COMPARISON OF POWER QUALITY SOLUTIONS USING ACTIVE AND PASSIVE RECTIFICATION FOR MORE ELECTRIC AIRCRAFT

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Abstract

This paper presents various three phase active and passive rectification schemes and compares them for more electric aircraft applications. The passive topologies involve multi-pulse transformer rectification systems while the active topologies look into active rectification. Passive rectification systems are to be used for the ac-to-dc conversion that comprises the first stage of the ac-to-ac conversion for applications such as motor drives in aircraft systems. Particular emphases are given to comparison of dc bus regulation, electromagnetic interface (EMI) filtering, current harmonic cancellation, power factor, size, weight, cost and reliability among the schemes. Results are summarized qualitatively in a table.

1 Introduction

One of the radical changes in the commercial aircraft industry has been the replacement of the traditional constant voltage, constant frequency (115 V, 400 Hz) alternating current (ac) with constant voltage and variable frequency (380 to 780 Hz) in the power distribution system. In traditional power distribution systems for aircraft, significant loads are comprised of fans and pumps driven by induction motors. When such devices are directly connected to the ac bus, it is common to have a large inrush current present at equipment start up. Apart from this problem, and the restriction of speed imposed by the distribution system generator, the motor load has little effect on the distribution and generation system and does not require EMI filtering.

The introduction of variable frequency distribution system on commercial aircraft results in the elimination of a mechanical interface device for variable ratio transmission that is positioned between the main engine and the ac electric generator. The ac electric generator can now be directly coupled to the main engine output shaft via a gearbox. The effect of such direct coupling is an ac bus frequency proportional to the engine speed (which can vary over a 2:1 range depending on application), while the magnitude of the ac bus voltage is regulated to a constant value via a generator control unit (GCU) for the generation system.

With such a distribution system, it is still possible to connect induction motors directly to the bus, however, such an approach yields an oversized motor when compared to the fixed frequency case. Since weight is critical in aircraft applications, such an approach is not feasible.

To interface these motors with the bus, a motor controller, where power is converted from one ac format to one that is compatible with the motor load is needed [1,2,3]. With the addition of the motor controller the selection of the electrical motor is no longer limited to induction motors, but can be other type of motors including PM motors. Further, the maximum speed of the motor is no longer limited by the bus distribution system frequency, allowing the individual system weights to be optimized. Also the large inrush current of an induction machine directly running from the constant frequency line can also be eliminated using motor controllers.

2 Reason for Current Harmonic Requirements

A logical method to achieve the conversion of power from the constant voltage variable frequency format to one compatible with the motor load is, at its front end, to use a simple six-pulse rectifier followed by an inverter. Unfortunately, due to the nonlinear nature of the operation of the 6-pulse rectification scheme, the input current drawn from the ac distribution system can become quite distorted. The frequencies at which characteristic harmonics are produced by such an input rectifier can be formulated as noted in equation (1) below.

$$f_H = (k \times q \pm 1) \times f_I \qquad (1)$$

In equation (1), f_H = the characteristic harmonic, H = the number of harmonics, k = an integer beginning with 1, q = an integer representing the number of commutations per cycle, and f_I = the fundamental frequency.

The characteristic harmonics of a 6-pulse rectification system (such as the 5th, 7th, 11th, 13th, 17th and 19th harmonics) can have considerable magnitudes. Therefore, the total harmonic distortion (THD) of current can become quite high and, in some applications, can exceed 40% of the fundamental current value. These harmonics are not desired in the distribution system because voltage distortion results from them, since the generator source impedance is not zero. Further, such undesired harmonics can result in increased rating for the generation and distribution system, and increased power dissipation. Additionally, the current harmonics can distort the voltage waveform at the point of regulation.

As in the dc systems, the ac current harmonics from nonlinear loads can excite ac resonances due to interaction of the power generation and distribution impedance and source impedance of various power conversion equipment in the aircraft. Unless sufficient damping is added at the equipment and/or system level, this resonance can cause significant concern and possible disruption of some of the aircraft equipment. Unlike terrestrial based systems where even today substantial damping is provided by resistive loads, aerospace electrical loads are of the constant power type, further aggravating the stability issue. Passive solutions can be used to achieve some damping. However, additional inductance or resistance is not desirable in aerospace applications due to their associated weight impact. Therefore, the aircraft manufacturers develop stringent power quality requirements [1].

