeromagazine/articles/2012_q3/pdfs/AERO_2012q3_article2.pdf (accessed 30 November 2012).
13. Boglietti A, Cavagnino A and Vaschetto S. The safety critical electrical machines and drives in the more electric aircraft. In: *IEEE IECON'09, 35th annual conference of IEEE*, Italy, 3–5 November 2009, pp.2587–2594.
14. Moir I and Seabridge A. Electrical systems. *Aircraft systems: mechanical electrical, and avionics subsystems integration*. 3rd ed. New York: John Wiley & Sons, 2008.
15. Kolar JW, Baumann M, Schafmeister F, et al. Novel three-phase AC-DC-AC sparse matrix converter. In: *Seventeenth annual IEEE applied power electronics conference and exposition (APEC)*, Texas, US, 10–14 March 2002, vol. 2, pp.777–791.
16. Ismail EH and Erickson R. Single switch 3 phase PWM low harmonic rectifiers. *IEEE Trans Power Electron* 1996; 11(2): 338–346.
17. Singh B, Al-Haddad K and Chandra A. A review of active filters for power quality improvement. *IEEE Trans Indus Electron* 1999; 46(5): 960–971.
18. Yousif SNAL, Wanik MZC and Mohamed A. Implementation of different passive filter designs for harmonic mitigation. In: *Power and energy conference (PECon2004) proceedings*, Malaysia, 29–30 November 2004, pp.229–234.
19. Trainer DR and Whitly CR. Electric actuation – power quality management of aerospace flight control systems. In: *Power electronics, machines and drives conference (PEMD'02)*, UK, Publication 487, 4–7 June 2002, pp.229–234.
20. Chivite-Zabalza FJ, Forsyth AJ and Trainer DR. Analysis and practical evaluation of an 18-pulse rectifier for aerospace applications. In: *2nd international conference on power electronics machines and drives (PEMD'04)*, UK, 31 March to 2 April 2004, vol. 1, pp.338–343.
21. Choi S, Enjeti PN and Pitel IJ. Polyphase transformer arrangements with reduced kVA capacities for harmonic current reduction in rectifier type utility interface. *IEEE Trans Power Electron* 1996; 11(5): 680–690.
22. Wheeler P, Clare J, de Lillo L, et al. A reliability comparison of a matrix converter and an 18-pulse rectifier for aerospace applications. In: *12th international power*

electronics and motion control conference (EPE-PEMC'06), Slovenia, August 2006, pp.496–500.

23. Wheeler P, Clare J, de Lillo L, et al. A comparison of the reliability of a matrix converter and a controlled rectifier-inverter. In: *European conference on power electronics and applications (EPE'05)*, Germany, 11–14 September 2005, pp.1–7.
24. Peng FZ. Harmonic sources and filtering approaches. *IEEE Indus Appl Mag* 2000; 7(4): 18–25.
25. Fujita H and Akagi H. An approach to harmonic current free AC/DC power conversion for large industrial loads: the integration of a series active filter with a double series diode rectifier. *IEEE Trans Ind Appl* 1997; 33(5): 1223–1240.
26. Semikron datasheet for the SKM50GB063D super fast NPT-IGBT module.
27. Semikron datasheet for the Skyper 32 R driver.