Advances in Electrical, Electronics, and Communication Engineering: Applications in Defense and Energy Systems

Editor Nevin Aydın

BIDGE Publications

Advances in Electrical, Electronics, and Communication Engineering: Applications in Defense and Energy Systems

Editor: Prof. Dr. Nevin Aydın

ISBN: 978-625-372-568-6

Page Layout: Gözde YÜCEL 1st Edition: Publication Date: 25.12.2024 BIDGE Publications,

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Güzeltepe Mahallesi Abidin Daver Sokak Sefer Apartmanı No: 7/9 Çankaya / Ankara



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CHAPTER I

Uninterrupted Protection for Military Vehicles with Next Generation Fire Suppression System

Mehmet Yavuz¹ Ali Üzer²

1. Introduction

Military ground vehicles operate in highly challenging environments where the risk of fire is a critical concern. Fires can originate from various sources such as fuel leaks, electrical faults or external threats like explosives or projectiles. Depending on the operational context, fires may occur in several parts of the vehicle including the crew compartment, engine bay, auxiliary power unit (APU) compartments, vehicle body or even tires. These fires, if not promptly and effectively addressed, can compromise the safety of

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personnel, endanger mission success and result in significant financial losses.

To mitigate these risks, Automatic Fire Detection and Suppression Systems (AFDSS) are employed in military vehicles. Designed and tested in compliance with NATO's STANAG-4317 standards, these systems ensure rapid detection and suppression of fires across different threat levels. The STANAG-4317 categorizes fire hazards into fife levels each with specific protection requirements.

1.1 Fire Levels and Protection Requirements

1.1.1 Level 0 (No Protection Required)

This level involves no protective equipment and serves only as a reference for environments where fire risks are negligible.

1.1.2 Level 1 (Very Slow Developing Fire)

Fires take over 10 seconds or minutes to develop. In such scenarios, personnel can evacuate the vehicle and extinguish the fire manually.

1.1.3 Level 2 (Slow Developing Fire)

Fires develop within a few seconds (up to 10 seconds). Although sensors are not mandatory, personnel must visually detect and respond manually.

1.1.4 Level 3 (Fast Developing Fire)

Fires ignite and spread within one second to a few seconds. Manual response is impractical, necessitating the use of onboard sensors for detection.

1.1.5 Level 4 (Explosion or Flash Fire)

Fires occur within milliseconds, leaving no time for manual intervention. Systems must detect fires in 3 milliseconds and suppress them within 250 milliseconds to prevent life threatening third degree burns and fatalities.

1.2 Protecting High-Tech Systems

The presence of high-tech systems such as radars, antennas, transmitters and weapon systems in military vehicles further underscores the importance of robust fire suppression solutions. These components, critical for operational effectiveness, are both high value and indispensable. Damage to such systems can disrupt communications, compromise situational awareness and hinder the ability to engage targets effectively. Additionally, their high acquisition and maintenance costs make fire protection an economic imperative.

AFDSS systems are tailored to the vehicle's configuration, with fire suppression mechanisms strategically placed to protect key areas based on the identified threat levels. For instance, in the event of a Level 4 fire in the crew compartment, the system must act within milliseconds to safeguard personnel while in the engine bay or APU compartments, the focus is on preserving equipment functionality and avoiding secondary damage.

Through the integration of advanced detection technologies and rapid suppression mechanisms, AFDSS ensures not only the safety of the vehicle and its occupants but also the operational continuity and economic efficiency of military missions. As threats evolve and the complexity of military systems increases our proposed AFDSS remains a critical enabler of mission success and vehicle survivability.

2. Methodology

2.1 Defining System Configuration and Design Based on Customer Requirements

In military land vehicles, the placement of Automatic Fire Suppression Systems (AFSS) is tailored to the vehicle configuration and the specific requirements outlined by the customer. This phase is critical to ensuring an optimal system design and solution that addresses potential fire risks in various compartments.

AFSS can be configured to protect key areas such as the driver's cabin, engine and transmission compartments, tires, fuel tanks and auxiliary systems like onboard generators. Each system is adapted to the customer's needs and the specific fire threat levels associated with each compartment. Following a thorough evaluation, suitable equipment is selected for each area to create a comprehensive system configuration that meets operational and safety demands. Key considerations for each protected compartment include:

Driver's Cabin: Ensuring the safety of military personnel is the top priority. Rapid detection and suppression mechanisms are selected to safeguard lives in the event of a fire.

Fuel Tanks and Power Units: Given their technical characteristics and potential hazards, detection and suppression systems are chosen for maximum efficiency in preventing or containing fires.

Engine and Transmission Areas: These high risk zones require robust sensors and suppression agents capable of managing heat and flammable materials.

Tires and Auxiliary Systems: Specialized solutions are implemented to address unique risks such as overheating or mechanical failure that could lead to fires.

By systematically assessing fire risks and incorporating customer preferences, the AFSS configuration ensures not only compliance with safety standards but also enhanced protection and operational reliability. (Firetrace International, 2019) This customized approach guarantees that each vehicle system is equipped to handle its specific fire suppression challenges effectively.

2.2 Detection of Fires and Selection of Appropriate Sensors

The rapid detection of fires is essential for ensuring the safety of military vehicles and their occupants. To achieve this, infrared (IR) and ultraviolet (UV) sensors are commonly employed as they can swiftly identify flames and trigger the activation of fire suppression agents. (Figure.1) The sensitivity of these sensors may vary depending on factors such as flame brightness, temperature or smoke density that allow effective detection under diverse conditions. (Khan & ark., 2022)

Explosion suppression systems use advanced detectors to continuously monitor areas at risk of fire or explosion. These detectors activate alarm and intervention mechanisms to either prevent explosions or mitigate their effects. By maintaining oversight of high risk zones, these systems significantly reduce fire and explosion risks. In military vehicles, such detectors play a vital role by identifying fires at an early stage which enable rapid intervention to minimize damage to the vehicle by ensure the safety of passengers and protect the payload.

The integration of UV-IR control detectors in explosion suppression systems enhances functionality by eliminating the need for a separate control unit. These detectors communicate directly with the vehicle's central computer using a CANBUS communication infrastructure. Through this system, errors, alarms, and activation statuses are reported seamlessly to the vehicle's main computer.



Figure.1 How UV, IR Detectors Work

UV-IR control detectors offer the capability to monitor up to two separate fire prone compartments. They utilize the electromagnetic spectrum in the UV/IR range for simultaneous radiation detection by generating an alarm output signal upon identifying fire related radiation. (AZoSensors, 2019) Importantly, these detectors are designed to distinguish non-fire related radiation sources such as sunlight or artificial light and filter them out to prevent false alarms.

The detectors are equipped with UV and IR sensors capable of identifying hydrocarbon fire emissions. With a response time of less than 3 milliseconds. They rapidly transmit feedback to the corresponding system for immediate action. This quick reaction capability ensures that the system can effectively suppress fires or explosions before significant damage occurs.

2.2.1 False Alarm Resistance

UV-IR control detectors are engineered to resist false alarms from various non-fire related light sources. Table.1 outlines the thresholds for different light sources for ensuring the detectors react only to genuine fire threats.

Light Source Type	Distance to Detector
Sunlight (direct illumination)	Direct illumination
Intermittent sunlight (direct)	Direct illumination
Burning cigarette or cigar	5 cm
Lighter flame (2 cm high)	10 cm
Burning match	20 cm
Vehicle lighting (any type or power)	Any distance
Photographic flash	45 cm
Arc flash from a 4 mm source at 300A	150 cm
Acetylene flame (16 mm diameter, 130 mm length)	150 cm
Muzzle flash	150 cm
Bright clothing (red or safety orange)	Any distance

Table.1 False Light Sources for UV-IR Detector

Reference: (Cahill, 2013)

By adhering to these parameters, UV-IR control detectors ensure reliable operation without being triggered by non-hazardous sources. This robustness, combined with their rapid detection and response capabilities makes them indispensable for military vehicles in terms of safeguarding critical systems and personnel during operations

2.3 Fire Suppression in Targeted Areas

The extinguishing agent used in fire suppression systems varies depending on the type of fire and the operational environment. In military vehicles, halocarbon based agents and dry chemicals are commonly preferred due to their effectiveness and adaptability. Halocarbon agents work by rapidly evaporating to isolate the fire from oxygen while providing efficient cooling. On the other hand, dry chemical agents, create a protective barrier that halts the chemical reactions driving the fire.

A key design consideration in military vehicles is the efficient use of internal space. For explosion suppression systems, the placement of extinguishing agent cylinders is critical for optimal suppression performance. (Figure.2) The agent is directly discharged from the cylinder into the surrounding environment, making the precise positioning of these cylinders essential for effective coverage and minimal delay in response. (Chang, 2023)



Figure.2 Sample Fire Suppression Equipment

Aerosol Suppressors are particularly effective in enclosed spaces, designed to neutralize Class A (solid fuel), Class B (liquid fuel), Class C (gas fuel) and Class E (electrical) fires. After determining the required concentration of the suppressant for each fire type and protected area, the quantity of suppressant and the number of cylinders are calculated accordingly. Aerosol suppressors are compatible with standard detectors and control units and can be installed directly within the protected compartments. (Jones, 2021)

Upon fire detection by thermal sensors or activators, aerosol suppressors act swiftly to contain and extinguish the fire. Their lightweight and compact design allows for easy installation and quick replacement which make them highly versatile and suitable for integration into various applications. (Kidde Technologies, 2024)

The extinguishing agents used in explosion suppression systems employ a combination of chemical and physical mechanisms to suppress fires effectively. These mechanisms aim to halt fire propagation in order to reduce oxygen levels and inhibit chemical reactions. Common extinguishing gases used in defense industry systems include halocarbons, inert gases and other specialized compounds, as outlined in the Table.2

Agent	Minimum design concentration n-heptane (Class B) fires [Vol-%]	NOAEL [Vol-%]	LOAEL [Vol-%]	GWP 100yr	ODP
CF₃I	4.2	0,2	0,4	5	<<1
CO ₂	36	0,5	~4	1	0
FK-5-1- 12	5.9	10	> 10	1	0
HFC 125	11.3	7,5	10	3400	0
HFC 227 ea	8.7		10,5	3500	0
HFC 236 fa	8.3	10	15	9400	0
N ₂	43.7	42.8	52.3	0	0
Halon 1301	5.0	5,0	7,5	6900	10
Halon 1211	5.0	0,5	1,0	1300	3

Table.2 Common Extinguishing Gases in Military Vehicles

Reference: (NATO, 2017)

By tailoring the extinguishing agent and system configuration to the specific risks and areas to be protected, military vehicle fire suppression systems ensure maximum safety, operational reliability, and asset protection. (Peters, 2021)

2.4 Applications in the Defense Industry

Fire suppression systems in the defense industry are employed across various platforms, tailored to operate under specific environmental conditions and performance requirements. Some notable application areas as follows.

2.4.1 Military Vehicles and Armored Transport

Military vehicles are at high risk of internal fires during operations, necessitating swift detection and response mechanisms. For instance, fires in the engine compartments or crew sections of tanks must be extinguished within milliseconds to prevent catastrophic damage and ensure crew safety. (Variex, 2022) Automated fire suppression systems in these vehicles are designed to handle such rapid and critical scenarios effectively. (Figure.3)



Figure.3 Military Vehicle Application of AFDSS

2.4.2 Ammunition Depots and Armories

A fire in ammunition storage facilities poses an immense risk of explosion. To mitigate this, automatic fire suppression systems are installed to activate immediately upon fire detection. These systems often integrate multi sensor detection technology and rapid response discharge mechanisms to neutralize fire threats in their early stages for preventing widespread destruction. (Smith, 2019)

2.4.3 Naval Platforms: Military Ships and Submarines

For naval forces, fire presents a significant hazard due to the enclosed and isolated nature of ship and submarine environments. Automatic fire suppression systems for these platforms are engineered to control fires effectively in confined spaces. They are designed to withstand harsh maritime conditions and use environmentally conscious extinguishing agents that minimize ecological impact while ensuring operational efficiency.

2.4.5 Aircraft and Aviation Platforms

In aviation, fire suppression systems must comply with stringent aerospace standards to protect critical components like engines, auxiliary power units (APUs) and secondary fire zones. These systems are tailored to aviation specific needs, providing rapid and reliable fire protection to ensure the safety of personnel and equipment during flight and on the ground.

By addressing the unique fire risks associated with each defense platform these systems play a pivotal role in maintaining operational integrity, safeguarding personnel and protecting valuable assets in diverse and challenging environments.

2.5 Military Standards for Performance and Testing Requirements

The performance and testing requirements for automatic fire suppression systems in the defense industry are governed by standards established by NATO and the U.S. Department of Defense. These standards ensure the operational capability and durability of the systems under various conditions.

2.5.1 STANAG 4317

This NATO standard defines the performance criteria for fire suppression systems used in military vehicles. Key requirements include the effectiveness of the suppression agent within a maximum of 3 seconds after fire detection. The standard also considers environmental factors such as temperature and humidity to ensure system reliability under diverse operational conditions. (NATO, 2017)

2.5.2 MIL-PRF-62546

This U.S. military standard outlines durability and reliability requirements for fire suppression systems. It mandates that the systems maintain consistent performance over extended periods and withstand extreme environmental conditions. Additionally, MIL-PRF-62546 emphasizes the need for suppression agents to be nontoxic and environmentally safe for ensuring both human safety and ecological protection. (ABD Savunma Bakanlığı, 2019)

Adhering to these standards is crucial for developing fire suppression systems capable of meeting the rigorous demands of military operations while ensuring the safety of personnel and equipment.

2.6 Advantages of the Proposed System Over Existing Solutions

Conventional Automatic Fire Suppression Systems (AFSS) typically draw the required energy directly from the vehicle's battery. When the vehicle is not operational, this continuous energy consumption can drain the battery, negatively impacting the

vehicle's ability to start and the performance of other onboard systems. Additionally, in cases where the system is linked to the vehicle's ignition signal, it only activates when the vehicle is running, leaving the vehicle unprotected during idle periods. (Awarefire, 2024)

The proposed system addresses these limitations by incorporating an auxiliary battery. (Figure.4) This design ensures that the system remains operational even when the vehicle is turned off. When the vehicle is running, the system draws power from the vehicle's battery but it switches to the auxiliary battery when the vehicle is inactive. This feature provides continuous protection, safeguarding the vehicle's critical and high value systems even when the vehicle is not running and personnel are not nearby.



Figure.4 Proposed AFDSS in Defence Industry

This enhanced capability ensures round the clock protection, making the proposed system a superior solution for military vehicles for sensitive and expensive equipment. Furthermore, one of the key features of the proposed system is its rapid response time, which meets the Level 4 fire protection requirements. The system detects fires within just 3 milliseconds and suppresses them in under 250 milliseconds. This high speed detection and suppression ensure life-saving response times and prevent the escalation of damage. This capability is crucial for military vehicles where quick intervention is essential to prevent catastrophic failure and protect both personnel and equipment.

