Advances in AC-DC Power Conversion Topologies for More Electric Aircraft	Những bước tiến trong Tôpô chuyển đổi công suất AC-DC dành cho máy bay tiêm kích hoạt động bằng điện AC: xoay chiều DC: một chiều Topology: tô pô hay dạng hình học, cấu trúc, cách sắp xếp các phần tử trong mạch điện. Để bản dịch ngắn gọn em sẽ để nguyên những từ này.
Abstract - The purpose of the paper is to review and compare the ac-dc electric power conversion topologies from the perspective of More Electric Aircraft (MEA) utilization. Advancements in power electronics encompass many evolving technologies including power semiconductor devices, microprocessors or digital signal processors (DSPs), thermal management, EMI and corona mitigation techniques, and mechanical packaging. The weight, volume, cost, and performance are critical design criteria, as is achieving other important requirements and specifications such as power quality, EMI/EMC, reliability, vibration, and shock for more electric aircraft applications. In this paper, an introduction will be made to the traditional versus modern aircraft power distribution systems illustrating the need of ac-dc power conversion systems. Then, the various power conversion topologies for more electric aircraft will be reviewed.	Tóm tắt - Mục đích của bài báo này là điểm lại những chặng đường phát triển (tổng quan) và so sánh các tôpô chuyển đổi công suất AC-DC ứng dụng trong máy bay tiêm kích hoạt động bằng điện (MEA). Những tiến bộ trong điện tử công suất đã hoàn thiện nhiều công nghệ có liên quan bao gồm các thiết bị bán dẫn công suất, các bộ vi xử lý hoặc các bộ xử lý tín hiệu số (DSP), các kỹ thuật kiểm soát nhiệt, EMI và kỹ thuật giảm thiểu corona (điện hoa, phóng điện vầng quang), và đóng gói cơ khí. Các tiêu chí thiết kế quan trọng đối với các ứng dụng máy bay tiêm kích hoạt động bằng điện là trọng lượng, kích thước, chi phí và hiệu suất, cũng như việc đạt được các yêu cầu và tính năng kỹ thuật quan trọng khác như chất lượng điện năng, EMI / EMC, độ tin cậy, độ rung và sốc. Trong bài báo này, chúng tôi sẽ giới thiệu các hệ thống phân phối điện năng trong máy bay truyền thống và hiện đại để minh họa sự cần thiết của hệ thống chuyển đổi công suất AC-DC. Sau đó, chúng tôi sẽ giới thiệu chung (tổng quan) về các tô pô chuyển đổi điện năng khác nhau cho máy bay tiêm kích hoạt động bằng điện.
I. INTRODUCTION	I Giới thiệu
The need of power conversion has been rising dramatically in the past ten years	Nhu cầu chuyển đổi công suất đã tăng đáng kể trong mười năm qua trong lĩnh