In order to facilitate the design of electrically powered subsystems and to maintain control of the power quality the aircraft manufacturers have developed stringent power quality requirements [1].

Because of these facts, more complex rectification systems or active schemes must be considered. A typical requirement for future commercial aircraft power quality requirement is provided in reference [1]. Table 1 illustrates the current harmonics limit requirements for loads larger than 5 kW presented in this reference.

Harmonic Order	Limits
3rd, 5th, 7th	I_h=0.02 I_1
Odd Triplen Harmonics (h=9, 15, 21,…, 39)	I_h=0.1 I_1/h
Odd Non Triplen Harmonics 11, 13	0.03 I_1
Odd Non Triplen Harmonics 17, 19	0.04 I_1
Odd Non Triplen Harmonics 23, 25	0.03 I_1
Odd Non Triplen Harmonics 29, 31, 35, 37	I_h=0.3 I_1/h
Even Harmonics 2 and 4	I_h=0.01 I_1/h
Even Harmonics > 4 (h=6, 8, 10, …, 40)	I_h=0.0025 I_1
Subharmonics and Interharmonics	I_h=0.0025 I_1 or 5mA (whichever is greater)

Table 1. Current Harmonic Limits for Three-Phase Equipment Greater Than 5 kVA [1]

3 Passive Solutions for Power Quality

There are passive solutions that incorporate more than one 6-pulse rectifier to feed the load. These solutions rely on canceling some lower characteristic harmonics of input ac current by using a multi-pulse transformer or autotransformer.

The multi-pulse rectification solutions are simple, robust, and reliable compared to active solutions. It should be noted that they achieve harmonic cancellation best at their rated power due to the smoothing effect of the source impedance during the commutation. They are amenable to be used for high ratio of peak current to nominal current applications with proper designs. From the perspective of rectification only this solution may appear to be heavier in weight compared to active solutions for levels above certain value. However, many factors have to be considered. These factors include thermal losses, EMI, and stress requirements with respect to mounting of the parts in a mechanical design. For example, the multi-pulse rectification solutions typically do not require an input ac common mode EMI filter unlike some active solutions. Therefore, a detailed application specific analysis is needed to evaluate the impact on weight of different active and passive solutions. What these systems cannot provide however is active damping of the input filter circuitry, since they are by nature, passive converters.

3.1 Series or Parallel Connection of Diodes

To reduce harmonics, two or three 6-pulse diode bridges for obtaining 12-pulse and 18-pulse rectification respectively can be either connected in series or parallel depending on the dc voltage magnitude requirement for a given input ac voltage magnitude. Parallel connections may require interphase transformers on the dc link to isolate the operation of the 6-pulse rectifiers if autotransformers are used. Series connection is not possible using an autotransformer due to the existence of the galvanic connection of secondary windings.

3.2 120 Degree vs. less than 120 Degree Angle Conduction for Autotransformer Rectifier Units (ATRU)

When 6-pulse rectifiers are paralleled, interphase transformers are normally used to achieve current sharing between the bridges, otherwise each bridge is required to alternately carry the full current for 30 degrees. Clearly, it is possible to achieve multi-pulse rectification systems whereby the conduction angle of diodes is not limited to 120 degrees. The advantage of this type of rectification is that they do not need to use interphase transformers. For example, a 40-degree conduction of diodes can be achieved by using a properly configured 18-pulse autotransformer [6]. The advantage of such systems is that although each diode and each associated transformer leg carries the full load current for a reduced conduction angle, the rms rating of the current sizes the transformer, and the peak current sizes the diode, resulting in a weight competitive solution.