3. Conclusion

The proposed Automatic Fire Suppression System (AFSS) represents a paradigm shift in fire safety technology for military vehicles by addressing critical gaps in traditional systems. With integrating an auxiliary battery, the system ensures uninterrupted protection even during vehicle downtime or when personnel are absent. This innovation not only safeguards sensitive and high value equipment but also enhances overall vehicle survivability.

Meeting Level 4 fire protection requirements, the system's rapid detection within 3 milliseconds and suppression in under 250 milliseconds provide life-saving response times and mitigate damage escalation. This advanced performance is particularly vital in high risk environments where even milliseconds can determine the difference between mission success and catastrophic failure.

Additionally, the proposed system demonstrates exceptional versatility by incorporating technological sensors, tailored configurations and environmentally conscious extinguishing agents. Its ability to comply with stringent military standards which include STANAG 4317 and MIL-PRF-62546 that ensures reliability and effectiveness across diverse operational scenarios.

In conclusion, the proposed AFSS offers a comprehensive solution that prioritizes personnel safety, asset protection and operational continuity. Its advanced capabilities and robust design set a new benchmark for fire suppression in military vehicles, solidifying its role as a critical enabler of mission success in demanding and hazardous environments.

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CHAPTER II

Preventing Hazardous Gas Intrusion in Missile Launch Vehicles Using Positive Pressurization

Mehmet Yavuz³ Ali Üzer⁴

1. Introduction

Military missile launch operations generate substantial amounts of exhaust gases, which can be extremely hazardous when inhaled by personnel. In environments where vehicles are required to operate in close proximity to missile launches, there is a significant need for protection from these toxic gases. Existing solutions often involve the use of CBRN filtration systems designed to filter out harmful chemicals and particles from the air before they enter the cabin. However, these systems have several drawbacks.

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They are expensive, require regular maintenance and filter replacements, and add complexity to vehicle configurations due to the large number of components involved.

Current CBRN filtration systems employed in military vehicles provide reliable protection against toxic chemicals but the operational costs and frequent filter changes make them less efficient for prolonged use in high exposure environments. (Akyıldız & Demir, 2019) Moreover, the filters have limited operational lifespans and must be replaced regularly, further increasing the long term costs associated with these systems.

The system proposed in this paper represents a shift from filtration based protection to a pressure based approach. By maintaining a higher pressure inside the vehicle cabin than the surrounding atmosphere, the positive pressurization system prevents hazardous gases from entering the vehicle. This system offers several key advantages over traditional CBRN filtration systems, including lower costs, fewer configuration elements and reduced maintenance needs.



Figure.1 Missile Launching Sample

2. Conceptual Framework

The positive pressurization system operates by creating a pressure differential between the vehicle cabin and the outside environment. Pressurized air tanks that filled with clean air are integrated into the vehicle and connected to a solenoid valve which is controlled by the operator. When activated, the system releases clean, pressurized air into the cabin and creating a pressure higher than the external environment. This pressure difference ensures that harmful gases cannot enter the cabin during missile launches or other hazardous operations.

Compared to existing CBRN filtration systems, the pressurization system has several distinct advantages. First, it eliminates the need for expensive and short lived filters. CBRN filters are both costly and have a short operational lifespan, leading to frequent replacements during extended military operations

(Yıldırım, 2021) This makes the proposed system more sustainable over long periods of use. Additionally, the pressurization system simplifies vehicle design by requiring fewer components. Thereby reducing the overall weight and complexity of the vehicle.

In contrast to traditional systems, which require complex air filtration processes, the positive pressurization system relies on a straightforward mechanical principle maintaining a higher pressure than the external environment. This simplicity translates into reduced maintenance requirements and less downtime for filter changes or system recalibration.

3. Methodology

The testing of the positive pressurization system was conducted in a simulated missile launch environment to evaluate its effectiveness under realistic conditions. The objective was to measure the system's ability to maintain a consistent pressure differential and prevent gas infiltration during a simulated missile launch.

3.1 System Design and Components

The positive pressurization system is designed to operate with minimal power requirements which makes it more efficient and simpler than traditional systems. It operates on standard 24 VDC and consists of components such as relays, check valves, push buttons, air tanks and solenoid valves. Since the system draws power directly from the vehicle's battery group. External power source is not required, which gives it a significant advantage over existing CBRN filtration systems. The total power consumption of the system is very low so it is more sustainable and reducing the overall operational costs. This system's low energy consumption and the absence of the need for additional power sources make it highly suitable for long term operations in military environments, where simplicity and reliability are critical. Furthermore, this system can be easily adapted to different configurations by considering the cabin capacity of the prototype vehicle, its usage scenarios and the duration of hazardous gas retention around the vehicle. All these factors are evaluated to determine the capacity of the air tank and to decide on the system's optimal operating pressure. (Smith, 2018)



Figure.2 Positive Pressurization System Layout

Number	Component	Function	Technical Specifications	Explanation
1	Air Tank	Stores pressurized clean air	0-10 bar	Supplies clean air for pressurization
2	Manometer	Monitors system pressure	0-10 bar	Allows visual monitoring of air pressure
3	On/Off Button	Turns the system on/off	24 VDC	General system control
3	Positive Pressure Button	Activates positive pressurization	24 VDC	Pumps clean air into the cabin
3	Tank Refill Button	Refills air tanks with fresh air	24 VDC	Refill of air tanks after launch
4	Air Line		NA	
5	Check Valve (One- way)	Ensures unidirectional air flow	0-10 bar	Prevents backflow of air

Tablo.1 Sample Configuration List Part A

Number	Component	Function	Technical Specifications	Explanation
6	Solenoid Valve	Starts/stops air flow	24 VDC, 0-10 bar	Used for positive pressurization
7	Pressure Regulator	Adjust the air pressure	Adjustable, 0- 10 bar	Can be set to the required pressure
8	24 VDC Relay	Control the electrical circuit	24 VDC	Powered from the vehicle battery
9	Vehicle Compressor	Supply pressurized clean air	8-12 bar	

Tablo.1 Sample Configuration List Part B

3.2 Pre Test Preparations

Before testing, the vehicle's pressurized air tanks were filled with clean air. Pressure sensors were installed inside and outside the cabin to monitor the pressure differential in real time. Additionally, simulated hazardous gases, representative of missile exhaust, were released near the cabin during the launch sequence.

3.3 System Operation

The required pressurized air is sourced from the vehicle's compressor. When the positive pressurization system is active, prepressurized clean air is stored in tanks to avoid contamination from external toxic gases. The air pressure can be regulated to the desired level using a pressure regulator with the system pressure monitored via a manometer. To facilitate operation within the cabin, three control buttons are provided. The On/Off button activates the system and conducts a general system check. Upon pressing the positive pressurization button the system releases air at the regulated pressure into the cabin that create positive internal pressure. This pressure generates an airflow from the cabin to the outside which prevents harmful gases from entering during missile launches. Once the launch operation is complete and harmful gases have dissipated, the air tanks can be replenished with fresh air using the tank filling button. The duration of positive pressurized air supply can be extended to desired levels by managing the capacity of the air tanks. (Koluman Otomotiv Endüstri Anonim Şirketi, 2021)

This operational mechanism is further illustrated in the accompanying system diagram which visually depicts the flow of clean and pressurized air into the cabin, the components involved, and the air regulation processes. (Figure.2) The diagram serves to enhance understanding of the system's functionality and the principles underlying its operation.

3.4 System Activation

The system was activated under two operational scenarios. In the first scenario, the operator was inside the vehicle and manually activated the pressurization system by pressing the control button which opened the solenoid valve to release clean air into the cabin. In the second scenario, the operator was located remotely and the system was triggered automatically by an electrical signal from the launch unit.

3.5 Pressure Monitoring

Throughout the tests, pressure sensors continuously monitored the internal and external pressures to ensure that the internal cabin pressure remained higher than the atmospheric pressure. (Demirbaş, 2020) This differential is critical to preventing the infiltration of hazardous gases. Data collected from these sensors were used to evaluate the system's performance in both manual and remote activation scenarios. (Thompson & Lee, 2022)

3.6 Gas Intrusion Tests

Simulated missile exhaust gases were released around the vehicle during the launch sequence to assess the system's ability to block gas infiltration. Air quality sensors inside the cabin measured any changes in gas concentrations with the goal of maintaining zero gas intrusion.

3.7 Data Analysis

The primary data points analyzed, included the time required to establish the pressure differential, the consistency of the pressure maintained, and the effectiveness of gas prevention. The system consistently maintained a positive pressure inside the cabin for preventing hazardous gas infiltration under both operational scenarios. This performance was compared to vehicles equipped with traditional CBRN filtration systems which showed minor gas leakage due to filter limitations.

3.8 Future Prospects and Potential Solutions

The development of positive pressurization systems and hazardous gas prevention technologies in the future will enhance their effectiveness and usability. The following areas for improvement and potential solutions can be considered.

3.8.1 Hybrid Solutions with Advanced Filtration

Combining positive pressurization system with advanced filtration technologies can address cost and efficiency concerns. For instance, while the positive pressurization system prevents the majority of hazardous gases, minimal intrusion can be managed using cost effective filtration. (Turaga & ark., 2012)



Figure.3 FT-90 Positive Pressure Filtration System

The FT-90 Positive Pressure Filtration System is designed to maintain a safe and controlled environment within military and high risk vehicles by providing continuous positive pressure, preventing hazardous gases, dust and contaminants from infiltrating the vehicle's cabin. This system is essential in applications such as missile launch vehicles, armored military vehicles and other defense platforms where personnel safety from chemical, biological, radiological and nuclear (CBRN) threats is a priority. (NERO Endüstri, 2023)

3.8.2 Remote Control Capabilities

Remote control functionalities and autonomous operation can enhance operational safety.

3.8.2.1 Automatic Activation

The system can automatically engage during missile launch operations.

3.8.2.2 Remote Monitoring and Control

Operators can manage the system from a safe distance and once the risk has been mitigated, the operator can intervene as needed to carry out maintenance or other operational tasks safely.

3.8.3 Integration of Smart Systems

The integration of sensor and upcoming technologies and artificial intelligence (AI) algorithms can make the system more adaptive and intelligent. (Kegyes, Süle, & Abonyi, 2024)

Real-time analysis of air quality, pressure differentials, and gas intrusion can enable the system to respond automatically to potential threats. Besides, the system can analyze the possibility of component failures and suggest preventive maintenance.

3.8.4 Improved Energy Efficiency

Future advancements may focus on reducing energy consumption with respect to advanced electrical components.

3.8.4.1 Low Power Components

Efficient solenoid valves, relays, and regulators can minimize energy requirements and create more portable system design then a modular system design could allow deployment across multiple vehicles or platforms.

3.8.4.2 Multi-Purpose Usage

The positive pressurization system holds significant potential for applications beyond missile launch vehicles. By adapting the system's design and functionality, it can be utilized in diverse operational environments, enhancing its utility in both military and civilian contexts like chemical plants, underground operations and so forth. (The Hague Centre for Strategic Studies, 2022)

4. Conclusion and Discussion

The results of the testing demonstrated that the positive pressurization system effectively prevents hazardous gases from entering the vehicle cabin during missile launches. By maintaining a higher internal pressure, the system successfully blocked gas infiltration, ensuring personnel safety. Compared to existing CBRN filtration systems, the proposed system offers several significant advantages, including lower operational costs, reduced maintenance needs and a simpler vehicle design.

Traditional CBRN systems are reliable but require significant resources to maintain, particularly in environments where frequent filter changes are necessary. (Brown, 2020) The positive pressurization system addresses these challenges by eliminating the need for expensive filters and reducing the number of components required to protect personnel. This makes the system a more sustainable solution for long term military operations especially in the environments where hazardous gas exposure is a recurring risk. (IAEA, 2017)

The pressurization system's ability to function automatically through remote signals adds another layer of convenience that allow personnel to remain at a safe distance during missile launches. Automation and remote operation are critical for reducing risk in high exposure environments (Kumar 2019) The proposed system's simplicity, combined with its robust protection capabilities, makes it a valuable innovation for military use.

Future advancements would position positive pressurization systems as essential solutions not only for missile launch operations but also for more extensive defense and civilian applications. In the long term, these systems are expected to become more sustainable, user friendly and efficient, marking a significant innovation in defense technology.

In conclusion, the positive pressurization system provides a cost effective, low maintenance alternative to traditional CBRN filtration systems. Its design reduces the complexity of military vehicle configurations while maintaining a high level of protection for personnel. Future work could explore integrating additional automation features or improving the efficiency of the pressurization system to further enhance its performance.

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CHAPTER III

Effects of Vibration on Permanent Magnet Synchronous Motors Used in Light Electric Vehicles

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1.INTRODUCTION

The automotive industry, which is one of today's fossil fuels and the most consumed areas, has begun a period of rapid growth and transformation due to the fact that fossil fuels are depletable and not environmentally friendly. This process has led to the emergence of new energy-producing vehicles, particularly electric vehicles and light electric vehicles. Electric vehicles are attracting more attention from governments as well as from society. The advancement of electric motors primarily relies on the progress in motor technology, control systems, and battery technology. Particularly, it is crucial to enhance the drive system of electric vehicles and the electric motor

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technology, which forms the core component of this system (Shi et al., 2009; Fodorean et al., 2017; Jinwen and Yumei, 2023).

According to the historical developments of electric machines, from the years following the production of the first electric motor in 1831 to the last phase of the 19th century, low magnet electric motors power density permanent were manufactured. In the motors manufactured during this period, chrome, cobalt and tungsten steel magnets with low magnetic energy densities were preferred. In the first phase of the 1930s, aluminumnickel-cobalt (AlNiCo) magnets with high flux density emerged. The development of these magnets was followed by the development of hard ferrite and ceramic magnets in the 1950s. The areas of use of permanent magnet motors developed due to this development of AlNiCo and ferrite magnets. The development of ferrite magnets was followed by the emergence of rare earth permanent magnets. The first rare earth permanent magnets were composed of samariumcobalt (SmCo) alloy. In the following years, SmCo alloys were replaced by neodymium-iron-boron (NdFeB) alloys (Furlani, 2001). It is seen that permanent magnet motors manufactured with the sintering method that emerged with today's technological development have many superior features when compared to electric motors with other stator-rotor windings.

Nowadays, it is seen that Permanent Magnet Synchronous Motors (PMSM) are increasingly widely used in many areas, especially in the electric vehicles and white goods industry. When PMSMs are compared to direct current (DC) motors and asynchronous motors, they are seen to be superior with many features (Jiang et al., 2021; Lee and Lim, 2021). These features are; high efficiency, long life, low maintenance cost, low volume-weight ratio, low noise level, easy control, high speed, high torque and output power.