for more electric aircraft design and development. To understand this need, one has to look at the differences of traditional and modern aircraft electric power system architectures. Traditional commercial aircraft systems typically employ a constant-voltage, constant-frequency (115 V, 400 Hz) alternating current (ac) power distribution network. Various electrical motors are connected to this ac bus typically without using a motor controller. Unfortunately, when such electric machines are directly connected to the ac bus, it is common to have a large inrush current present at equipment start up. As commonly found in such a system, the variable speed of the main engine is converted into a constant frequency output via a mechanical interface device positioned between the main engine and the ac electric generator. A shaft running at a constant speed at the output of this mechanical device is used to rotate the accessories, including the main engine generator, thereby providing a constant frequency ac bus.	vực thiết kế và phát triển máy bay tiêm kích hoạt động bằng điện. Để hiểu được nhu cầu này, chúng ta cần phải hiểu được sự khác nhau về kiến trúc của các hệ thống cung cấp điện trong các máy bay truyền thống và hiện đại. Hệ thống máy bay thương mại truyền thống thường sử dụng mạng phân phối điện xoay chiều tần số và điện áp không đổi (115 V, 400 Hz). Các động cơ điện khác nhau được kết nối với bus ac này thường không sử dụng bộ điều khiển động cơ. Tuy nhiên, khi những máy điện như vậy được kết nối trực tiếp với bus ac, một dòng điện lớn đột biết có thể xuất hiện lúc khởi động thiết bị. Thông thường, trong những hệ thống như thế, tốc độ biến đổi của động cơ chính được chuyển đổi thành đầu ra tần số không đổi thông qua một thiết bị giao diện cơ đặt giữa động cơ chính và máy phát điện xoay chiều. Một trục chuyển động với tốc độ không đổi ở đầu ra của thiết bị cơ khí này được sử dụng để quay các phần phụ kiện, bao gồm cả máy phát điện-động cơ chính, nhờ đó tạo ra bus ac tần số không đổi.
However, as advancements in electrical power systems become reality, it is clear that the constant frequency ac bus can be abandoned to allow the elimination of the mechanical interface between the main engine and the generator described above. Such advancements could further enable a system, which would directly couple the ac electric generator to the main engine output shaft via a gearbox device. This achieves a highly reliable generator system because of the elimination of the variable speed to constant speed mechanical device.	Tuy nhiên, khi những tiến bộ trong hệ thống điện bắt đầu đi vào thực tế, rõ ràng là bus ac tần số không đổi không còn cần thiết nữa và điều này cho phép loại bỏ giao diện cơ học giữa động cơ chính và các máy phát điện mô tả ở trên. Những tiến bộ này cho phép hình thành một hệ thống ghép trực tiếp máy phát điện xoay chiều với trục phát động của động cơ chính thông qua hộp số. Điều này tạo ra một hệ thống máy phát điện có độ tin cậy cao do việc loại bỏ thiết bị cơ khí tốc độ biến đổi và chuyển sang thiết bị cơ khí tốc độ không đổi.
The result of such direct coupling is an	Kết quả của sự ghép trực tiếp như vậy

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. For example, at main engine idle speed the frequency can be 360 Hz, whereas at full throttle, frequency increases to 720 Hz. The accessory motors, such as those used for pump and fan applications for constant-voltage, constant-frequency systems, become significantly larger if each is directly connected to the constant voltage-variable frequency distribution system. Moreover, power cannot be controlled to the shaft but rather will be a function of load. For example, for a fan application, at twice the frequency, there will be eight times the power demand from the fan, assuming torque is proportional to the square of the speed. This kind of nonlinear power demand is not acceptable for many applications. Similarly, the inrush current requirements based upon these devices can also become substantially greater than traditional commercial aircraft power system loads.	là tần số bus ac tỷ lệ thuận với tốc độ động cơ (đại lượng này có thể thay đổi trên khoảng 2:1 tùy thuộc vào ứng dụng), trong khi đó độ lớn của điện áp bus xoay chiều được điều chỉnh ở giá trị không đổi qua bộ điều khiển máy phát điện (GCU) trong các hệ thống máy phát. Ví dụ, ở tốc độ không tải của động cơ chính, tần số có thể là 360 Hz, trong khi ở tốc độ cực đại, tần số tăng tới 720 Hz. Kích thước của các loại động cơ phụ, chẳng hạn như những động cơ sử dụng cho các ứng dụng bơm và quạt trong các hệ thống điện áp không đổi, tần số không đổi, sẽ phải lớn hơn nhiều nếu mỗi thiết bị này được kết nối trực tiếp với hệ thống phân phối tần số thay đổi-điện áp không đổi. Hơn nữa, công suất không phải do trục điều khiển mà thay đổi theo tải. Ví dụ, đối với một ứng dụng quạt, nếu tần số tăng lên hai lần thì nhu cầu điện năng của quạt sẽ tăng gấp tám lần, giả sử mô-men lực tỷ lệ thuận với bình phương tốc độ. Nhiều ứng dụng không phù hợp với nhu cầu điện năng phi tuyến như thế.Tương tự như vậy, các yêu cầu dòng tăng đột biến của những thiết bị này cũng có thể trở nên lớn hơn đáng kể so với tải hệ thống điện của máy bay thương mại truyền thống. Tải hệ thống điện là lượng điện năng tiêu thụ của tất cả các thiết bị điện
For all of these reasons, it is not feasible to directly couple these electrical machines directly to the constant voltage- variable frequency ac bus [1,2]. Both ac-dc and then dc-ac conversion is needed, unless direct ac-ac conversion is used, such as matrix converter. The purpose of this paper is to investigate the possibilities and advancements of ac-dc conversion for aerospace	Vì những lí do như vậy, việc ghép trực tiếp những máy điện này với bus ac tần số thay đổi-điện áp cố định không khả thi [1,2]. Cả chuyển đổi ac-dc và dc-ac là cần thiết, nếu không sử dụng chuyển đổi ac-ac trực tiếp, chẳng hạn như bộ biến tần ma trận. Mục đích của bài báo này là nghiên cứu khả năng và những tiến bộ của kỹ thuật chuyển đổi ac-dc cho các ứng dụng hàng không vũ trụ và