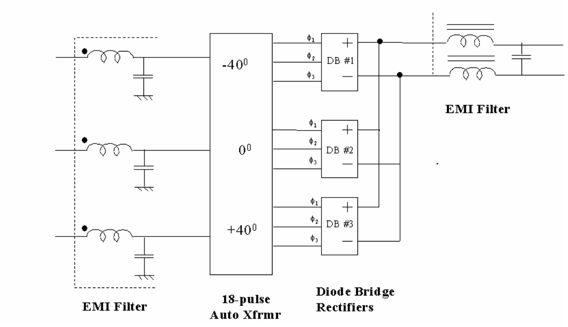


Fig.1. Schematic of 18-pulse rectification using autotransformer

The 5th and 7th harmonics of input ac current are cancelled in a 12-pulse rectification system. Similarly, the 5th, 7th, 11th, and 13th harmonics are canceled in an 18-pulse rectification system. Fig. 1 shows the schematic of an 18-pulse rectification using an autotransformer. In reality, these harmonics are not fully canceled due to the finite source impedance that extends the commutation of dc link current from one diode to another through either the bottom or top dc bus, but they are significantly reduced.

Manufacturing and design limitations also affect the degree of cancellation since complete cancellation requires fractional turns, which must be approximated by full turns. Some experimental waveforms of input current and voltage waveforms and FFT of the input current are shown in Fig. 2 and Fig. 3, respectively.

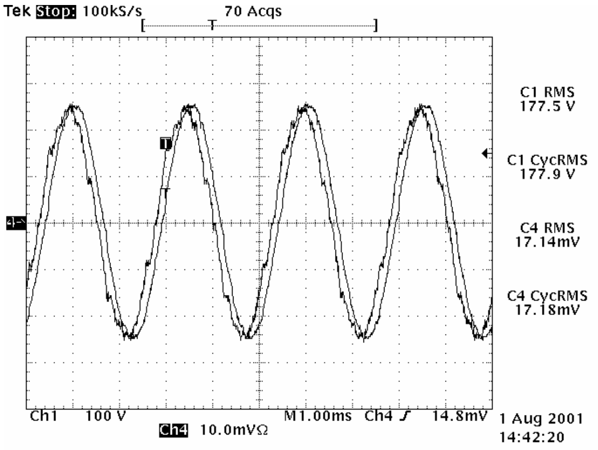


Fig. 2. Experimental results: Input AC voltage and current waveforms for 18-pulse ATRU

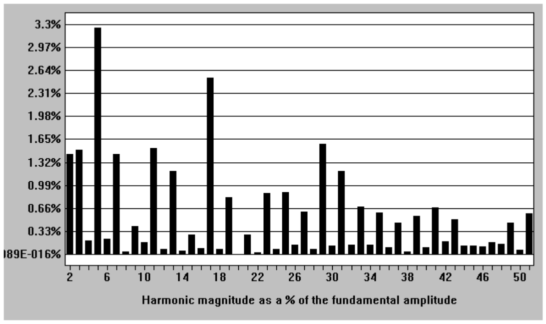


Fig. 3. Experimental results: FFT of input current waveform

4 Active Solutions for Power Quality

There are various ac-to-dc or ac-to-ac power conversion topologies that can be used to achieve compliance with power quality requirements.

- Active Rectifier (ac-to-dc)
- Matrix Converters (ac-to-ac)
- Reduced Switching Element Matrix Inverter (RESEMI) (ac-to-ac)
- Active Filtering

There has been significant research on active rectifiers and matrix converters in past years. Hence, in this paper emphasis will be given to a novel topology called RESEMI and active filtering. There are other topologies such as reduced switch converter topologies [4] and VIENNA rectifier [5] that are also viable solutions which were not included to this paper.