Since PMSM motors do not contain an excitation winding in the stator or rotor, the total winding amount is low and therefore copper losses are reduced. Since these types of motors operate with field excitation, they do not have mechanical losses caused by brushes and collectors (Liu et al., 2024). In addition, losses due to temperature effects have decreased due to the wider cross-sectional area in the stator windings and easier heat transfer along the body. Since the air gap flux is provided by permanent magnets, the armature current is higher than in asynchronous motors..

In electric motors with brushes and collectors, their dimensions are large, their costs are high and they need constant maintenance due to the brush-collector arrangement. Brushless machines have emerged by performing the function of the collector and brush in brushed machines by the power electronic switching components. PMSMs, which are one of the prominent ones among these types of electric machines, are in the permanent magnet brushless electric motor class. When a permanent magnet synchronous motor is driven by an inverter fed from DC source, the resulting machine characteristic is similar to the characteristic of a direct current shunt motor. Therefore, these types of motors are called Brushless Direct Current Motors (BLDCM). When these types of motors are fed with a voltage with a sine wave, they are called PMSMs. In industrial applications and in the electric vehicle industry, brushed electric motors or asynchronous motors were preferred due to their costs and ease of control. Since there is no collector and brush system, maintenance requirements are quite low and maintenance costs are quite low (Gieras, 2010). For the same reason, its lifespan is also extended. The absence of collector and brush reduces the length of the motor. This not only saves space, but also allows the rotor to reach high speeds since the distance between the bearings is reduced, and the rotor's stability under the effect of force or torque is optimized (Nguyen et al., 2024). It is smaller and lighter than DC motor and an asynchronous motor of the same capacity due to the reduction of windings and the absence of brush and collector assemblies.

Compared to brushed DC motors, the electromagnetic interaction and electromagnetic noise caused by the arcs created by the brushes of these motors are so low that they are not important in PMSMs (Yu and Zhang, 2024).

Since the PMSM shaft torque is related to the motor input current, it is seen that their control is quite easy when compared to asynchronous motors. However, since the rotor structure does not contain windings, the control parameters are reduced and therefore speed control is easy. The structure of PMSM, which has many advantageous features, is as shown in Figure 1.



Figure 1. In-Wheel Permanent Magnet Synchronous Motor

In addition to the superior features of PMSM, there are also disadvantages. Researchers are optimizing many design parameters to correct the disadvantages that can be considered as deficiencies. A suitable rotor structure and secure fixation of permanent magnets are required for flexible centrifugal forces. From a thermal perspective, it is important to control operating temperatures to prevent damage to windings, permanent magnets and machine structure due to excessive thermal overload (Ahn et al., 2018; Petrov et al., 2017; Chawrasia et al., 2020). The permanent magnet serves as the excitation source for a PMSM. Thus, choosing an appropriate permanent magnet is directly linked to the cost, size, and performance of the motor (Zhang and Jiang, 2019). The primary factors influencing the selection of a permanent magnet include a high magnetic energy product, superior magnetic properties, higher excitation magnetic potential, strong coercive force, and minimal demagnetization in complex alternating magnetic fields. In PMSMs, magnetic field harmonics contribute to core losses. Reducing loworder harmonics leads to improved performance and increased reliability, particularly in high-speed applications (Ping et al., 2017). Table 1 presents a compare between Permanent Magnet Synchronous Motors (PMSMs), DC Motors, and Induction Motors (Asynchronous Motors).

Table 1 A comparative between Permanent Magnet SynchronousMotor (PMSM), DC Motor, and Asynchronous Motor (InductionMotor) (Krishnan, 2009; Hughes and Drury, 2019; Jung et al.,

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Feature	Permanent Magnet	DC Motor	Asynchronous Motor
	Uses permanent magnets to	Converts electrical energy	(Induction Motor)
	create a constant	to mechanical energy	electromagnetic induction
Working	magnetic field; rotor and stator	through a commutator and	between stator and rotor
Principle	fields synchronize in frequency	brushes	fields
	Web off classes have to as down d	Malanta officiana lana	Lower efficiency compared
	losses	due to	losses due to rotor
Efficiency	(no rotor winding)	commutator and brushes	resistance and slip
	- · · · · · · · · · · · · · · · · · · ·	High, due to wear and tear	Low, no contact between
Maintenanc		on brushes and	rotor and stator
e	Low, no brushes or commutator	commutator	components
	Complex control algorithms	Simple control (speed is	Relatively simple control
Control	(requires precise control of	directly proportional	control for speed
Complexity	stator current)	to applied voltage)	regulation)
			Low to moderate starting
Starting	High starting torque, but		torque
Torque	requires controlled start	High starting torque	(depends on rotor design)
			Speed can vary with load,
Speed	Precise speed control over a	Simple speed control	requires VFD (Variable
Control	(through field-oriented control)	(using variable resistance or voltage)	precise control
control	(unough held offented control)	Moderate to high torque	preense control
		ripple	
Torque	Low torque ripple (smooth	(due to commutation	· · · ·
Ripple	operation)	process)	Low torque ripple
	Smaller and lighter for		Larger and heavier
Size and Weight	equivalent power rating	Bulkier for equivalent	compared to PMSM for
weight	(due to high power density)	power output	the same output
	High, mainly due to permanent	Moderate, but varies based	Torrest and and the
Cost	complex control systems	(brushed or brushless)	available and inexpensive
0050		(orabiled of crushiess)	
Application	erospace	Toys small appliances	compressors
s	industrial automation	industrial machinery	general industry
		Higher heat due to	Moderate heat, mostly from
Heat	Less heat generated	commutator and	rotor
Generation	(due to reduced losses in rotor)	brushes friction	resistance losses
	Requires electronic control for		Direct-on-line (DOL) or
Starting	starting	Simple starting via direct	using soft starters,
Method	(cannot self-start)	power application	requires slip
			Poor to moderate power
Power	High power factor, close to	Variable, depends on	factor, improves
Factor	unity	motor load	with capacitors
			Long, due to lack of contact
Lifosnon	Long, due to lack of mechanical	Shorter lifespan due to	between rotor
Litespan	wear (no prusnes)	orusn wear	and stator

2.VIBRATION EFFECT ON ELECTRIC MOTOR

Vibration is the repetitive movement of a system or object around a position in which it is in equilibrium. By definition, vibration is generally defined as periodic motion caused by forces acting on a system or object. Vibration occurs in mechanical systems as oscillations or fluctuations and is related to the natural properties of the system.

Vibration in electric motors can be defined as the periodic movement of the rotor, stator, shaft and other parts deviating from their normal operating position due to imbalances, wear or incompatibilities in the mechanical or electrical components of the motor. Electric motors make this oscillatory movement due to some external or internal factors during rotation.

Vibration in motors is usually related to the rotation frequency and creates constantly repetitive forces on the components of the motor. These forces can disrupt the structural balance of the motor, causing loss of efficiency and wear. Vibrations are generally seen as a significant problem affecting the performance of the motor, because they can damage the motor components and shorten its operating life (Thomson, 2021).

Vibration usually occurs due to reasons such as incompatibility between the rotor and stator of the motor, mechanical errors or electrical problems. The causes of vibration in electric motors are as follows

1-Mechanical Causes:

a)Unbalanced Rotor: The rotor being unbalanced or eccentric can cause vibration. Weight imbalance creates unequal forces in each rotation of the rotor.

b)Shaft and Bearing Failures: Wear on the motor shaft or improper operation of the bearings creates vibration.

c)Coupling Problems: If the connection (coupling) between the motor and the load is not proper, vibration occurs.

d)Loose Parts: Looseness in the assembly or connection points of the motor creates vibration.

2-Electrical Causes:

a)Unbalanced Phase Current: Current imbalances in the phases of the motor create variable forces on the rotor and vibration occurs.

b)Harmonic Distortions: Harmonic distortions or power quality problems originating from the electrical network prevent the motor from working properly, which creates vibration.

c) Electrical Failures: Short circuits or insulation faults in rotor or stator windings can cause vibrations.

3- Load-Related Causes:

a) Unbalanced Load: If the load to which the motor is connected is unbalanced, vibration occurs during the rotation of the rotor.

b) Load Changes: Sudden load changes can disrupt the mechanical and electrical balance of the motor and cause vibration (Yu et al., 2024; Barros et al., 2024).

In electric motors, vibration has major destructive effects on the motor itself and the system it is connected to. These effects can be grouped as follows.

1-Wear and Tear: Vibration causes wear and premature wear of motor components (shaft, bearing, rotor).

2-Bearing Failures: Continuous vibration can cause bearings and bearings to overheat and deteriorate.

3-Noise: Vibration increases the sound level of the motor, causing disturbing noise sources, especially in industrial environments.

4-Loss of Efficiency: Vibration can reduce the efficiency of the motor, causing more energy consumption and increased costs.

5-Mounting Damage: Vibration can damage the motor's mounting components and cause the motor to move or its connections to loosen.

6-System Failures: Long-term vibration can lead to complete failure or malfunction of the motor and the system it is connected to (Thomson, 2021).

In addition to these destructive effects, it affects the life of the electric motor and maintenance costs. In electric motors used for propulsion in EV, it influences driving performance. For all the reasons mentioned, it is important to analyze the effects of vibration both in the design phase and during use.

The natural frequency is the rate at which a system oscillates in the absence of external forces or damping. A system can have several different natural frequencies. Resonance occurs when the frequencies of electromagnetic excitation forces approach the natural frequencies of the stator, causing significant vibrations in the system. To prevent resonance, the natural frequencies can be shifted to higher values, where there are minimal excitation forces and a lower likelihood of resonance at these elevated frequencies. The natural frequencies of the system can be altered by adjusting its dimensions, inertia or certain features of the systems that affect the forces. Periodic motion has an effect on electric motors. The term periodic motion can be defined as a type of movement that replicates varying over time and can also be defined as oscillation. Vibrational motion is a periodic movement that repeats at regular time intervals. This can be categorized into harmonic and non-harmonic periodic motion. Harmonic motion is the simplest form, characterized by movements that repeat over equal time intervals. It involves the repetitive motion of a rotating machine or its components completing one full cycle during each time interval. Among the time and displacement components defined for harmonic motion;

$$X = A\sin(wt) \tag{1}$$

where X is the displacement component and A is defined as the amplitude (Thomson, 2021).

Vibration measurement and calculation methods in electric motors are used to monitor the performance of the motor and to detect possible problems in advance. Vibration measurement is usually done on parameters such as displacement, speed and acceleration.

1-Displacement Measurement: Displacement measures how much the moving parts of the motor are displaced due to vibration. Vibration usually refers to how the motor shaft moves relative to a specific reference point. This measurement method measures in microns (μ m) or millimeters (mm). When measuring vibration on an electric motor, contact sensors such as Eddy current or LVDT (Linear Displacement Transformer) are used as measuring devices. These sensors detect how far the motor moves from a fixed point.

2-Velocity Measurement: Measuring the vibration velocity means monitoring the speed as a function of the vibration frequency. Measuring the vibration velocity is used to understand the speed at which the motor is vibrating and whether this speed is dangerous. The unit used in this measurement method is mm/s or inch/s. Piezoelectric sensors are widely used as measuring devices.

3-Acceleration Measurement: Acceleration measurement determines how fast the motor is moving due to vibration and is measured in m/s^2 or g (gravitational force). Acceleration is used to detect higher frequency vibrations and usually occur in smaller amplitudes. Piezoelectric accelerometer is used as the measuring device. Accelerometers are very sensitive in measuring accelerations caused by mechanical vibrations (Thomson, 2021).

The vibration effects on PMSM, which is especially preferred in light electric vehicles, should be analyzed well. This disruptive effect, which directly affects driving performance and motor lifespan, should be analyzed before the prototype production of the motor. Vibration measurement is important in the real driving phase. However, analyzing and damping the vibration effects during design is more important (Vance et al., 2010. Wiley, Wang et al., 2023; Jang at al., 2014). Therefore, the effect of vibration on design parameters and the internal force that affects vibration, the moment effect, should also be determined well. An important source of vibrations in electric motors are various moment forces. These moment forces can disrupt the balance of the motor and cause unwanted vibrations and mechanical strains. The moment forces occurring in electric motors are formed by the effects of forces on different components such as rotor, stator, shaft, and bearings. The main types of these forces are as follows:

1. Electromagnetic Torque

Electromagnetic torque is the electric current passing through the stator windings of a motor, creating a magnetic field in the rotor, producing a turning force (torque). This torque allows the motor to produce mechanical power, but imbalances in this force can cause vibrations. Electromagnetic torque is calculated with the following equation

$$T_e = P_{out}/w \tag{2}$$

where P_{out} is output power, w is angular velocity (Vance et al., 2010. Wiley, Wang et al., 2023; Jang at al., 2014).

2. Inertial Torque

Inertial torque is a force resulting from the inertia effect of the rotating parts of the motor (rotor). Sudden speed changes of the rotor, especially during acceleration and deceleration processes, can cause high moments. These moments can disrupt the balance of the rotor and create vibration. The calculation of this is

$$T_i = J \alpha \tag{3}$$

where T_i is inertial torque, J is rotor moment of inertia and α is angular acceleration (Vance et al., 2010. Wiley, Wang et al., 2023; Jang at al., 2014).

3. Bearing Friction Torque

Bearing friction torque is the force caused by friction on the bearings of the motor. Friction in the bearings can prevent the motor from operating properly and create additional vibration. Wear on the bearings causes the bearing friction torque to increase and the vibration level to increase. Bearing friction torque is calculated with the following equation

$$T_f = \mu F r \tag{4}$$

where μ is friction coefficient, *F* is force on motor shaft and *r* is radius of shaft (Vance et al., 2010. Wiley, Wang et al., 2023; Jang at al., 2014).

4. Rotor Eccentricity Torque

Rotor eccentricity torque is caused by the rotor being misaligned or deviated from the center axis of the motor. The unbalanced rotation of the rotor disrupts the rotational motion of the motor, which causes vibrations. The eccentricity torque is related to the centrifugal force of the rotor and can be expressed as follows

$$T_r = m \, e \, w^2 \tag{5}$$

where *m* is rotor mass, *e* is eccentricity (rotor deflection in meters) (Vance et al., 2010. Wiley, Wang et al., 2023; Jang at al., 2014).

5. Friction Torque

Also called Coulomb friction torque, this torque is caused by the static and dynamic friction of the motor shaft or rotor in contact with the bearings. This type of friction torque is especially important when the motor is starting or running at low speeds. Coulomb friction can make the motor difficult to start and cause vibration. The Coulomb friction force is found by multiplying the friction coefficient between the surfaces and the normal force and is expressed as in the equation below.

$$T_r = \mu N \tag{6}$$

where N is normal force (Vance et al., 2010. Wiley, Wang et al., 2023; Jang at al., 2014).