applications and compare the advantages and disadvantages of major topologies. II. PASSIVE AC-DC CONVERSION TOPOLOGIES FOR MORE ELECTRIC AIRCRAFT Power quality and EMI/EMC requirements are becoming very important for more electric aircraft applications due to the complexities around the increased power generation and utilization in the aircraft. Typically, each aircraft manufacturer can specify standard specifications such as in D0-160 [3] or customized version of these standards for power quality. It is even possible that aircraft manufacturers can develop and utilize their own requirements based on their assessment and experience. The size of the aircraft, details of the generation system and loads, bus structure, cable lengths, overall characteristic of the power generation system, and loads are typically carefully analyzed for many different steady-state and transient conditions to develop power quality requirements. A typical requirement for future commercial aircraft power quality is provided in reference [1]. TABLE 1 illustrates the current harmonics limit requirements for loads larger than 5 kW presented in this reference. TABLE I CURRENT HARMONIC LIMITS FOR THREE-PHASE EQUIPMENT GREATER THAN 5 KVA [1] Harmonic Order Limits Odd Triplen Harmonics (h=9, 15, 21,..., 39) Ih=0.1 11/h	so sánh ưu và nhược điểm của các tô pô chính. [redacted]

Odd Non Triplen Harmonics 11, 13 3 Odd Non Triplen Harmonics 17, 19 4 Odd Non Triplen Harmonics 23, 25 3 Odd Non Triplen Harmonics 29, 31, 35, 37 Ih=0.3 11/h Even Harmonics 2 and 4 Ih=0.01 11/h Even Harmonics > 4 (h=6, 8, 10, ..., 40) Ih=0.0025 I1 Subharmonics and Interharmonics Ih=0.0025 I1 or 5mA (whichever is greater)	[redacted]
A. Six-pulse Rectifier The simplest three-phase passive rectifier is a six-pulse rectifier. However, due to large current harmonic distortion, the six-pulse rectification is not typically feasible to meet the current harmonic requirements. Therefore, at a minimum, 12- or 18-pulse rectification using autotransformer or transformer rectifier unit is needed for passive rectification to achieve reasonable current harmonic distortion and power factor.	[redacted]
The passive rectification for multi-pulse capability can be achieved by specially wound transformers or autotransformers with six- or nine-phase secondary outputs for 12- and 18-pulse rectification, respectively. One of the major disadvantages of passive rectification is that the dc bus voltage droops as a function of dc-bus loading. This voltage droop affects the sizing of the downstream components. For example, if an inverter will be used for a motor control, achieving full power regardless of the ac input frequency and voltage variations requires a minimum	[redacted]

dc bus voltage analysis. This droop effect increases the sizing of the inverter components compared to the constant dc bus voltage regulation that can be achieved using active rectifiers.

