Modelling and analysis of vienna rectifier for more electric aircraft applications using wide band-gap materials

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Abstract. This paper presents a comprehensive study on the switching effects of wide bandgap devices and the importance of power electronics in an aircraft application. Silicon (Si), silicon carbide (SiC), and gallium nitride (GaN) are wide bandgap devices that act as a power electronic switch in the AC-DC converter for More Electric Aircraft (MEA) applications. Therefore, it is important to observe their converting efficiency to identify the most suitable wide bandgap device among three devices for AC-DC converters in aircraft applications to provide high efficiency and high-power density. In this study, the characteristics of Si, SiC, and GaN devices are simulated using PSIM software. Also, this paper presents the performance of the Vienna rectifier for aircraft application. The Vienna rectifier using Si, SiC, and GaN devices are simulated using PSIM software for aircraft application. GaN with Vienna rectifier provides better performance than Si and SiC devices for aircraft applications among the three devices. It gives high efficiency, high power density, low input current THD to meet IEEE-519 standard, and high-power factor at mains.

1. Introduction
The trend of MEA has become more and more sought-after in the aviation transport industry for the past few years due to the rising issue of climate change. The transport industry produces a whopping 29% of total carbon emissions and is ranked the highest among other sectors in the whole US alone in 2018 [1-3]. As a result of the desire to optimize the performance of the aircraft industry, reduce fuel consumption, and most importantly, reduce greenhouse gas emission, the aviation industry is gradually but steadily moving towards the concept of More Electric Aircraft (MEA) and eventually towards fully electric propulsion [4]. Moreover, MEA is the future of transportation as the technology of sustainable system development.

With the goal of electric propulsion aircraft, the emerging technology removes the aircraft's conventional functional system, heavily relying on hydraulic and pneumatic systems, and changes into an electrical generation and distribution system. However, with existing technology of electrical storage systems such as a battery, the removal of Internal Combustion Engine (ICE) and replacement with the electric motor could not be accomplished due to the energy density of batteries, which is extremely low.
compared to the fossil fuel [5]. Therefore, a Hybrid Electric Propulsion System (HEPS) system consists of both electrical motors and an ICE system. Hence, the HEPS introduces electric motors that utilize the high efficiency of the electrical system and reduce the reliance on ICE to reduce carbon emissions [6].

For electrical systems to function, various power electronic converters play a significant role in the MEA system. The electrical system uses power electronic converters such as AC-DC converter/rectifier, DC-DC converter, and DC-AC converter. This paper mainly focuses on the AC-DC converter. The power electronic converters are used in various industries, including wind power, MEA, electric train, electric cars, EV charging station, welding, solar panel, power factor corrector, and data center. Among different converters for the various applications, the Vienna rectifier provides better performance in terms of input current THD less than 5%, unity power factor at mains, high power density, high efficiency, and low construction cost in building compared to the conventional electric aircraft AC-DC converter. In this research work, the Vienna rectifier is studied and simulated for aircraft application [7-10].

In power electronics, silicon has been adopted as the mainstream technology as silicon diodes, power semiconductor switches over the past few decades. However, with the newly emerging technology of gallium nitride that has a wider bandgap, higher electron mobility, and better saturation electron drift velocity, it is promising that the implementation of gallium nitride will boost the functionality of semiconductor devices [11, 12]. The properties comparison between the three different wide bandgap devices is shown in Table 1.

|                      | Si   | SiC-4H | GaN |
|----------------------|------|--------|-----|
| Bandgap (eV)         | 1.1  | 3.2    | 3.4 |
| Electron mobility $\mu_n$ ($\text{cm}^2/\text{V s}$) | 1450 | 900    | 2000|
| Breakdown Electric Field $E_{br}$ (MV/cm) | 0.3  | 3      | 3.5 |
| Saturation electron drift velocity $V_s$ ($10^7$ cm/sec) | 1    | 2.2    | 2.5 |
| Thermal conductivity (W/cm K) | 1.5  | 3.8    | 1.3 |

Although gallium nitride technology is relatively new in this industry, it is still subjected to deep investigations and study due to its superior performance. The electrical power system with 270 V DC supply and 230 V AC supply is shown in Figure 1 and Figure 2.

![Figure 1. Electrical power system with primary 270V DC](image-url)
Though an AC-DC rectifier is inevitable, an EPS with a primary 270V DC system operates with less ac-dc rectifier and lower weight for the whole system [14]. Hence, this study focus on the AC-DC rectifier EPS with primary 230V AC. Fig. 2 shows the electrical power system for airbus B787, a hybrid aircraft that runs on EPS and fossil fuel. Based on Fig. 2, 3 buses with the primary bus are 230V AC, 115V AC on the secondary bus and 270V DC on the High Voltage DC (HVDC) bus, and finally 28V DC bus.

2. Research Methodology

In this research, the study on characteristics of three wide bandgap devices is conducted by simulation of silicon (Si), silicon carbide (SiC), and gallium nitride (GaN) using PSIM simulation software. The characteristics of three devices, such as power loss, switching loss, and converter efficiency, are calculated. The comparison is made between the simulation data and the physical experimental data. Also, the most suitable device for aircraft application is identified based on the performance of three WBG devices proposed for the power semiconductor device in an AC-DC converter.

Furthermore, the simulation of Vienna rectifier with Si, SiC, or GaN devices is conducted using PSIM simulation software for aircraft applications. The three primary characteristics, power loss, switching loss, and converter efficiency, have been calculated and compared for the WBG devices. Figure 3 shows the block diagram of the research methodology.
3. Simulation and Results

3.1 Simulation of Wide Bandgap Devices using PSIM software

The three wide-bandgap devices, such as silicon (Si), silicon carbide (SiC), and gallium nitride (GaN), are simulated using PSIM software.