3.VIBRATION ESTIMATES DURING DESIGN

One of the problems observed after the prototype manufacturing of electric motors is that the predicted motor output values and the performance test results are not compatible. Finite Element Analysis (FEA) based computer software is utilized to solve this problem. The parameters that can be seen as negative after the prototype manufacturing are not obtaining the desired power, torque and speed, high vibration effects, and overheating problems. Manufacturers use various methods to solve these types of problems. The most optimal of these solution methods is to detect and correct these negativities during the design process. Therefore, simulation software is very useful for both manufacturers and researchers.

There are many commercial simulation software for use in electric motor designs. One of the most preferred software by researchers and manufacturers is ANSYS software. ANSYS is a software used for different engineering problems and allows simulation in different disciplines (such as electromagnetism, mechanics, thermal, electric field, fluid dynamics). This software allows engineers to simulate real-world conditions by testing product designs in a digital environment, thus saving time and cost in product development processes. ANSYS offers a wide range of solutions in engineering by offering various modules such as electromagnetic field analysis (ANSYS Electronics Desktop), thermal analysis (Motor-CAD), analysis of external force effects such as vibration effects (ANSYS Workbench), structural analysis (ANSYS Mechanical), fluid dynamics (ANSYS Fluent) and high frequency application analysis (ANSYS HFSS).

Permanent Magnet Synchronous Motor is an electric motor with permanent magnets in its rotor and rotating synchronously. PMSMs have superior features such as high efficiency, high power density, better torque-speed characteristics and lower energy losses. At the same time, PMSMs require less maintenance, operate quietly and have a long life because they are brushless. While their high efficiency minimizes energy consumption, their ability to reach high speeds makes them an ideal motor type for many process applications. PMSMs are greatly preferred in electric vehicles because they provide powerful acceleration and torque performance, improving driving comfort. Their high efficiency extends the battery life of electric vehicles and increases their range. In addition, PMSMs take up less space in vehicles thanks to their compact design, which provides flexibility in vehicle design. The durability and high performance of PMSMs are the main reasons why electric vehicle manufacturers use this type of motor on a large scale.

Vibration is a significant issue in PMSMs at low speeds. To ensure a smooth starting and driving experience for electric motors, it is essential to minimize vibrations. The primary causes of vibration in electric motors include shaft misalignment, rotor axial misalignment, bearing noise, cogging torque (tooth torque), fluctuations in commutation torque, and electromagnetic forces. Among these factors, electromagnetic forces are the most influential. At the same time, vibration can be minimized by simulating it before the manufacturing process. Other parameters pertain to postmanufacturing conditions and can be managed with additional equipment. Therefore, during PMSM design, the frequency response of the system showing the resonance frequencies should be obtained and the parameters affecting the vibration such as harmonic analysis should be determined (Yu et al., 2024; Barros et al., 2024).

ANSYS Workbench software is the most preferred simulation program for determining the mentioned vibration effects. ANSYS Workbench is a Computer-Aided Engineering (CAE) software developed by ANSYS, aimed at analyzing and optimizing engineering and design projects. It is applicable across various engineering disciplines and can simulate different physical interactions. The software also enables users to implement design changes and compare various scenarios to assess how these changes impact the overall design. This capability makes it a user-friendly interface for examining the mechanical effects of electric motors.

In order to perform the simulation under ANSYS Workbench software, it is first necessary to introduce a Maxwell analysis model and results of ANSYS Electronics Desktop, where the electromagnetic analysis is performed. For this introduction and vibration analysis, the model given in Figure 2 is created.



Figure 2. ANSYS Workbench vibration analysis model

ANSYS Workbench is a versatile platform that integrates with ANSYS Electronics Desktop, allowing for multi-physics simulations such as vibration analysis in electric motors. For vibration simulations, the geometry and dimensions of the structure must first be accurately defined within the Workbench environment. Electromagnetic analysis results, generated from ANSYS Electronics Desktop using RMxprt or Maxwell, are imported into ANSYS Workbench to serve as input data for the simulation. This integration ensures that both the motor geometry and the results of the electromagnetic analysis are available for the vibration model, enabling a comprehensive assessment of motor performance. To conduct a vibration analysis, the mechanical parameters of the PMSM must be specified alongside the chosen vibration analysis methodology. ANSYS Workbench utilizes numerical methods to solve the governing equations of the chosen physical phenomena. The solver refines the solution iteratively until a stable result is reached. Specifically, the platform employs the FEA for structural

analyses, the Finite Volume Method (FVM) for fluid dynamics, and hybrid approaches, such as finite element-boundary element techniques, for electromagnetic simulations. These methods break down the geometry into smaller elements and solve the system iteratively to achieve precise numerical solutions For a deeper understanding of the solvers and algorithms used across different physics domains, ANSYS-specific documentation should be consulted.

In the ANSYS Workbench model depicted in Figure 2, columns A, B, and G are designated to define the PMSM geometry and the electromagnetic field, along with the simulation results of the analytical solution. Column C contains the geometric data related to the mechanical conditions of the PMSM and the motor shaft parameters, preparing the model for analysis. The PMSM is set up for modal analysis based on the parameters entered in column C. Modal analysis is a crucial tool in structural engineering and product design, as it enables engineers to prevent costly failures and enhance product performance by ensuring that designs operate safely and efficiently under varying dynamic conditions. Column D is dedicated to creating the modal analysis, while columns E and F specify the type and conditions for vibration analysis. There are many sub-analysis types for vibration analysis. These are total deformation, harmonic response, directional vibration, harmonic acoustics.

The vibration analyses can be performed for different parameters such as different operating speeds and different operating frequencies. The ANSYS Workbench simulation results for PMSMs are as given in Figures 3 and 4.



Figure 3. Result of vibration analysis for rotor in ANSYS Workbench



Figure 4. Result of vibration analysis for stator in ANSYS Workbench

The results of electric motor vibration simulation obtained with ANSYS Workbench are of critical importance for motor designers in terms of evaluating the structural durability and operating conditions of the motor. Vibration simulation results reveal the vibration amplitudes, natural frequencies and mode shapes of the motor at different operating speeds and load conditions. These results help designers identify the source of mechanical vibrations that directly affect the reliability, efficiency and life of the motor.

Designers compare the natural frequencies of the motor with the operating frequencies in the simulation results. If the operating frequencies of the motor overlap with the natural frequencies, resonance may occur, which increases the vibration amplitudes, shortens the life of the motor and may lead to mechanical damage. For this reason, designers aim to keep the natural frequencies of the motor outside the operating frequencies. Vibration amplitudes are evaluated by comparing them with certain limit values; these limits are usually determined according to industry standards and motor type. However, it is important to control the different effects and vibrations caused by the imbalances between the rotor and stator. Testing whether the mechanical structure and components of the motor are resistant to these vibrations is important to determine whether the motor design is successful. The data obtained from the vibration simulation results are used to understand whether the motor will resonate, whether there is excessive vibration, and whether the structural design of the motor provides sufficient durability. Whether the design is suitable in terms of vibration can be determined by examining it with international standards (such as ISO 10816, ISO 20816). It is also decided by comparing it with the operating conditions of the motor.

In vibration analyses of electric motors conducted in ANSYS Workbench, the results for the rotor and stator are typically visualized using color maps (contour plots) and deformation displays. These results provide crucial data, including vibration amplitude, speed (mm/s), displacement (mm), and deformation. In these analyses, color coding represents the intensity of vibration and deformation across different regions of the motor, with this intensity corresponding to a specific scale.

The following parameters should be considered for the interpretation of the results of the obtained vibration analysis.

1- Color Coding and Amplitude Values: Color maps illustrate the vibration amplitude or deformation on the rotor and stator. Typically, red and yellow represent high vibration amplitudes or significant deformations, while blue and green indicate areas with lower vibration and deformation. This color coding allows designers to quickly identify regions of the motor that experience high vibration and assess the potential risks of resonance, mechanical wear, or structural damage in those areas

2- Displacement (mm): The displacement results, expressed in millimeters, indicate the extent to which the rotor and stator are physically shifted under various operating conditions of the motor. High displacement values may pose a risk of collision or wear between motor components, particularly in areas with minimal mechanical clearances.

3- Vibration Velocity (mm/s): Maps depicting vibration velocity (mm/s) illustrate the vibration energy present in different areas of the motor. High velocities indicate excessive vibration energy, which may lead to mechanical wear or a reduced service life

for the motor. Designers compare these velocity values against industry standards (e.g., ISO 10816) to assess whether the motor's vibration performance is satisfactory.

4- Deformation Representations: Deformation is typically illustrated in simulation results alongside the original geometry. Images of the deformed rotor or stator visually depict how the motor bends or alters shape during operation. This visualization is particularly crucial for evaluating the mechanical stability of critical components, such as bearings or shafts.

Designers analyze the results of these assessments to evaluate the risks of resonance, mechanical stability, and component durability. They scrutinize the deformation and vibration maps to determine if the operating frequencies align with the motor's natural frequencies. Regions with high amplitude and speed may jeopardize the mechanical stability of motor components, prompting an evaluation of whether these areas are subjected to excessive stress. They investigate whether critical components, particularly the rotor and stator, can endure long-term vibration effects. If vibrations are found to be excessive, design improvements may be necessary.

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CHAPTER IV

Powering Military Vehicles with Strategic Energy Solutions for Extreme Geographical Conditions

Mehmet YAVUZ

1.Introduction

Military vehicles are engineered to meet stringent requirements that ensure their reliable performance in harsh environments. These vehicles must be equipped with energy systems capable of operating in extreme temperatures, fluctuating climates and challenging geographical terrains. Military products are designed to withstand such conditions by complying with specific standards that guarantee durability, functionality and safety.

There are some crucial factors which must be considered in the design and operation of military electronics such as Electromagnetic Interference (EMI), Electromagnetic Compatibility (EMC) and Radio Frequency Interference (RFI). (Chalasani, Kim & Martinez, 2022) EMI refers to the disruption caused by electromagnetic radiation while EMC ensures that devices can operate together without interference. RFI specifically targets issues caused by radio frequency emissions. These all factors can compromise the performance of critical military systems. MIL-STD-461, MIL-STD-464 and NATO STANAG 4370 are established to guide the development and validation of military electronics with respect to these factors by providing specifications for the tolerances of EMI-EMC and RFI. MIL-STD-461 outlines the allowable electromagnetic emissions and susceptibility of military systems for ensuring that they can function in various electromagnetic environments without interference. MIL-STD-464 emphasizes the overall compatibility of systems while NATO STANAG 4370 addresses the interoperability of equipment used by NATO forces.

In the context of this study, how military vehicles meet their power needs, including battery selection, charging methods and how power is distributed among subsystems by considering the tolerances which are given by Military Standard. Furthermore, the implementation of these military standards will be examined in relation to the selection of components such as connectors and power panels by ensuring that military vehicles are capable of enduring extreme operational conditions while maintaining reliable and secure performance. Through a structured examination of power consumption calculations, battery configuration, power distribution and connector specifications, this paper aims to contribute valuable insights into creating dependable energy systems for military applications, ultimately supporting mission success and vehicle safety.

2.Research and Findings

2.1 Calculation of Total Energy Consumption

The total power consumption of vehicle and its subsystems is carefully calculated to ensure operational reliability in challenging conditions. This begins by determining the maximum power consumption of all onboard subsystems, along with any independent units within the superstructure that may operate separately. (Figure.1) The combined power needs of both the vehicle and any additional systems are evaluated by considering scenarios where all systems could be operational simultaneously.



Figure.1 Sample Subsystems of Military Vehicle

A: Detection System, B: Weapon, C: Weapon Sensors, D: Drive Cameras (7StarLake, 2021)

To accommodate unforeseen demands or potential future system upgrades, a reserve power allocation is also included. One critical aspect in calculating total power consumption is accounting for environmental conditions by considering the harshest climate conditions. The vehicle may encounter throughout its operational life such as extreme temperatures of -32°C to +55°C, are used as a reference. (Sachin, 2024) This approach ensures that the selected batteries and energy systems can perform efficiently even in severe conditions. Evaluating system simultaneity and battery performance under these extreme temperatures allows for an optimal power configuration for supporting both reliability and resilience in diverse operational contexts.

2.2 Determining Battery Capacity and Charging

For scenarios where the total energy demand is manageable with vehicle batteries, military grade batteries are selected based on design considerations. Military systems, unlike civilian ones, require rapid response and high energy intensity so selected batteries must have high energy density and the ability to handle sudden and substantial power demands.



Figure.2 The discharge curve of Ampxell low temperature battery at different temperatures, keeps high discharge efficiency at low temperature. (Ampxell Technology Co. Ltd)



Figure.3 Ampxell Low temperature profiled battery charge 20°C /-30°C discharge cycle test. Discharge by 0.2C @-30°C, over 85% of the capacity is maintained after 300 cycles. [10]

Military batteries must also have advanced recharge capabilities for prolonged use, typically recharged via the vehicle's alternator. (Figure.4) A critical factor here is the energy required when the vehicle is stationary. High power demand while engine is not running can deplete batteries quickly in the absence of alternator support and also reducing battery life. Consequently, configurations prioritize system operation during vehicle activity.

In cases where power demands exceed the capacity of vehicle batteries or if superstructure specific batteries are employed, alternator capacity may fall short. There are two options here, include installing additional alternators or increasing existing alternator capacity. If an additional alternator is necessary, the PTO (Power Take-Off) system is evaluated.

Military vehicles usually have two types of PTOs engine and transmission PTOs which can be leveraged for additional alternator connections. (Inventus Power, 2024) If one of the PTOS are not included in vehicle configuration, the problem can be solved with a PTO multiplier to drive multiple alternators. Operational scenarios are assessed to determine whether the PTO outputs should function simultaneously or individually. For separate operations, electronic control circuits can be added for allowing operators to manage each unit from the vehicle cabin.



Figure.4 Battery Charging Layout

2.3 Power Management and Distribution

In designing power systems for military vehicles, understanding power requirements for different subsystems and defining optimal voltage levels are essential. Military vehicles often use voltage levels like 24 VDC, 220 VAC and 380 VAC so categorizing power needs ensures accurate selection of inverters and converters. The aim is to enable reliable power conversion from the vehicle's batteries to match each subsystem's needs. (Harrison, Patel & Li, 2021)

For power management across various units, Power Distribution Units (PDUs) provide versatile, centralized control, distributing energy at multiple voltage levels and allowing for the selective activation of specific systems. As emphasized in research,
"Advances in power distribution systems for military applications" (Harrison, Patel & Li, 2021). PDUs not only simplify functional testing but also enhance operational resilience by enabling energy flow adjustments to critical systems as conditions demand.

In addition, selective power cut offs within PDUs help manage energy loads, preventing overdraw on the vehicle's battery. This flexibility supports continuous, reliable operation under varied loads and environmental demands which make PDUs indispensable for complex military power architectures.