B. Multi-pulse Transformer Rectifier Unit (TRU)

The typical choice is to use 12- or 18-pulse arrangement. The main advantage of the transformer is its capability of providing galvanic isolation. However, its weight, volume, and cost are significantly higher than those of autotransformers. The reason is that equivalent kVA of the transformer is larger than that of an autotransformer. Hence, more copper and iron is needed for the multi-pulse transformer-based. For aerospace application, galvanic isolation may or may not be required.

C. Multi-Pulse Autotransformer Rectifier Unit (ATRU)

If galvanic isolation is not needed, autotransformers become the natural choice for passive solutions for multi-pulse applications, i.e. 12-pulse or 18-pulse, due to weight, volume, and cost savings. More than i8-pulse can also be considered, but a larger number of diodes are needed. Isolated three-phase rectifier operation with 120-degree conduction of diodes can be achieved using interphase transformer (IPT) in the dc link. There are also ATRU topologies whereby the IPT can be eliminated by allowing the diodes to conduct shorter than 120 degrees, i.e. 40 degrees, for 18-pulse ATRU as shown in Fig. 1.

[redacted]

Fig. 1 18-pulse ATRU without interphase transformer in the dc link

[redacted]

This area of study is rich with opportunity to innovate new autotransformer winding topologies to minimize the equivalent kVA rating of the autotransformer to further minimize the weight, volume, and cost. The input power quality requirements, including normal and abnormal voltage transients and input frequency variations, should be carefully to be taken into account for proper sizing and design of the autotransformer. The other important factor is to trade off the efficiency with respect to size and weight. Cooling and minimizing the thermal impedance between between the autotransformer and mounting area is also another important factor to achieve minimum weight and volume.

III. ACTIVE AC-DC CONVERSION TOPOLOGIES FOR MORE ELECTRIC AIRCRAFT

A. Active Rectifier - Two Level

Active rectifier is a well-established pulse width modulation converter topology with three-phase AC input. This architecture is supported by many digital signal processors (DSPs) as a basic building block. If a motor controller will be incorporated into the design, the overall design effort can be minimized with synergies by designing both the rectifier and inverter stage with common hardware and software. This includes commonality on active semiconductor switches, diodes, gate drives, ac current measurements, protection, and interface with the DsP. some commonality is also utilized for software development because of the similar inner loop control design for

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current regulators and pulse width modulation.

six semiconductor switches and six anti-parallel diodes along with input filtering and ac inductance form the two-level active rectifier as shown in Fig. 2. The dc link requires a capacitor without forming a neutral point. Hence, having no neutral point connection of capacitors makes control easier than Vienna or other-multi level rectifiers.

Fig. 2 Schematics of active rectifier

The input ac current can be regulated using a sinusoidal reference current waveform. Typically, the terminal voltage of the active rectifier and input ac current can be controlled to achieve unity power factor for the optimum power generation and minimum able losses in the aircraft. The dc bus voltage typically can be regulated at a constant voltage with fast dynamic transient response. This requires a careful selection of modulation switching frequency of the active rectifier and controller bandwidth. Active damping can be eliminated to prevent any undesired resonances between the filters and the rest of the power distribution system. Two-level active rectifier can achieve bi-directional power flow via proper control. Hence, it can be used for aerospace applications where bi-directional power flow is needed. If this requirement is not needed, it is still an attractive choice due to the various advantages mentioned above.

B. Active Rectifier - Multi-level

Using a multi-level active rectifier is difficult to justify in aerospace applications due to the low ac voltage

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usage because of safety and corona issues. Three-level neutral point clamped topology can be considered if benefits can overcome the complexities and increased number of parts.