4.1 Active Rectifiers

At a minimum, active rectifiers are comprised of an input filter (made of inductors and capacitors), six controllable switches, six diodes and a dc link capacitor as shown in Fig. 4. Therefore, the input to this topology is a current source and the output is a voltage source converters. Typically, a unity power factor at the input of the active rectifier filter is required by the distribution system. Such control can easily be obtained by properly controlling the six switches. The minimum kVA requirement of the input converter is equivalent to the product of the maximum ac current (at minimum voltage) and the maximum input voltage. Clearly operating at unity power factor at the active rectifier terminals requires the inverter to operate at a reduced power factor, thereby increasing its size, weight and cost. Significant research has been devoted to this topology and results are widely published in literature. Typically, an additional three-phase inverter bridge is used to convert the dc link power to variable voltage and variable frequency ac power to drive a load, such as an ac motor. The advantage of using this scheme is that active filtering can be incorporated into the control of the three phase inverter bridge, and can be used to stabilize the input filter that might be excited by line harmonics generated by other loads.

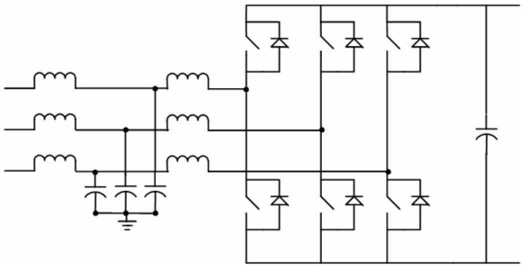


Fig. 4. Active rectification topology

4.2 Matrix Converters

Matrix converters are forced commutated converters to transform the ac input power to desired variable voltage variable frequency output power and have the capability of four-quadrant operation via control. The matrix converters do not include either a dc link inductor or dc link capacitor. The cardinal rules of operation are typically the input is voltage source and, hence, cannot be short circuited and the output is a current source such as an electrical machine that cannot be opened. The schematic of a matrix converter is shown in Fig. 5. Matrix converters utilize more switches than an ac-to-dc-to-ac conversion system formed by an input side active rectifier and a load side converter. Bidirectional switches are used to provide blocking voltage and to conduct current in both directions. Matrix converters can be expensive because of additional switches and associated control system. The control of the matrix converter is more complex due to the greater number of switches used when compared to other schemes. Also voltage output is generally limited to 0.866 times the input. Hence, reduction in reliability due to additional switches and complex circuitry must be evaluated against the increase in reliability due to the elimination of the dc link capacitor. The capability of regeneration of the matrix converter is not useful for aerospace applications, as aircraft manufacturers do not typically allow regeneration of ac power back to the power distribution system.

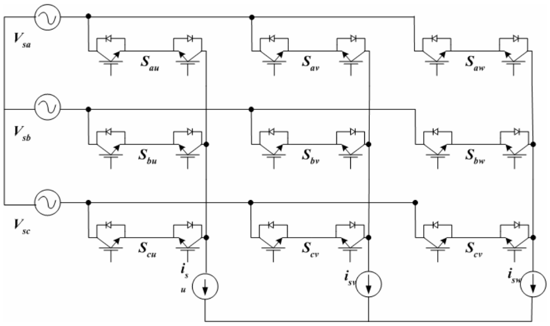
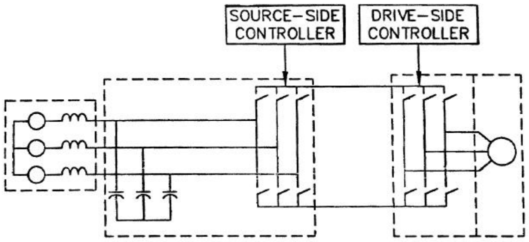


Fig. 5. Matrix converter topology (Input EMI section not shown)

4.3 Reduced Switching Element Matrix Inverter

This topology attempts to eliminate the large and heavy capacitors used in active rectification while at the same time provides many of the benefits of the matrix converter with one third less switching devices [2,7]. It also attempts to reduce the switching losses by only requiring one inverter to operate at the modulation frequency. Further, it is easily adaptable to active filtering of the input capacitor. Simplifying the switching modulation scheme and reducing the switching frequency reduces losses. Similarly, this topology reduces the number of switches and, hence, its associated complexity when compared to the matrix converter. A lower weight and more reliable power conversion system can be achieved using this topology.



(a)

(b) (c)

Fig. 6. (a) Schematic of RESEMI topology and switch definition for (b) source-side controller and (c) load-side controller.