2.4 Military Connector and Cable Selection

Selecting suitable cables and connectors is crucial for military vehicles which operate in extreme conditions such as high humidity, dust, vibrations, temperature fluctuations and exposure to chemicals. Cables and connectors need robust shielding against electromagnetic and radio frequency interference to maintain signal integrity. (Rahman & Qadir, 2023)

For example, power inputs such as those at alternator outputs and control units, utilize connectors specifically rated for harsh environments. When defining connector codes, a few critical factors must be considered such as panel compatibility and connector matching to ensure proper fit during assembly.

Military connectors come in two primary types which are cable-type connectors and panel-mounted connectors. (Figure.5) For connectors passing through panels, the panel-mounted connector code must match the connector on the cable. Connectors also need to be mounted at the correct boot angle, often 90 degrees in tight spaces in order to prevent damage. Moreover, pin count and arrangement play a significant role in military connector selection to ensure reliability and compatibility under operational stress.



Figure.5 Connector and 90° Boot Sample of Control Unit

2.5 Military Standards for EMI-EMC and Electrical Systems

Ensuring military systems comply with standards for Electromagnetic Interference (EMI), Electromagnetic Compatibility (EMC) and Radio Frequency Interference (RFI) is vital for secure and efficient performance. (Elisha, 2023) Standards such as MIL-STD-461 and MIL-STD-464 guide the design and validation of military electronics to limit interference. (Department of Defence, 2015, 2019) For example, MIL-STD-461 defines the levels of electromagnetic emissions a system may produce, as well as its immunity to external interference. Meanwhile, MIL-STD-464 emphasizes compatibility testing across various electromagnetic NATO STANAG 4370 provides environments. further

comprehensive EMC guidelines for NATO forces for ensuring resilience and interoperability. (Figure.7)

Power distribution panels enhance protection by incorporating lightning protection modules, varistors and EMI-EMC filters for shielding sensitive components from external disturbances. This design, enables military systems to function reliably across diverse electromagnetic settings which prevent unwanted emissions and ensuring internal and external device compatibility during large scale integration in military applications. (Arshon Technolog, 2023)



Figure.6 RFI Testing Layout

2.6 EMI-EMC Test

Military vehicles must adhere to stringent EMI/EMC standards such as MIL-STD-461 and MIL-STD-464. These standards define acceptable levels of electromagnetic emissions and susceptibility, ensuring that the vehicles do not interfere with or are not adversely affected by other systems in their environment



Figure.7 EMI-EMC Testing Overview

2.6.1 Test Types

Emission Testing: This evaluates whether the vehicle or its components emit electromagnetic radiation within acceptable limits.

Susceptibility Testing: This assesses the vehicle's ability to function correctly when exposed to external electromagnetic disturbances.

Coupling Mechanisms: Tests address conductive, radiative, capacitive, and inductive coupling to identify and mitigate interference pathways

2.6.2 Test Setup

Vehicles are tested in shielded environments like anechoic chambers or open test ranges to isolate and measure electromagnetic interactions accurately. (Shukla and Nirmala, 2006)

Equipment such as spectrum analyzers, antennas, and current probes are used to measure emissions and assess immunity to electromagnetic signals. (Shukla and Nirmala, 2006)

2.6.3 Critical Focus Area

Power Systems: Ensuring the compatibility of power supplies and electronic control units with surrounding systems.

Signal Integrity: Verifying data communication lines for resistance to noise and interference. (Murata Manufacturing, 2023)

Antenna and Sensor Placement: Positioning to minimize internal interference.

2.6.4 Control Measures

After identifying potential EMI risks, countermeasures such as shielding, grounding, filtering, and circuit design adjustments are implemented to ensure the vehicle meets EMC requirements

3.Conclusion

Military vehicle energy systems are integral to ensuring that vehicles perform optimally under diverse and extreme conditions. This study highlights the importance of accurately determining total energy needs for these vehicles and meeting the power requirements of various systems through careful design and configuration. The effective management of power distribution is essential to ensure that each system functions without interference, maintaining operational stability across components. Using Power Distribution Units (PDUs) and other power management techniques that allows for reliable energy delivery across all systems without risk of overload or mutual disruption for operational resilience.

The selection and validation of electronic components in military systems are guided by stringent military standards like MIL-STD-461, MIL-STD-464, and NATO STANAG 4370 which establish clear guidelines for EMI/EMC compliance and protection.

These standards demand high reliability under extreme conditions by pushing designers to implement solutions that mitigate interference risks while enhancing component durability. Compliance with these standards allows military vehicles to be built for resilience against harsh environmental conditions in order to make them suitable for a wide range of operational scenarios.

To sum up, by aligning energy system design with military standards, this approach not only meets the current functional demands of military vehicles but also supports future upgrades and enhancements. These measures ensure that military vehicles are equipped to handle the operational challenges of modern warfare, providing secure, robust, and long lasting performance essential to mission success.

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CHAPTER V

Modern Assembly Management for Military Vehicle Production with Advanced Techniques and Combining Past Insights

Mehmet Yavuz⁶

1. Introduction

In the defense industry, projects often involve unique and complex prototype vehicles equipped with advanced and highly specialized technologies. The assembly and serial production of such vehicles are challenging, labor intensive and frequently leading to assembly errors. To find out all possible faults which occur during serial production by personnel's inspection is not perfect way since it is a time consuming method and not an exact solution. These challenges not only extend the production timeline but also create delays in project schedules and result in additional costs.

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Having a mass production line in this context is often inefficient and costly as each vehicle in these varied projects has distinct features and subsystems. Conversely, in facilities without mass production lines, assembly errors are more prevalent and progress tends to be slower. Discrepancies between mass produced vehicles and their prototypes can have significant adverse consequences such as diminished brand reliability and reduced market trust. To address these challenges, it is crucial to ensure that vehicles in serial production are produced with absolute fidelity to their prototypes. This can minimize errors, streamline processes and prevent potential complications. Achieving this objective necessitates a holistic approach such as comprehensive transfer of knowledge and experience from completed projects, integration of Kaizen improvements from prior assembly and design processes into adaptation of proven projects. automotive industry new methodologies to military production, and utilization of emerging visual processing technologies for precise fault detection.

This study aims to explore and propose modern methods to overcome assembly challenges in military projects with focusing on improving efficiency, reducing errors and ensuring the seamless transition from prototype to serial production. The goal is to establish a robust framework that supports project timelines, optimizes costs and enhances the overall quality of military vehicle production by leveraging advanced techniques and insights from past experiences.

1.1 Assembly Challenges in Military Projects

Military vehicles are designed to perform in diverse and extreme conditions often incorporating custom built subsystems like

weapon mounts, communication systems and advanced sensor arrays. For instance, a prototype vehicle might include a new radar system requiring precise alignment and integration with the vehicle's power system. (Sokolova, 2024) Such subsystems often have unique mounting requirements that differ from mass production techniques that makes it easy to misinterpret or miss critical steps during assembly.

1.2 Limited Production Runs

Unlike automotive vehicles, which are produced in high volumes, military vehicles are often manufactured in small batches. This creates challenges such as limited repetition of assembly processes, reducing the opportunity for process refinement. That is why, it is difficult to justify the cost of fully automated production lines, which are typically viable for large scale manufacturing. (Krauza, 2024)

1.3 Dynamic Requirements

Military contracts often involve last minute changes to specifications due to operational feedback or updated mission objectives. For example, a vehicle initially designed for reconnaissance might need modifications to incorporate additional armor or weaponry. Such changes can disrupt established assembly workflows, increasing the likelihood of errors.

2. Research and Findings

2.1 Modern Assembly Methods for Error Reduction

2.1.1 5S Implementation

In a military vehicle assembly facility, tools and parts can be organized using the 5S methodology. For instance, tools required for assembling suspension systems can be labeled and stored in dedicated areas to reduce time spent searching for equipment. (Moro & Ilie, 2019)

2.1.2 The Value of Lessons Learned Platforms

Incorporating experiences from past projects, improvements made and even minor factors that enhance processes into new projects provides significant advantages in terms of cost efficiency, time management and resource allocation. To manage this effectively and ensure the right information reaches the appropriate personnel, organizations should establish a dynamic and structured "lessons learned platform."

Through such a platform, insights and outcomes from previous projects can be systematically shared with stakeholders at the right time. When a lesson is entered into the system, it automatically notifies relevant departments via email. This ensures real time management of the knowledge. Additionally, at predetermined intervals, reports summarizing the lessons entered are sent to R&D teams for review. After analysis, these insights are evaluated for their applicability to new projects, contributing to process management. (Keller Technology Corporation, 2020)

When implemented correctly, this approach supports project management by improving time efficiency, reducing costs and enhancing productivity. Moreover, it elevates customer satisfaction while contributing to overall quality standards.

2.1.3 Kaizen for Continuous Improvement

The Kaizen philosophy, focused on continuous improvement, can generate thousands of improvement ideas

annually in companies that adopt it. Managing and utilizing these ideas effectively, especially in the context of military projects, is a critical and challenging task. The key to effective process management is centralizing these ideas into a shared platform and ensuring they are communicated to the right stakeholders. (Sangwa, & Sangwan, 2020)

Military projects often involve unique designs and prototype developments tailored for specific missions. These prototypes may feature various subsystems that despite differing project goals, begin to repeat in functionality. Kaizen's continuous improvement philosophy allows enhancements from previous projects to be applied to subsequent ones. However, given the dynamic nature of military projects where teams often consist of different stakeholders across projects transferring these improvement ideas is not always straightforward.

Regular workshops involving technicians and engineers can identify bottlenecks or recurring errors in the assembly process. For example, if wiring harness misrouting is a frequent issue, a Kaizen event could focus on redesigning assembly fixtures to guide wires automatically.

2.1.3.1 Proposed Approach for Kaizen Idea Integration

Following the example of the lessons learned platform, a system should be implemented where Kaizen ideas are centralized and accessible. These ideas would be evaluated and relayed to relevant stakeholders for actionable insights.

The Kaizen process typically involves identifying an existing system, proposing improvements and refining it into a new form. To

manage this effectively, kaizen ideas should be categorized under headings such as "current state" and "proposed state." These categories should then be compiled into periodic reports and shared with project management teams. After analyzing the data, applicable ideas are incorporated into new projects, thereby fostering a culture of continuous improvement.

For instance, consider a prototype military vehicle project where a previous Kaizen improvement optimized the installation of communication subsystems. By leveraging the centralized platform this idea can be reviewed and adapted to similar installations in new projects for ensuring efficiency and reducing potential errors.

2.1.4 Poka Yoke (Error Proofing)

Poka-yoke techniques prevent errors by design and assembly. For instance, using color coded connectors that only fit the correct sockets. For instance, green connectors for communication systems and red connectors for power systems. Adding sensors to verify the correct torque is applied when tightening bolts on critical components like radar antenna.

2.2 Advanced Technologies in Assembly Management

2.2.1 Standardized Work Instructions

In the automotive industry assembly lines use detailed visual work instructions to minimize errors. Military projects can adopt this approach by creating illustrated guides for assembling complex subsystems like suspension or drivetrain components. These guides can include QR codes that link to video tutorials for ensuring technicians have immediate access to additional support.

2.2.2 Augmented Reality (AR) for Assembly Guidance

AR devices like smart glasses provide technicians with realtime instructions. For examples, an AR headset can overlay holographic assembly instructions onto a vehicle frame, showing where to place brackets or route wiring. This approach is particularly beneficial for training new technicians or handling complex assemblies such as installing missile launch systems. (Chen & ark., 2020)

2.2.3 Just-in-Time (JIT) Production

Delivering parts to the assembly line only when needed, reduces inventory costs and errors. For instance, military vehicle manufacturers can implement JIT for critical components like engines and transmission systems. (Blog, 2021) A tracking system ensures the right component arrives at the right workstation at the right time for reducing storage space and misallocation risks.

2.3 Proposed System

One of the best techniques for detecting all the faults and deficiency between prototype and mass produced vehicles is to use image processing methods. Among the most effective machine learning methods that could address this issue is Generative Adversarial Network (GAN).

GAN is a deep learning based system which contains two main artificial neural networks which are generator and discriminator. (Figure.1) This system might be effective to follow up the mass production if data collection process managed perfectly. The main aim of proposed system is to detect all possible faults by using GAN and to ensure that the production proceeds in accordance with prototype. (Overview of GAN Structure, 2022)



Figure.1 Classical GAN System

The first thing that we notice when we take a look at the classical GAN system is competition between artificial neural networks. (Buyukkinaci, 2018) Additionally, the basic logic behind the classical GANs is to generate fake images based on real samples which are supplied externally. (Öngün, 2022) In the proposed system, prototype vehicle images which focus on the sub-systems and components will be uploaded as real samples. Then, vehicle will be break into pieces by identifying each component. (Figure.2) By this way, each details that potentially miss out during assembly will be taken into account. On the other part, fake images are not going to be created by generator. The images which are taken from mass production vehicles will be used instead of fake data. On this subject, the crucial point is to take perfectly identical images in terms of angle, light and focal point since the goal is to find out the differences between prototype and serial production vehicles so images must be taken with same conditions. Identified components will be searched on the images in order to sort out all incompleteness. If installation is perfectly done, 1(one) will be assigned to the images by discriminator. This value will be decrease according to number of faults and drop rate will be indicated as error value. Some --89--

assembly process will be done with regard to given feedbacks. After this step, next iteration will perform with new images.



Fig.2- Proposed system block diagram

2.3.1 How to split a vehicle to components?

One possible way to split the vehicle into small pieces is to make several patches by patchify library which save the cropped images in a NumPy array. (Uspenyeva, 2024) Then, system will be ready to comparison stages for each patches. (Figure.3) Although increasing the number of patch will enable us to get more accurate results, it will cause to division of the components which is an undesirable situation. For that reason, every single component must be defined to the system during the training process in order to avoid missing out any detail.