3.1.1 Silicon MOSFET

The characteristics of SiC devices are simulated using PSIM software and are shown in Figure 4. Figure 5 shows the switching operation of the devices, and the single switching phase of turn-on and turn-off operation of the Si device is shown in Figure 6 and Figure 7.
Figure 4. Simulation of silicon MOSFET using PSIM software

Figure 5. Simulation of silicon MOSFET using PSIM software (Drain current and Drain to Source voltage).

Figure 6. Silicon MOSFET turn-on period
3.1.2 Silicon Carbide MOSFET

The characteristics of SiC devices are simulated using PSIM software and are shown in Figure 8. Figure 9 shows the switching operation of the devices, and the single switching phase of turn-on and turn-off operation of the SiC device is shown in Figure 10 and Figure 11.
3.1.3 Gallium Nitride MOSFET
The characteristics of GaN devices are simulated using PSIM software and are shown in Figure 12. Figure 13 shows the switching operation of the devices, and the single switching phase of turn-on and turn-off operation of the GaN device is shown in Figure 14 and Figure 15.

Figure 10. Silicon Carbide MOSFET turn-on period

Figure 11. Silicon Carbide MOSFET turn-off period

Figure 12. Simulation of gallium nitride MOSFET using PSIM software
Figure 13. Simulation of gallium nitride MOSFET using PSIM software (Drain current and Drain to Source voltage).

Figure 14. Gallium Nitride MOSFET turn-on period

Figure 15. Gallium Nitride MOSFET turn-off period
### 3.2 Discussion and mathematical calculation

Based on the simulation results shown above, several key-values such as the time taken for the MOSFET to turn on ($T_{on}$), time taken for the voltage to drop ($T_{off}$), forward diode resistor value ($R_{DS}$), duty cycle ($D$), and switching frequency ($F_{sw}$) is extracted, and mathematical calculations have been made in order to compare three WBG devices. The mathematical formulas that are used to calculate the conduction loss ($P_{cond}$), power loss during turn on ($P_{on}$), and power loss during turn off ($P_{off}$) are shown in Equation (1) to Equation (5):

\[
\begin{align*}
    P_{cond} &= I_{D(on)}^2 R_{DS(on)} D \\
    E_{on} &= I_{D(on)} V_{DD} T_{on} \frac{1}{2} \\
    P_{on} &= E_{on} F_{sw} \\
    E_{off} &= I_{D(on)} V_{DD} T_{off} \frac{1}{2} \\
    P_{off} &= E_{off} F_{sw}
\end{align*}
\]

Subsequently, the efficiency is calculated using the formula stated below.

\[
\text{Efficiency(\%)} = \frac{\text{input power} - \text{total power loss}}{\text{input power}}
\]

**Table 2. Loss and efficiency calculation [15]**

| Parameters | Duty cycle | Conduction loss | Switching loss (on) | Switching loss (off) | Total power loss | Efficiency |
|------------|------------|-----------------|---------------------|---------------------|-----------------|------------|
| Si         | 0.5        | 1107W           | 1.2mW               | 0.6344mW            | 1107.0018W      | 88.2%      |
| SiC        | 0.5        | 1022W           | 4.83mW              | 3.21mW              | 1022.008W       | 89.1%      |
| GaN        | 0.5        | 431W            | 1.1mW               | 1.88mW              | 431.0029W       | 95.4%      |

Therefore, from the simulation results, it is confirmed that GaN has high efficiency than Si and SiC devices, which counterparts as the simulation results show that the GaN has less power loss among the WBG devices, and it has the highest efficiency. Section 3.3 discusses the study on the most suitable energy-efficient AC-DC converter design for MEA application.

### 3.3 Simulation of Vienna rectifier using PSIM software

The Vienna rectifier based on GaN devices is simulated using the PSIM software, as shown in Fig. 16. The input current, output current, and output voltage are plotted. The main objective is to identify the suitable WBG device for the Vienna rectifier to improve the system's performance, such as efficiency and power density for the aircraft application [16].

Figure 17 shows that the Vienna rectifier can produce an output voltage of 400V DC, which meets the basic requirement for aircraft application. In this study, three WBG devices of the MOSFETs are simulated for the resistive load of 10 ohms. The THD values of all three WBG devices of the MOSFETs with Si, SiC, and GaN are shown in Figure 18, Figure 19, and Figure 20, respectively. Among three devices, GaN device-based Vienna rectifier produces better input current THD and power factor at mains than Si and SiC devices-based Vienna rectifier.
Figure 16. The simulation of the Vienna rectifier using the PSIM software.

Figure 17. DC output voltage
Figure 18. Input current of the Si MOSFET

Figure 19. Input current of the SiC MOSFET
4. Conclusion
In this study, the wide bandgap devices that such as silicon (Si), silicon carbide (SiC), and gallium nitride (GaN) have been studied and simulated using PSIM software. Among three different power semiconductor devices, it has been concluded from the simulation that the gallium nitride (GaN) device is the most suitable WBG device for aircraft application as it has superior performance of high efficiency, high switching frequency, and low power loss. On the other hand, the Vienna rectifier has been selected as the AC-DC rectifier for the aircraft application as it has high power density, high efficiency, low input current THD. Further, the Vienna rectifier based on GaN device is simulated using PSIM software for the aircraft application. The Vienna rectifier provides input current THD of less than 5%, which meets IEEE-519 standards, and 400 V DC output voltage required by the aircraft application.

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