As shown in Fig. 6a, the system includes an input three-phase capacitor bank, source-side converter, and a drive-side converter. The input is connected to the aircraft power distribution system and the output is connected to the load such as a three-phase ac motor.

Each switch of the source-side inverter includes a controllable semiconductor device (e.g., an IGBT or MOSFET) and a diode. The drive-side switches are also comprised of controllable semiconductor device (e.g., an IGBT or MOSFET) as shown in Fig. 6b and 6c.

A current mode of operation is used for the source-side inverter in which only two switches conduct current at any time. One unique feature of this input topology is that unlike many current fed space vector modulation (SVM) inverters, it is not required that the inverter be short circuited during the null vector; the current path for the load is provided by the inverter freewheel diodes. The drive side inverter employs a commutation mode of operation where three switches conduct at any given time. A 60-degree conduction period is used for the drive-side inverter to achieve a simple control. This inverter is not required to operate at the input modulation frequency.

Some of the features of the RESEMI topology include power factor control and active damping in the input. The detail control topology is presented in references [2] and [7]. An optional regeneration scheme can be configured by using a full bridge rectifier at the dc link as illustrated in the references.

4.4 Active Filter with Selectable Harmonic Elimination – A Harmonic Scrubber

Reference [8] discloses a novel active filter control topology where the harmonic currents are removed without cutting into the power distribution line and measuring main distribution current. In aircraft power distribution systems, the main distribution current can be quite large. In Fig. 7, a single line diagram of a power distribution of an aircraft is shown. Typically, a wound-field synchronous generator is connected to three-phase loads. Power generation can also be achieved by other types of electrical machines such as PM generators. The power source provides three-phase ac power to the bus at a fixed or variable fundamental frequency. The fundamental frequency can vary between 350 Hz and 800 Hz.

Multiple aircraft loads including non-linear loads, for example due to 6-pulse rectification, can be connected to the power distribution bus. An active filter is connected in parallel to the power bus between the power source and the loads to supply harmonic currents. These harmonics can be characteristic harmonics of the fundamental, i.e. $(6n\pm1)f$ (n is integer and f is the fundamental frequency) due to rectifier operations and non-characteristic harmonics due to the resonances of filters. For example, this topology allows use of 6-pulse rectification to eliminate the individual power quality compliant equipment for the aircraft loads. Other harmonics can also exist, such as those caused by the resonant oscillation of filters that are excited by other conducted emissions injected into the power bus. These harmonics are referred to as non-characteristic harmonics, since they are not intimately related to the fundamental frequency, as are the characteristic harmonics. The active filter deals with both the characteristic and non-characteristic harmonics. Nonlinear loads can be modeled as current sources that inject harmonic currents into the power bus.

The inductor shown in Fig. 8 represents the inductance of the power distribution system and source impedance associated with the power sources connected to the power bus.

An active filter is connected in parallel to the power bus, between the ac power source and the loads. It is placed upstream of any non-linear loads. The active filter supplies harmonic currents to the nonlinear devices such that the ac power source supplies only current at the fundamental frequency to the power bus.

The details of the control topology will be discussed in a future paper.

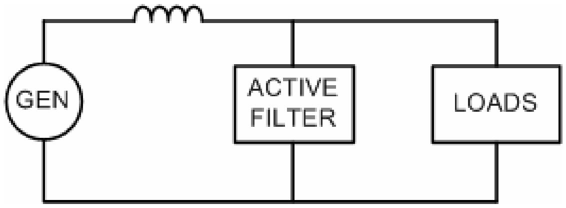


Fig. 7. Single line diagram using active filter

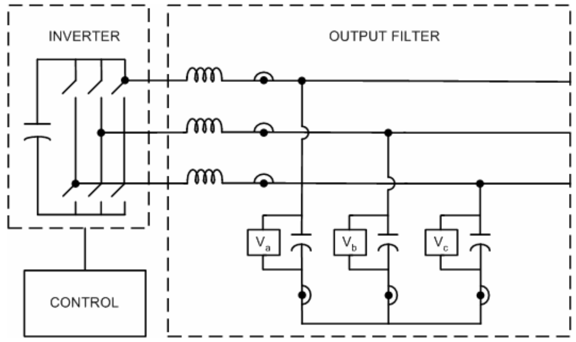


Fig. 8. Schematic of active filter with selectable harmonics

5 Comparison of Power Quality Solutions

The comparison of power quality solutions is summarized in Table 2. Main system characteristic of solutions will be compared below.