Fig.3- To split an image into the patches

2.3.2 Equations

2.3.3 Min Max Game

The GANs are formulated with the function given below which is named a minimax game, where the discriminator is trying to maximize V (D, G) and the generator is trying to maximize discriminator's loss. (GeeksforGeeks, 2024)

$$\min_{G} \max_{D} V(D, G)$$
$$V(D, G) = \mathbb{E}_{x \sim p_{data}(x)}[\log D(x)] + \mathbb{E}_{z \sim p_{z}(z)}[\log(1 - D(G(z)))]$$

Figure.4 The value function

where,

G = Generator

D = Discriminator

Pdata(x) = Distribution of real data

P(z) = Distribution of generator

x = Real data

z = Latent vector

D(x): Evaluation of real data

D(G(z)): Evaluation of fake data by discriminator

G(z): Fake data

2.3.4 Training

In the training section of GAN, just one neural network is trained at a time. If the training of discriminator occurs, generator is accepted as fix by the system. After that, analysis of value function is proceeded. The main aim of the discriminator is to detect all fake and real data. Then, fake ones are called false (0) and real images are called true (1). In order to calculate the loss value, the given function is used. (Figure.5)

$$LD=Error(D(x),1) + Error(D(G(z)),0)$$

Figure.5 The loss function for discriminator

To maximize the value function by discriminator a partial derivative of V (G, D) with respect to D(x) is applied. The optimal discriminator is denoted as D(x) like the formula below. (Figure.6)

$$rac{p_{data}(x)}{D(x)}-rac{p_g(x)}{1-D(x)}=0$$

Figure.6 The value function after partial derivative After rearranging:

$$D^*(x) = rac{p_{data}(x)}{p_{data}(x) + p_g(x)}$$

Figure.7 The value function after partial derivative

During the training the generator, the discriminator accepted to be fixed. The main logic behind the generator is to confuse discriminator and make the fake images accepted by discriminator as real data. (Tae, 2020) The loss value of the images is calculated by the formula below. (Figure.8)

LG=Error (D(G(z)),1)

Figure.8 The loss function for generator

After training stages, we expect that the value of pdata(x) close to one (1) and pg(x) close to zero (0) if the sample is assigned true (1) by the discriminator. Likewise, to train a perfect discriminator we hope that pdata(G(z)) to be assigned to zero (0) by discriminator. Briefly, pg and pdata must be close to each other if we want a perfect trained system. (Mao, 2023)

During the training stage, a data package consisting of images from prototype and mass production vehicles is uploaded into the system to aid decision making and provide feedback to assembly teams. Assembly process continues efficiently by addressing potential assembly errors and deficiencies. After completing the process, a new data package comprising updated images is re-uploaded to the system. If the system approves it with a passing score, the mass production vehicle receives system approval. The proposed system introduces a new perspective to GANs, ensuring that vehicles on the mass production line are assembled to match the prototype. This approach reduces human dependency to some extent and enhances quality by minimizing errors in the production line.

3. Conclusion

To sum up, global economic crisis and rising inflation have made it difficult for companies to survive and have made it necessary to reduce costs. Efficient management of assembly processes has become more critical than ever. In industries where vehicles are produced in small quantities such as the defense sector, establishing mass production lines is neither practical nor cost effective. Therefore, alternative approaches to inspect and ensure the quality of production are indispensable.

Recent advancements in deep learning techniques offer promising solutions to address these challenges. Generative Adversarial Networks (GANs), a form of artificial neural networks, present an innovative approach for managing mass production quality. This paper proposed a new perspective to application of GANs, instead of generating fake images, the system leverages real images from serially produced vehicles and compares them with prototype images. This automated comparison can effectively identify discrepancies, significantly reducing inspection time and costs.

In addition to utilizing advanced technologies, this study emphasizes the importance of systematic process improvements through methodologies like Kaizen and lessons learned platforms. Kaizen which focus on continuous improvement, enables companies to refine their processes incrementally. By systematically collecting and analyzing improvement ideas from previous projects, organizations can enhance their operational efficiency. For example, integrating Kaizen ideas from earlier projects into new prototype assembly workflows ensures that successful practices are carried forward by reducing the likelihood of recurring errors.

The lessons learned platform complements this approach by serving as a structured repository of past project experiences. This platform not only documents assembly errors and their solutions but also ensures their timely dissemination to relevant stakeholders. For instance, insights from past challenges in integrating complex subsystems can guide new projects for improving project timelines, reducing costs and fostering knowledge sharing.

By combining modern technologies like GANs with structured methodologies such as Kaizen and lessons learned platforms, companies can address assembly challenges comprehensively. This integrated approach helps reduce assembly errors, optimize resource utilization and improve overall production efficiency. These measures are essential not only for maintaining competitive advantage but also for ensuring the timely delivery of high quality vehicles and meeting both customer expectations and operational requirements in critical sectors like the defense industry.

This strategy which balance technological innovation with process optimization, lays the companies for sustainable and efficient assembly management in modern military vehicle production.

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CHAPTER VI

An overview of AlGaN-GaN HEMTs Improvements over the Years

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1. Introduction

The development of Gallium Nitride (GaN) semiconductor technology marks one of the most transformative advancements in modern electronics. GaN's high-efficiency, high-power capabilities have solidified its role in applications spanning telecommunications, radar systems, and power electronics (Iannaccone & et al. 2021), (Roccaforte & et al., 2018), (Calle & et al., 2003), (Rocha & et al., 2023). Central to this evolution has been the High Electron Mobility

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Transistor (HEMT), a device first developed in 1969 to leverage the unique electronic characteristics of semiconductors with high electron mobility and low capacitance, qualities that GaN embodies with exceptional potential (Goray & et al.,2024).

Historically, the first wide-bandgap (WBG) semiconductor to gain attention for power electronics was silicon (Si). Silicon (SiC), with its native oxide, SiO₂, first Carbide saw commercialization in Schottky diodes, becoming widely used in high-voltage MOSFETs, JFETs, and diodes, achieving voltages up to 1700V (Iannaccone & et al. 2021). With a bandgap energy of 3.2 eV, electron mobility of 650 cm²/Vs, and thermal conductivity superior to silicon, SiC emerged as a crucial substrate in GaN HEMT technology, RF amplifiers, and power electronics (Hsu et al. 2021), (Islam et al., 2022), (Wu et al., 2001), (Jarndal, 2014), (Felbinger et al., 2007), (Kumar et al., (2002). GaN, however, soon became a frontrunner for high-power and high-frequency applications, given its 3.4 eV bandgap, high electron mobility of 2000 cm²/Vs, and high breakdown voltage, enabling rapid switching speeds (Flack, Pushpakaran, & Bayne 2016), (Joshi et al. 2024). Researchers saw the potential of GaN's properties in HEMT technology and chose SiC as a substrate to harness GaN's capabilities more fully.

The origins of HEMTs trace back to pioneering work on gallium arsenide (GaAs) and aluminum gallium arsenide (AlGaAs) in the late 1960s and 1970s (Rocha & et al., 2023). These materials were selected for their closely matched lattice structures, allowing for efficient electron mobility across a heterojunction interface—a boundary where two materials with different electronic properties meet. At this interface, HEMTs generate what is known as a two-

dimensional electron gas (2DEG), a thin layer of highly mobile electrons confined within a narrow channel (Hsu et al. 2021), (Islam et al., 2022), (Flores, 2012). This 2DEG, a groundbreaking concept at the time, allows HEMTs to operate at high frequencies by significantly reducing electron scattering (Ladugin et al., 2019), (Mehta & Jolly, 2016), (Pattnaik & Mohapatra, 2021), (Lenka & Panda, 2011), (Taylor et al., 1994), (Jiang et al., 2018), (Ha, 2002). Consequently, AlGaAs/GaAs-based HEMTs achieved high cutoff frequencies, reaching up to 110 GHz (Fletcher & Nirmal, 2017) in early implementations and nearly 1 THz in advanced models. This revolutionized high-frequency application, establishing HEMTs as the foundation of microwave communication, radar, and radiofrequency (RF) systems.

Despite these achievements, GaAs-based HEMTs eventually faced limitations in high-power applications. The breakdown voltage of GaAs, while suitable for many RF applications, fell short of the requirements for emerging high-power technologies, leading researchers to explore materials with wider bandgaps. The first AlGaN/GaN heterojunction was produced in 1991. Due to the similar atomic structures of AlGaN and GaN, the lattice mismatch remained minimal, providing stability. By 1993, AlGaN/GaN HEMTs were developed on SiC substrates, combining GaN's wide bandgap benefits with SiC's high thermal conductivity. This structure, termed the "GaN HEMT," allowed devices to handle high voltages, efficiently dissipate heat, and maintain stability in highpower applications (Figure 1).



Figure 1. Epitaxial Layer structure of GaN HEMT (Joshi et al. 2024).

In a GaN HEMT, the interface between GaN and an aluminum gallium nitride (AlGaN) layer creates the 2DEG, forming a conductive channel for electrons to move freely between source and drain. When voltage is applied to the gate, it modulates the electron density in the 2DEG, enabling precise control of current flow. This mechanism not only supports high-speed switching but also minimizes energy losses, making GaN HEMTs ideal for highfrequency and high-power applications. Compared to silicon-based counterparts, GaN HEMTs excel in applications demanding high efficiency and power density, as well as in emerging fields like electric vehicles, renewable energy systems, and advanced communication networks.

To provide a more generalized understanding of how GaN HEMTs function, this paper will begin by focusing on the operation of a basic GaN HEMT. While many variations of GaN HEMTs have emerged to enhance performance, the most foundational GaN HEMT leverages the properties of the heterojunction formed between its GaN and AlGaN layers. This heterojunction creates a two-dimensional electron gas (2DEG) at the interface, serving as a highly conductive pathway for electron flow from the drain to the source. The gate of the transistor controls electron density within this

2DEG, allowing precise modulation of current flow and enabling high-speed, efficient switching. The wide bandgap of GaN gives the device its ability to handle high voltages, while the high electron mobility within the 2DEG reduces resistance and supports highpower applications.

Since their commercialization, GaN HEMTs have undergone continuous refinement to address specific challenges, such as enhancing thermal management, improving electron mobility, and reducing power losses. These advancements have expanded GaN HEMTs' functionality across a wide array of electronic applications, positioning GaN as a foundational material for the future of power and RF electronics. This paper will examine the development of GaN HEMTs, with an emphasis on structural and performance enhancements that have been pivotal in realizing GaN's full potential.

2.Fundamental Properties of GaN-Based HEMTs

2.1 Structural Properties

As GaN is mainly a property of the Nitride semiconducters family (GaN, AlGaN, InGaN, InAlN, InAlGaN, AlN) its best that we consider its properties in a comprehensive manner. But to do that, a breakdown of this family's properties are needed.

As the terms suggest, all of nitride semiconducters are a good candidate for optoelectronics and microelectronics applications. Although the change in their physical and chemical structures create a difference in their values. This difference is shown Table 1 for researchers to classify and use these materials in a cost-effective and optimized way (Roccaforte & Leszczynski, 2020). Gallium Nitride (GaN) is known for a variety of properties, but when it comes to the performance of GaN High Electron Mobility Transistors (HEMTs), three characteristics stand out as particularly important: a wide bandgap, high electron mobility, and low intrinsic carrier concentration. These features make GaN HEMTs ideal for use in high-power and high-frequency applications.

Beyond these key material properties, the methods used to grow GaN thin films also play a significant role in how well the devices perform. There are several techniques for GaN epitaxy, including Metal-Organic Chemical Vapor Deposition (MOCVD), Molecular Beam Epitaxy (MBE), and Hydride Vapor Phase Epitaxy (HVPE). Of these, MOCVD is often preferred because it offers advantages like low surface roughness, high material purity, and the ability to scale up for mass production.

While the basic working principle of GaN HEMTs was introduced earlier, here it will take a deeper look at the most crucial factors that drive the outstanding performance of GaN-based devices in cutting-edge electronic applications.

Table 1. Properties of GaN, its comparisons with other nitrides andtheir implications in material growth, optoelectronics and power-high frequency electronics (Roccaforte & Leszczynski, 2020).

	Property	Value/range	Comparison with other semiconductors
Material growth	Density, p	6.1 g/cm3 (GaN)	Because of the high melting point and low
	Atomic density	4.37×10 ²² atoms/cm ³ (GaN)	decomposition temperature, nitride crystals (bulk and epi) are grown at low temperatures. Therefore, the crystals (substrates) cannot be grown from the melt as other semiconductors
	Melting point	2573°C at 60 kbar for GaN, 1100°C for InN, 2200°C for AlN	Moreover, the epilayers grown at low temperatures have a large number of imperfections.
	Decomposition temperature at 1bar	900°C for GaN 600°Cfor InN	
	Small influence of dislocations on luminosity of InGaN QWsandon electron scattering at low currents		Blue/green GaN-based LEDs and HEMTs can be fabricated using foreign substrates (Si, sapphire, and SiC)
	High critical Peierls– Nabarro shear stress for slip systems (1123){1122} and (1123){1101}	29.8–54.7GPa	Dislocations do not move upon stress or illumination (no degradation of optoelectronic devices related to dislocation motion as it is the case for other III–V materials)
Optoelectronics	Direct band gap	From 0.7eV (InN) to 6.1 eV (AIN)	Nitrides dominate in the green/blue/UV spectral range. II–VI compounds are comparable, but they are too fragile to be used in devices. In infrared and red spectral range, GaAs- and InP- based devices have still much higher efficiencies
	Build-in internal electric field	Up to 2MV/cm (InGaN/GaN)	T hestrong build-in internal electric field increases the spatial separation of electrons and holes, thus reducing the efficiency of radiative recombination in optoelectronic devices
Power/high- frequency (HF) electronics	Wide band gap, E_g Critical electric field, E_{CR}	From 3.4eV (GaN) to 6.1 eV (AlN) 3–3.75MV/cm (GaN)	Possible applications of GaN-based materials in high-voltage, high-power, and high-temperature electronics, in competition with SiC (and possibly in future, with Ga ₂ O ₃ and diamond). The high defects density still hinders the full
	Electron affinity, χ Dielectric constant, ε r	3.1-4.1eV (GaN)	exploitation of the electric f ield strength
		9.5 (GaN)	
	concentration, n _i	≈10 ¹⁰ cm ³ (GaN) at room temperature	Lowleakage currents and high operation temperatures are possible, if the GaN material quality is improved
	Electron saturation velocity, ν	3×10 ⁷ cm/s (GaN)	Enable the fabrication of devices operating at high frequencies, in competition with the traditional GaAs technology
	Electron mobility, μ_n	1100–2000cm ² /V s (GaN, AlGaN/GaN)	
	Thermal conductivity, κ	1.3–2.1W/cm K (GaN)	Comparable to Si but significantly lower than SiC and diamond, making the heat dissipation a concern for GaN-based power devices

2.2 Formation of AlGaN/GaN Heterojunctions

The core of a HEMT (High Electron Mobility Transistor) structure relies on a heterojunction formed between two semiconductors that influence the electron density at the gate.

Originally, the two semiconductors used in this structure were AlGaAs and GaAs. However, these materials were not powerful enough for certain applications, leading researchers to develop a new heterojunction design. This new structure combines a semiinsulating GaN base layer with an AlGaN barrier layer. The GaN base layer plays a crucial role in the overall growth and performance of the GaN HEMT material. As a result, much of the recent research has focused on improving the properties of this base layer to enhance the performance of the device (Supryadkina et al., 2013), (Shih et al., 2022).



Figure 2. Difference of AlGaN and GaN structures (Liu & et al., 2021).



Figure 3. Difference of Lattice Constants between GaN, AlGaN, InGaN (Shih et al., 2022).