The three-level topology uses four active semiconductor switches, four anti-parallel diodes, and two clamping diodes per converter phase leg as shown in Fig. 3. The increase in active switches requires more gate drive circuits, more interface of the gate drive circuit to DSP, and more real estate for heatsink and cooling performance. More diode usage increases both the part counts and real estate usage for cooling, even though the current required by each diode is lower. An active control is needed to achieve a neutral point between the two diodes in the dc link.

The advantage of the three-level active rectifier is its ability to achieve three steps in phase-to-phase voltages. This feature minimizes the ac input current ripple. The other potential benefit can be reduction in EMI filtering. A three-level active rectifier is capable of bi-directional power flow.

Reference [4] illustrates that, with the assumptions made in the paper, the switching loss of a three-level converter is smaller than that that of a two-level converter, while conduction losses is higher in the three-level converter. The total loss appears to be lower for three-level converter. Hence, this benefit should be traded off with respect to

Fig. 3 Schematics of three-level active

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rectifier

C. Vienna Rectifier

The Vienna rectifier is a three-phase, three-level pulse width modulation converter [5]-[8]. A Vienna rectifier is formed by using one active semiconductor switch and six diodes per rectifier phase leg as shown in Fig. 4. The dc side uses two capacitors connected in a series, connected to the negative and positive rail of the dc bus. The connection point that is formed between the two capacitors needs to be controlled to achieve neutral point potential. Hence, additional control effort and complexity is needed to develop the Vienna rectifier for aerospace applications. Many aerospace applications require stringent software development guidelines as specified in DO-178B [9]. This additional complexity will require more software design, development, and verification and, hence, will increase the cost of development.

Fig. 4 Schematics of Vienna rectifier

A Vienna rectifier achieves uni-directional power flow, i.e. power flows from ac to dc side only, and is a boost converter topology with continuous input current. Typically, bi-directional power flow is not allowed for many aircraft applications so this attribute of the Vienna rectifier is not a limitation. The Vienna rectifier reduces the total number of active semiconductor switches from six to three of the two-level active rectifier topology. This reduction in switches translates into additional savings in the overall topology because less gate drives, less power supply outputs, less protection circuits, and less interface between the

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gate drives and the digital controls are needed. Moreover, the heat sink and cooling requirements can be reduced.

An additional advantage of the Vienna rectifier is that the dc bus cannot be shorted due to the failure of the active semiconductor switch, i.e. no shoot-through. Another major advantage is that the blocking voltage of the active semiconductor switch is reduced by a factor of two. The power factor can be regulated at unity [10]. All of these attributes of the Vienna rectifier can contribute to higher reliability for the ac-dc conversion. These benefits should be evaluated with respect to increased software development effort and increase in capacitor requirements.

D. Single Switch Three Phase Boost Rectifier

The boost function can be achieved with a three-phase diode bridge rectifier and a dc/dc boost converter connected in series [11]. However, the ac input current harmonics would be similar to that of a diode bridge rectifier, assuming that the dc/dc boost converter is operating in continuous conduction mode (CCM). This topology, as shown in Fig. 5a, will most likely not meet aerospace application requirements due to high ac input current harmonics.

(b)

Fig. 5 (a) CCM Single Switch Boost Topology, (b) DCM Single Switch Boost Topology

To improve the input current waveform, the dc link inductor can be moved to ac input side. In this case, the input current becomes discontinuous with a sinusoidal envelope [12]-[16].

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However, the fifth, seventh, eleventh, and thirteenth harmonics of the ac input current are high. This discontinuous current mode (DCM) single switch topology is shown in Fig. 5b. Various strategies were investigated to eliminate certain harmonics. The advantage of this topology is the use of only one active switch. However, in order to be adopted for aerospace applications, further study is needed with regards to EMI/EMC and power quality requirements with special attention to current harmonics compatibility. COMPARISON Comparison of various passive and active rectifier topologies are provided in Table II for some key properties. Active rectifiers are attractive from the perspective of achieving higher efficiency, unity power factor, and its potential to decrease weight and volume. Active solutions can also provide a constant dc link voltage at steady state as a function of loading, which prevents higher current rating and, hence, kVA rating of the downstream inverters for motor drives. Among the passive solutions, the autotransformer is the forerunner if galvanic isolation is not required. For active solutions, the Vienna rectifier and the two-level converter appear to be the most competitive candidates for aerospace applications. The two-level active rectifier is attractive to reduce the development and procurement cost if another two- level inverter would be used for motor drive because of commonality in hardware and software design. The Vienna rectifier is attractive from the perspective of simplicity and low switch part count. Hence, it can	[redacted]