5.1 DC Bus Regulation

The passive solutions do not have a voltage regulation capability and, therefore, the output dc link voltage droops as the transformer-rectifier unit is loaded. The voltage droop is a function of input source impedance and the leakage reactance of the transformer. The voltage droop could be quite substantial at full load due to the commutation effect of the diodes and reactive voltage drop of the source and leakage inductance of the transformer. The smaller the dc voltage, the smaller the output voltages of the inverters become. Therefore, an electrical machine that is run by a ATRU-fed inverter needs to be designed to be compatible with the worst-case minimum output voltage of the rectifier. This requirement increases the dc or ac link currents for a given power output. This may translate into additional losses in the dc link inductance and cables. Also, the kVA rating of the inverter has to be increased.

Certain active topologies, such as the active rectifier, can regulate the dc link voltage. This is advantageous because the current at the inverter and motor can be lowered. This means kVA rating of the inverter can be optimized and lower losses incurred for the filter inductors and cables.

5.2 EMI Filtering

Typically, the passive solutions need a differential-mode EMI filter, but no common-mode EMI filtering is needed at the input due to the high common mode impedance. The active solutions need both differential- and common-mode filtering. The common-mode filtering is needed mainly due to the switching associated with the input inverters, and the stray capacitance to chassis ground of the inverter switches and transformer windings.

5.3 Current Harmonic Cancellation

The power quality provided by transformer-based solutions depend upon manufacturing limitations and the effectiveness of the transformer topology. Manufacturing limits can include the impact of approximating non-integer turns with integer turns for some windings. One of the primary disadvantages of the passive solutions is incapability to adjust the current harmonic cancellation once the design is completed. Moreover, harmonic cancellation is a function of loading of the transformer rectifier unit. Transformer topology also has an effect on the operation of the cancellation. Typically a delta winding is required to circulate the triplen harmonics produced in the rectification process [6]. A magnetically coupled delta is considerably less efficient than a galvanically coupled delta, so transformer topology has to be carefully evaluated. For this reason, it is believed that active solutions offer more flexibility to meet power quality requirements. Additionally, it is thought that continued improvement in active switching devices in the coming generations of switches will enable higher switching frequencies, and this coupled with ever faster computational power of digital signal processors will enable significant reduction in the input filter components. Whereas, it is unlikely in the magnetic material technology that any significant increase in flux density will be obtained in the near future, so the passive solution has effectively significant limitation for growth. Furthermore, due to the high switching frequencies of the active rectifier, the lower harmonic frequencies such as 5th, 7th, etc. of the fundamental input frequency are not encountered at the input. This can be considered an additional benefit of the active solutions.

5.4 Power Factor

The power factor cannot be controlled with a passive solution once the design is complete. Typically, the power factor of the transformer rectifier unit is lagging without the EMI filtering and it is function of loading. With the EMI filtering the power factor can be made to range from leading, at low loads, to lagging, at nominal loads. Leading power factor is typically not desired in power systems, particularly at rated operation. The input power factor of active solutions can be controlled using a proper control algorithm. With a proper implementation, the active solution can compensate the reactive current of the input EMI filter and, therefore, unity power factor at the input can be maintained.

5.5 Overloading Capability

One of the attractive features of transformer-based rectification is its capability to provide current in excess of its nominal value. This is needed for applications where more than nominal current is needed for a short time. The active solutions do not typically allow for large overloading capability due to the limitation of switching devices. Hence, the kVA ratings of the active solutions are penalized for applications where overloading capability is needed.