The formation of a heterojunction requires minimal lattice mismatch between the semiconductors involved. Lattice mismatch arises from differences in lattice constants, which represent the spacing between atoms in the crystal structure. In AlGaN/GaN highelectron-mobility transistors (HEMTs), the lattice structure of GaN slightly differs from that of AlGaN due to the incorporation of aluminum, which alters the atomic arrangement. Although these differences may appear minor, they induce mechanical strain during the cooling process, potentially leading to cracks in the material.

In recent years, advanced techniques have been developed to address these challenges. Buffer layers, such as AlN or AlGaN, have been employed to mitigate lattice mismatch by compensating for the thermal expansion stress, thereby reducing strain. Furthermore, advancements in multi-layered structures and stress management during the epitaxial growth process have significantly improved material stability. These innovations have made AlGaN/GaN structures suitable for commercial applications, including lightemitting diodes (LEDs) and power electronic devices (Cheng & et al., 2016), (Cummings, 2004), (Shiojiri & et al., 2006).

However, despite these advancements, the issue of stress and cracking persists, particularly in the growth of thicker GaN films. Further research and innovation are required to fully eliminate these challenges.

AlGaN/GaN semiconductors exhibit two key types of polarization: Spontaneous Polarization (PSP), Piezoelectric Polarization (PPE).

Spontaneous polarization arises from the noncentrosymmetric wurtzite crystal structure, where the asymmetrical alignment of gallium and nitrogen atoms creates a built-in electric dipole along the c-axis. This effect is more pronounced in AlGaN due to aluminum's influence on the crystal lattice.

Piezoelectric polarization occurs when the lattice mismatch between AlGaN and GaN induces strain during epitaxial growth. This strain generates additional polarization, further enhancing the total polarization at the AlGaN/GaN interface (Liu & et al., 2021), (Cheng & et al., 2015).

The combination of PSP and PPE results in a strong electric field at the interface, enabling the formation of a high-density twodimensional electron gas (2DEG) without doping. This unique feature distinguishes HEMTs from GaN-based JFETs.

2.3.Two-Dimensional Electron Gas (2DEG)

As mentioned in the polarization effects, 2D electron gas (2DEG) is a produce of the both spontaneous and piezoelectric polarization's combined effect. This happens because AlGaN and GaN each have different band gaps, which leads them to having electrons flow at different energy levels. The energy level difference of GaN is shown in Figure 4. This difference of energy levels cause them to feature polarization effects, which is why 2 types are polarization exist in the first place. Thus, the polarization we mentioned refers to the seperation of positive and negative charges at the interface between AlGaN and GaN (Fletcher & Nirmal, 2017)



Figure 4. The energy difference in energy levels of AlGaN and GaN in order to 2DEG to be produced (Fletcher & Nirmal, 2017).

a. Polarization-Driven Formation Mechanisms of the 2DEG

Due to the polarization effect featuring in the interface of the heterojunction, a positive net charge forms at the specified interface. This positive charge, pulls down the conduction band in GaN layer, and in turn lowers the energy level of electrons.

Because of the downward shift of the conduction band, the electrons from nearby energy levels get attracted to this interface region. And in turn, they accumulate in a very thin region. This creates a conduction path or in other words a "channel" of electrons and forms the 2DEG at the interface of heterojunction. Electrons can move freely in this thin channel, but its only in two dimensions as the 2DEG name suggests. The movement of electrons in this 2D gas enchances the mobility of the transistors. And this is why HEMTs are called electron mobility transistors.

b. Theoretical and Experimental Models for 2DEG Density Estimation

How the 2DEG comes into place with the consideration of polarization effects, resulting in a charge accumulation has been reviewed. But reflecting the relationship between the polarization
charge in the interface and energy band offset between materials should be shown with an equation for comparations.

This formula shows the influence of material properties, device design parameters such as schottky barrier height and fermi energy level and insight into polarization effects. All this helps to optimize the device performance. Thus the equation of 2DEG density has come into place.

The 2DEG density n_s depends on several material and physical parameters, can be expressed as Eq.1. 1;

$$n_s = \frac{\epsilon r \Delta E_C}{q(t_{AlGaN})} - \frac{q \phi_b - E_F}{q}$$
(1.1)

Where values are:

- ε_r is the dielectric constant of AlGaN, determining ability to hold charge.
- ΔE_c is the energy difference between the conduction bands of AlGaN and GaN.
- *q* is the elementary charge (charge of an electron)
- t_{AlGaN} is the thickness of the AlGaN layer
- $q\phi_b$ is the schottky barrier height of the gate contact (this influences the threshold voltage)
- E_F is the fermi energy level relative to the GaN conduction band.

In summary, the equation represents the relationship between the polarization charge at the interface, the energy band offset between the materials, and the material properties that control the distribution of electrons. In 2024, the highest 2DEG density reached has been 10^{13} electrons per square meter, especially in materials where high-Al-content barriers or innovative materials such as ScAlN was used as a substrate to GaN (Lenka & Panda, 2011).

2.4 Gate Modulation and Control Mechanisms

In a GaN/AlGaN HEMT, gate control is achieved via the Schottky Barrier formed between the metal gate and the AlGaN layer as said in section 2.3. Simply said, the gate controls the 2DEG at the interface of AlGaN/GaN by modulating the electric field. If a voltage is applied to the gate, It changes the potential in the AlGaN layer, effecting the electron concentration in the 2DEG. Thus the device can operate and called "operating mode" And if a negative gate voltage is depleted the 2DEG, this turns off the device by applying a reverse electric field that repels electrons from the AlGaN/GaN interface. This change in the 2DEG, reduces the number of free electrons in the conduction channel, creating the "depletion mode" of HEMT where it doesnt operate.

As its mechanism suggests, the gate controls the conduction channel without direct contact with 2DEG. In short, relies on the polarization-induced electric field to adjust the charge density (Islam & et al., 2022), (Rao & et al., 2022), (Wang & et al., 2024). This can also be visualised by the Figure 5.



Figure 5. The Basic AlGaN/GaN Structure (Li, 2024).

2.5 High Breakdown Voltage Capabilities

High breakdown voltage, as shown in the general features of GaN HEMTs, refers to the maximum voltage that a semiconducter device can withstand before it experiences a significant electrical breakdown. Electrical breakdowns occur when the material within the device becomes conductive, leading to an uncontrollable flow of current, which has been called as "leakage current" or "off-state leakage current" in recent papers. Thus this permanently damages the device.

In context of semiconducters, high breakdown voltage is critical, especially for high-power and high-voltage applications. The key factors that influence a device's breakdown voltages can include material properties, device structures and doping levels. Since the wide bandgap of GaN is 3.4eV and has a high electron mobility like mentioned, the high breakdown voltage often exceeds kilovolts. Thus GaN being able to handle larger voltages before a breakdown.

This feature of AlGaN/GaN HEMTs allows the devices to handle higher power densities, making them ideal for applications such as power converters, RF amplifiers and switching systems for the area of high breakdown voltage (Liu & et al., 2014), (Yang & et al., 2019).

2.6 Low On-State Resistance (Ron)

Low on-resistance (R_{ON}) in HEMTs refers to the minimal resistance the device exhibits when its in the "on" state, in order to allow current flow through the device with minimal voltage drop. The matter of low on-resistance is important for efficiency and heat management concerns.

For AlGaN/GaN HEMTs, the value of R_{ON} is dependent on the 2DEG. Since 2DEG forms a high density and high mobility electron channel, it facilitates efficient current conduction, reducing the device's on-resistance compared to conventional silicon-based transistors. The key factors of low on resistance could be found as 2DEG formation, material properties like high critical electric field and device geometry for optimizing the gate lenght.

The typical on resistance values of advanced AlGaN HEMTs have been shown to be 1 to $10m\Omega \cdot cm^2$ as of 2024 (Inada & et al., 2006), (Subramani & et al., 2016). This enables GaN to have a much better thermal management and able to handle high current densities with minimal power. Thus, it has been most used in power electronics.

3. Evolutionary Advances in AlGaN/GaN HEMT Technology

GaN HEMTs have shown clear improvements over the years as newer and better technological tools and methods have been developed. Most of these developments have been produced handin-hand or on top of each other. Thus, its important to evaluate how far the GaN technology has gotten via comparing those.

So, in this section, ~4 decades by each year's examination will be observed on the improvement of GaN HEMTs.

3.1 The Early Development Phase: 1990–2000

3.1.1 First Experimental Realization of AlGaN/GaN Heterojunctions (1993)

Asif Khan et al.(Khan et al., 1993) grew the first AlGaN/GaN heterojunction succesfully, using Metal-Organic Vapor Phase Epitaxy (MOVPE). Despite the initial challenges of crystallographic quality, they have achieved the two-dimensional electron gas (2DEG) mobility of around 600 cm²/V.s located at the AlGaN/GaN interface. This development has marked the beginning of the nitride-based high electron mobility transistors (HEMTs).

This version of HEMTs were qualified as "depletion mode HEMTs". This came from the fact that when no voltage was applied to GaN HEMT, the transistor was "on". This was because of the presence of 2DEG at the AlGaN/GaN interface. This "normally on" behaviour is the typical behaviour of "depletion mode transistors", where the device conducts currents without any gate bias, requiring a negative gate voltage to turn off. The structure of a depletion HEMT is shown in Figure 6.



Figure 6. Structure of a p-HEMT (Zeng & et al., 2018).

The first HEMT, which is depletion HEMT works via a schottky gate mechanism as represented in the introduction. The source and drain metal stacks make use to facilitate the ohmic contacts. This metal stack, in turn provides the transistor a schottky contact. Thus when a voltage of V_{DS} is applied near drain and source, a lateral electrical field is created and 2DEG under the gate channel flows along the AlGaN/GaN heterojunction as the HEMT's main current: I_{DS} . However, if the gate voltage falls below the threshold

voltage and the drain remains highly biased, the device enters the block (off) region (Zeng & et al., 2018), (Aadit & et al., 2017).

Thus, this concludes the working structure of depletion HEMTs. Topics like 2DEG and heterojunction of AlGaN and GaN were already explained in the properties section.

3.1.2 Elucidation of Polarization Effects in AlGaN/GaN Systems (1997)

In 1997, Bernardini et al. (Bernardini & et al., 1997) made a significant contribution to the AlGaN/GaN heterostructures via determining the spontaneous and piezoelectric polarization constants in nitride metarials. This was regarded as important because the polarization effects that were examined in the Table 2 and 3 are critical to the formation of the 2DEG at the interface of AlGaN/GaN. Thus, becoming important for the operation of HEMTs.

 Table 2. Structural examination of AlN, GaN and InN (Bernardini & et al., 1997).

Material	a₀(bohr)	<i>c</i> ₀ / <i>a</i> ₀	U ₀
AIN	5.814	1.6190	0.380
GaN	6.040	1.6336	0.376
InN	6.660	1.6270	0.377

Via this examination, researchers could accurately determine the polarization constants and better predict the control mechanism of 2DEG in especially the density-mobility area.

Table 3. Parameters that calculate the spontaneous polarization (in units of C/m2), Born effective charges (e units), piezoelectric constants (in units of C/m2) for the III-V wurtzite of Nitrides and for the II-VI wurtzite of oxides.

	p ^{eq}	Z*	du/de3	e 33	e 31	<i>e</i> ₃₃ ⁽⁰⁾	$e_{31}^{(0)}$
AlN	-0.081	-2.70	-0.18	1.46	-0.60	-0.47	0.36
GaN	-0.029	-2.72	-0.16	0.73	-0.49	-0.84	0.45
InN	-0.032	-3.02	-0.20	0.97	-0.57	-0.88	0.45
ZnO	-0.057	-2.11	-0.21	0.89	-0.51	-0.66	0.38
BeO	-0.045	-1.85	-0.06	-0.02	-0.02	-0.60	0.35
ZnO ^a	-0.05	-2.05	-0.25	1.21	-0.51	-0.58	0.37
BeO ^a	-0.05	-1.72	-0.09	0.50		-0.29	

3.1.3 Experimental Validation of 2DEG Characteristics in GaN HEMTs (1999)

In 1999, 2 different researchers have put their researchs. These will be researched sequentially with a and b.

a. The Role of Polarization and Heterostructures in 2DEG Formation

Ambacher et al. (Ambacher & et al., 1999) proposed a model that became widely adopted in GaN research community and analytically described the properties of the 2DEG in AlGaN/GaN heterostructures. While Bernardini et al. (Bernardini & et al., 1997) published his paper also on polarization effects, it mostly focused on the theorization of AlGaN/GaN heterostructures, calling the-now HEMTs "HFETs". Meanwhile this paper focused most on the practicality of these polarizations' effects, and on top of that 2DEG prodution caused by it. Because of such reasons, this paper became a crucial for improving 2DEG properties.

Researchers examined the heterostructures grown by MOCVD and PIMPE. In these examinations, they used the "Halleffect" and C-V profiling techniques to measure the sheet carrier concentration of the 2DEG. The observations showed that the aliminum concent of the AlGaN barrier increased from x = 0.15 to x = 0.31. Thus, the sheer carrier concentration rose from 6 x 10^{12} to 2 $x \ 10^{13}$. This increase was examined to the compensation of a positive polarization-induced sheet charge by the high-density carriers. The sheet charge resulted from the differing spontaneous and piezoelectric polarizations between the GaN channel and AlGaN barrier. Likewise, as Al in the AlGaN barrier increased, its spontaneous and piezoelectric polarization also did. This leaded to a sheet carrier concentration of 1.67 x 10^{13} cm⁻² for x = 0.3. This heterostructure also exhibited low sheet resistivities with a minimum number of 190 and 300Ω for undoped material with Al content between x = 0.2 and x = 0.3. The Figure-data graph is given in the Figure 7 (Ambacher & et al., 1999).



Figure 7. 2DEG Mobility sheer carrier concentration products and sheet resistivities for AlGaN/GaN interface roughness (Ambacher & et al., 1999).

b. Transition from Sapphire to SiC Substrates: A Comparative Analysis

At the same time, another researcher, Sheppard et al. (Sheppard & et al., 1999) demonstrated high-power microwave AlGaN/GaN HEMTs grown on a Silicon Carbide (SiC) substrate, highlighting the potential of high-power applications.

The difference of this improvement being mainly the Si 4H-SiC substrate. While Ambacher et al. (Ambacher & et al., 1999)'s paper used sapphire as a substrate, Sheppard et al. (Sheppard & et al., 1999) changed it with SiC. This this resulted in having a much higher thermal conductivity such as $3.3W / cm_iK$, higher power densities (due to better heat management) raging from 5.3 to 6.9 W/mm, higher efficiency gain, reduced parasitic effects, higher breakdown voltage and minimized heating. A graphic for 10 GHz

CW power sweep for 0.25mm GaN/AlGaN HEMT has been shown in Figure 8.