offer higher reliability and potentially smaller weight and volume. The DCM single switch topology is attractive because it uses only one active switch, but further study is needed to understand its capabilities and compatibility for aerospace applications, particularly lowering the low frequency ac input current harmonic content. Hence, for this reason, it is not included in the Table II. Since many requirements such as power quality, EMI, cooling, and reliability change from one application to another, more detailed analysis is needed for the final decision on topology use.

V. FUTURE ADVANCES

A. Adaptation of SiC Technology

Many future advances in power electronic technology are explored by the industry to reduce the weight and volume while increasing the reliability of the power conversion systems in more electric aircraft. One significant development is to utilize silicon carbide (SiC) diodes to replace silicon diodes (Si PiN) when used with IGBTs. SiC diodes are majority carrier devices and, hence, offer almost zero reverse recovery current during turn-off [17]. This translates into considerably lower switching losses in the IGBTs. In [18], it is shown that SiC diodes reverse recovery current and time was reduced by a factor of six each. Similar savings in switching losses occur for the upper IGBT turn-on due to reduction in reverse recovery current of lower diode and vice versa. The total switching losses of the IGBT with SiC diodes can be reduced by 53% when compared to Si PiN based IGBT [18]. This translates into lower weight and volume power

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conversion for aerospace applications.

B. EMI Filters with High Switching Frequency

Another advancement can be achieved by exploring and understanding the impact of higher switching frequencies to the sizing of the EMI filtering. The EMI filtering can be formed by using differential and common mode filter capacitors and inductors both in the dc link and ac input. Increasing the switching frequency of active topologies can lower the weight and volume of these filters. However, increasing switching frequency also increases switching losses and other losses in EMI filter components, which impacts cooling. In [19], an optimum frequency concept is presented whereby a balance between reduction in filter sizing due to increased switching frequency and impact of increased switching losses to cooling and other important considerations are reviewed. Another area is to improve EMI filtering and increase power density by making topological changes in the power electronic circuitry. For example, additional paths can be added to circulate or limit the common-mode emission internal to the unit. In [20], the center point of the dc link capacitors of the Vienna rectifier is tied to an artificially created mains star point where the common mode currents as seen by the input of the unit are reduced significantly.

VI. CONCLUSIONS

Various advances in active and passive rectifier topologies have been reviewed

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for more electric aircraft applications. Aerospace applications require a low-weight, low-volume, more efficient, highly reliable rectification system. Passive rectification is reliable and can potentially decrease recurring and non-recurring costs. Active rectifiers are attractive from the perspective of achieving higher efficiency, unity power factor, and its potential to decrease weight and volume. For active solutions, the Vienna rectifier and the two-level converter appear to be the most competitive candidates for aerospace applications. The DCM single switch topology is attractive because it uses only one active switch, but further study is needed to understand its capabilities and compatibility for aerospace applications, particularly lowering the low frequency ac input current harmonic content. The area of rectification in the field of power electronics is very rich, growing, and open to new innovations. Especially, advances in various technologies including new active switch technologies can achieve higher densities that have never been achieved before; for example, the incorporation of SiC diodes into power semiconductor switches increases switching frequencies, and can potentially achieve smaller EMI filters, new compact cooling, and packaging techniques. Hence, checking each power electronic topology for its attractiveness with the new technological advances frequently is a prudent exercise towards achieving the optimum solution for more electric aircraft applications.	[redacted]

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