5.6 Size and Weight

It is critical to understand the impact of EMI to the overall size and weight. As mentioned above the transformer-based solutions may not require a common-mode EMI filter at the input while active solutions would. Also, cooling type (liquid, forced air, convection) of the EMI components is another factor in the size and weight trade study.

5.7 Cost

Complexity generally determines what will be the most cost effective system. With respect to passive solutions, particularly for low power applications, an ATRU can offer the lowest cost. Active solutions certainly cost more as semiconductor devices and additional control and gate drive circuitry increase the cost. However, RESEMI topology can be one of the least expensive among active topologies due to the elimination of a dc link capacitor and input inductors while also providing substantial weight reduction and added reliability. Active filtering can also be a candidate for the least cost solution if it eliminates the necessity of complying with the power quality requirements for each load in the aircraft.

5.8 Reliability

The passive solutions offer the highest reliability compared to active solution. For example, in the case of active rectifier and RESEMI, the reliability can be as low as half that of a converter using transformer-based rectification and an inverter. However, with advances in power electronics the reliability of the active solutions is expected to improve in the future.

	Passive Solutions		Active Solutions			
	TRU	ATRU	AR	MATRIX	RESEMI	AF
DC Bus Regulation	◔	◔	●	N/A	N/A	N/A
EMI Filter	●	●	◐	◐	◐	◐
Current Harmonic	◐	◐	●	●	●	●
Power Factor	◐	◐	●	●	●	●
Power Quality	◕	◕	●	●	●	●
Weight	◐	◕	◕	◕	●	●
Cost	◕	●	○	◔	◐	●
Reliability	●	●	◔	◔	◐	◕

Table 2. Comparison among passive and active solutions

ATRU – Autotransformer Rectifier Unit
TRU – Transformer Rectifier Unit
AR – Active Rectifier
AF – Active Filter

● - Best, ○-Worst

6 Conclusion

In this paper, various active and passive solutions for developing power quality compliant solutions were presented for more electric aircraft. The solutions were compared from the perspective of important system level considerations including EMI filtering, dc bus regulation, power factor, current harmonics, size, weight and cost. Passive solutions are simpler and offer higher reliability compared to active solutions. Moreover, passive solutions can have a cost advantage, particularly for low-power applications. Active solutions are very attractive for controlling power factor and current harmonics. Active solutions can also be designed to achieve active damping which can be very important for certain power distribution systems. The main drawback of active solutions is lower reliability compared to the passive solutions. Advancements in power electronics, processors, and semiconductor technology will enable improved reliability of active solutions in the future.

7 Acknowledgments

Colin Huggett and Gabor Kalman (both retired Honeywell employees) are acknowledged for their mentorship to the author and innovative contributions to aerospace power conversion solutions, including RESEMI and active filtering techniques.

References

[1] Matheson E, and Karimi K. Power quality specification development for more electric airplane architectures. *SAE Power Systems Conference*, Coral Springs, Florida, 2002.

[2] Sarlioglu B. Power quality solutions using active and passive rectification for future more electric aircraft. *SAE Power Systems Conference*, Reno, Nevada, 2004.

[3] Gong G, Heldwein M L, Drofenik U, Mino K, and Kolar J W. Comparative evaluation of three-phase high power factor AC-DC converter concepts for application in future more electric aircrafts", *Nineteenth Annual IEEE Applied Power Electronics Conference and Exposition*, Anaheim, California, 2004.

[4] Gi-Taek K and Lipo T.A. VSI-PWM rectifier/inverter system with a reduced switch count. *IEEE Transactions on Industry Applications*, pp. 1331-1337, Nov/Dec 1996.

[5] Chongming Q and Smedley K.M. Three-phase unity-power-factor VIENNA rectifier with unified constant-frequency integration control. *IEEE International Power Electronics Congress*, pp. 125-130, Oct. 2000.

[6] US Patent 6,995,993, Rectification system for improving power quality of electrical power systems, Honeywell International

[7] US Patent 6,839,249, Ac-to-ac power converter without a dc link capacitor, Honeywell International

[8] US Patent 6,882,549, Active filter for power distribution system with selectable harmonic elimination, Honeywell International