Figure 8. 10GHz power sweep for 0.25mm GaN/AlGaN HEMT on Si 4H-SiC demonstrating a power density of 5.28W/mm. (This device was biased at $V_{DS} = 32V$ and $V_{GS} = -2.25V$ (Sheppard & et al., 1999).

3.2. Key Technological Advancements During 1990–2000

Surface State Characterization of Nitride-Based Materials (2000)

This new research paper produced by Ibbetson et al.(Ibbetson & et al., 2000) has a difference in the main properties of 2DEG and AlGaN/GaN heterostructure field-effect transistors (HFETs). As a different perspective, he demonstrates that surface states and particularly donor-like surface states play a crucial role in supplying the electrons for the 2DEG rather than thermal generation or unintentional doping. The polarization induced charges at the

interface are important for enabling high electron densities that are responsible for generating the 2DEG.

Its important to point to where this study directly links experimental Hall data to the presence of 1.65eV surface donors and their impacts on the 2DEG. Thus challenging the idea that polarization charge alone can explain this behavior, Emphasizing the surface donor model. Donor model of undoped AlGaN barrier has been also shown in Figure 9. Thus, this paper has mainly clarified the nature mechanism of the 2DEG heterostructure



Figure 9. Illustration of donor model with undoped AlGaN barrier thickness (a), less then (b) and greater than the critical thickness of formation for 2DEG. Fermi level relative to the surface of the state is examined. (c) Calculated 2DEG density as a function of barrier thickness according to the surface donor model. (Ibbetson & et al., 2000).

Novel Reduction Techniques for GaN Substrate Defects (2001)

This document produced mainly by the Motoki, K., Okahisa, T., Matsumoto, N. et al. (Motoki, 2010) researchers' group, respresenting the Sumitomo Electric, bought patent of DEEP method from Tokyo Agriculture University to grow GaN crystals on GaAs substrates using the HVPE method, bowing dislocations in the small regions.

Initially for the GaN epitaxical growth, sapphire (Al_2O_3) was used as a substrate, similar to the use of GaN in LEDs. However, since the mismatch in crystal lattice constants between GaN and sapphire was around %16, this lef to high dislocation densities in GaN layers, which are acceptable for LEDS but causing long-term stability problems for laser diodes that require higher densities.

Besides the usage of sapphire, GaAs as an alternative substrate offered better thermal expansion compatability than sapphire, but suffered from a %20 lattice mismatch, leading to significant dislocation generations at the interface of GaN/GaAs. The approach done in Sumitomo Electric was growing thick GaN layers on foreign substrates using Hydride Vapor Phase Epitaxy (HVPE). This method was chosen because of its similarity existance of chlorine-based vapor phase epitaxy techniques. The sequence of the HVPE went on like this:

- GaN was grown on GaAs substrate, which were then removed through mechanical process of lapping and polishing.
- This left behing a freestanding GaN crystal.

Despite the improved thermal expansion match, dislocation densities remained high due to significant lattice mismatching. Although another method for crystal dislocations were also used. This method that Sumitomo Electric created was called "A-Deep (Advanced-DEEP)". This was a technique built and improved upon the older one called "DEEP (Dislocation Elimination by Epitaxical-Growth with Inverse-Pryamidal Pits)". Normally DEEP process went on by naturally forming large inverse-pyramidals pits on the surface during GaN growth. As the crystal grew, threading dislocations propagated horizontally along the facet planes. This eventually concentrated in the center of these pits, leaving the surrounding areas with much lower dislocation densities of around 10^5 cm⁻².

Sumimato Electric improving the DEEP technique, they reacher A-DEEP which improved the process by controlling the position of pits using polarity inversion techniques. It operated with pre-determining the pit locations by patterned layers and in turn providing a more uniform reduction in dislocation density, thus ensuring the low-dislocation areas concided with the intended locations of the laser diodes. By achieving dislocation densities low as 10³ cm⁻², a critical breakthrough for producing long-lifetime high-power violet laser diodes were made. Showing the difference of substrates is given in Figure 10.



Figure 10. Comparison of laser lifetime and dislocation densities (Motoki, 2010). --121--

The diodes grown on low-dislocation GaN substrates achieved lifetimes excelling 100.000 hours, which was a tenfold improvement over the earlier technologies based on sapphire and GaAs (Motoki, 2010), (Motoki & et al., 2001).

3.3 Progress Achieved During 2000–2010

Due to safety concerns and faster switching speeds, a lot of researchs have been doing research on Enchancement HEMTs (E-HEMTs). And for a long time, this process has been achieved with developing a E-HEMT operation by recessing the AlGaN layer under the gate. Meanwhile this method being widely used to convert the depletion mode HEMTs into enchancement mode by reducing the 2DEG density, this technique was causing damage and non-uniformity in the structure. So it has been puzzling the researchers for a new structure to be made. So in 2006, Saito et al. (Saito & et al., 2006) and Cai et al. (Cai & et al., 2006) respectively proposed that by recessing the HEMT structure and fluorine implantation, "Enchancement HEMTs (eHEMTs)" could and have been achieved in a better and safer way. Thus, an alternative has been found.

3.3.1 Surface Passivation through Fluoride-Based Plasma Treatments (2006)

This fluoride-based plasma treatment also came with CF₄. Meaning that this method involved the incorporation of fluorine ions (F^-) into the AlGaN barrier layer. These fluorine ions, being highly electronegative, acted as immobile to negative charges, in turn raised the energy potential of the AlGaN barrier, depleting the 2DEG channel under the gate at zero gate bias. As a result, the threshold voltage (V_{TH}) was also shifted positively, allowing for the creation of E-mode HEMTs without altering the physical structure of the AlGaN layer.

The key production of the E-mode HEMTs could be divided into two, for the sake of clarity. One of which is CF_4 treatment. This treatment includes that before gate electrode deposition, the gate region gets treated with CF_4 plasma. In basic terms, this implants fluorine ions into the AlGaN barrier. The treatment time and power of this process determins the degree of threshold voltage shift.

Second is the post-gate annealing. After gate metal deposition, the devices undergo a rapid thermal annealing (RTA) at tempratures of 400°C, just so it can recover from plasma-induced damage without affecting the threshold voltage.

The mechanism of the e-HEMT operates based on the positive shift of its threshold voltage (V_{TH}). Normally, in a D-Mode HEMT, the device is normally on, thus allowing the current to flow freely. And when the gate voltage (V_G) is zero, then a negative gate voltage is required to turn it off. However in the E-HEMT structure, the threshold voltage shifts positively, which in turn makes the device "normally-off" at zero gate voltage. So it requires positive gate voltage to turn on. The new e-HEMT Figure is shown in the Figure 11.



Figure 11. The old structure of a fabricated AlGaN/GaN HEMT's recessed-gate (Saito & et al., 2006).



Figure 12. Immobile negative charges incorporated directly under the gate to the AlGaN/GaN HEMT, making it E-HEMT (Cai & et al., 2006).



Figure 13. Conduction-band diagram of CF4 plasma treated Emode AlGaN/GaN HEMT (Cai & et al., 2006).

Thus with this new technique, while the older depletionmode HEMTs typically has a threshold voltage around -4V, fluorinebased plasma treatments could hold a threshold voltage up to 0.9V, while the older recessed E-HEMTs has shown a general threshold (V_{TH}) of 0.35V to 0.5V (Lanford & et al., 2005). While fluorinebased AlGaN/GaN HEMTs can seem disadvantegious, the real advantage of them come from the precision and uniformity of the fabrication process, which makes them improve overall in device reliability. And the gate leakage reduction that's a big problem for the HEMT devices, has been also lowered thanks to the fluorine ions suppressing the current in forward and reverse bias conditions. All thanks to this, the E-HEMT has been improved ever since.

3.3.2 Introduction of Gate Injection Transistor (GIT) Architectures (2007)

The first ever AlGaN/GaN metal-insulator semiconducter (MIS) HEMT, made by a normally-off GaN based transistor using conductivity modulation, was found to be developed in 2007, by Uemoto et al. and his research group (Uemoto & et al., 2007). Being

another alternative to the families of E-HEMTs, the GIT-HEMT uses hole injection and has more complex heterojunction.

The gate of GIT is made from p-type AlGaN, which has an abundance of positive charge carriers. And when a sufficient high positive is applied to the gate, holes are injected from p-AlGaN into the AlGaN/GaN heterostructure. The holes that were injected travel from p-AlGaN into the undoped GaN layer, thus this action increases the electron density in the channel and enchancing drain current. Its important to note that this hole injection leads to conductivity modulation, which is very similar to how insulated gate bipolar transistors (IGBTs) function.

The structural of GIT design offers a silicon substrate, which reduces costs compared to devices made on sapphire or silicon carbides. GIT also includes other buffer layers to manage the strain due to the lattice mismatch between GaN and silicon substrate (Figure 14).



Figure 14. The Structure of AlGaN/GaN GIT-HEMT (Uemoto & et al., 2007).

Performance vise, the GIT exhibits a threshold voltage of 1.0V and in turn it achieves a maximum drain current of 200 mA/mm. The device at the time could only handle a gate voltage up to 6V. The on-state resistance of the GIT device is also calculated to be $2.6m\Omega.cm^2$, and the off-state breakdown voltage being 800V, makes it very suitable for power switching applications.

In summary, the device's properties include high breakdown voltage and low on-state resistance achieved with a normally-off HEMT, making it advantageous for high-power and high-efficency switching applications (Uemoto & et al., 2007).

3.4. Recent Innovations and Refinements: 2010–2021

3.4.1 Integration with Silicon Substrates for Cost-Effective Fabrication (2012)

Silisium (Si) wafers opened the way to integrate GaN HEMT device fabrication in Si complementary metal-oxide semiconductor (CMOS). This progression was demonstrated by Dolmanan et al. (Dolmanan & et al., 2012) in 2012. The main premise of this paper included the inclusion of 200mm Si (111) substrates below AlGaN/GaN heterostructures.

By growth on large silicon substrates, researchers have achieved a crack-free growth of AlGaN/GaN heterostructure on a 200mm diameter Si (111) substrate. This process was carried out by using a metal-organic chemical vapor deposition (MOCVD) with a total nitride stack thickness of around 3.3μ m. But structural analysis via transmission electron microscopy (TEM), high-resolution x-ray diffraction (HRXRD) and raman spectroscopy has shown high crystal quality and low dislocation density. Hall measurements also confirmed high electron mobility (1800-1900 cm²/V.s) and a low sheet resistivity across the 200mm vafer, indicating good electrical properties suitable for device applications.

The fabricated performance of the $1.5\mu m$ gate length demonstrated promising performance, with a maximum drain current density of 660mA/mm and an entrinsic transconductance of 210mS/mm. While the results of this has shown that they are suitable for high-power electronics devices, there were also challenges. One of which was that the lattice mismatch and thermal expansion coefficient differences between GaN and silicon were high, causing mechanical strain and dislocation effects in the HEMT.

While it wasn't perfect, it still was very suitable for integration of already existing silicon-based microelectronics. Thus this development made possibilities for cost-effective production of GaN devices (Dolmanan & et al., 2012).

3.4.2 Development of Hybrid Schottky–Ohmic Drain Structures (2012–2016)

a. Initial Innovations in 2012

In general, GaN HEMTs require higher breakdown voltages, as their name suggests. Improvements such as lower on-resistance and robust high-temperature performance are also necessary. To address these challenges, in 2012, S. H. Hsu and his group (Lian & et al., 2012) experimented with silicon-based AlGaN/GaN HEMTs featuring a hybrid Schottky-ohmic drain structure. Their research has benefits to enchance the device's perfomance particularly in properties of breakdown voltage, leakage current, ON-resistance.

The structure they grew was with the method of metalorganic chemical vapor deposition (MOCVD), and consisted a 2- μ m buffer layer, 2- μ m GaN channel, 25-nm Al_{0.25}Ga_{0.75} barrier layer and a 3---128--

nm UID cap layer. The drain design involved a schottky extension of varying lenghts like 1,2,3 and 4μ meters, placed between the ohmic contact and the drain edge. This was done in order to smooth the electric field and enchancing performance. The structure they made reduced the source-drain distance (LSD) for a higher RF performance.



Figure 15. The comparison of different types of drain electrodes of AlGaN/GaN HEMTs on silicon. (a) Ohmic drain ,(b) Schottky drain ,(c) Hybrid drain (Lian et al., 2012).

The fabrication process of the hybrid drain HEMTs were done by combining the ohmic contacts and schottky gate in a multilayer structure. Ohmic contacts of this device were fabricated via recessing the area to reduce contact resistance and the metals used were Ti/Al/Ni/Au (as given in the Figure 16) and were deposited via e-gun evaporation followed by rapid thermal annealing at 800°C for 30 seconds.

The schottky gate and the schottky extension were fabricated using Ni/Au deposited by, again, e-gun evaporation. These layers --129--

were followed by a liftoff process which allowed better control of the schottky extension.

Thus this devices were passivated using a multilayer SiNx/SiOx/SiNx structure deposited via PECVD. This helped it protect the layers of oxidation and other damage during the high-temperature process.



Figure 16. Different types of drain electrodes for the Device layout of AlGaN/GaN HEMTs on silicon. (a) Ohmic drain, (b) Schottky drain, (c) Hybrid drain (Lian et al., 2012).

This version of AlGaN HEMT was tested for its DC characteristics and the result of On-resistance (Ron) for the hybrid drain device was around $3.4m\Omega$.mm. This is slightly lower than $3.7m\Omega$.mm that the schottky extension had. And the breakdown voltage was significantly improved to a maximum of 960V due to the addition of schottky extention, also improving the hybrid drain's ability to enchance off-state performance. (Lian & et al., 2012).

So in conclusion, the hybrid schottky-ohmic drain drain has presented that offered substantial benefits for the improvement of AlGaN/GaN HEMTs. Especially in important areas like breakdown voltage, leakage current and ON-resistance. Thus making it highly suitable for high-frequency devices once more.

b. Optimizations Achieved by 2016

This research of Shawn S.H. Hsu and the department of electrical engineering research group (Tsou & et al., 2016) has improved the newly mentioned Hybrid Schottky–Ohmic Drain HEMT's in a way that improved the breakdown voltage, lower leakage current reduction and such. This difference was achieved with the refinement of the hybrid drain that acts similarly to a field plate, which helped to further smooth the electric field and reduce electric field peaks at the drain, leading to enchancing the breakdown voltage and leakage suppression. The thicker epitaxical buffer layer also helped to lower the leakage currents, while the Schottky extention of Γ -shaped electrode refines the electric field distribution, resulting the field crowding near the ohmic contact.

The newly made hybrid drain structure refined the design in a way that it can focuse on optimizing the electric field distribution at the drain side. The newly structure also used a thicker epitaxial layer up to 4.8µm and an enchanced buffer design to help manage the vertical leakage current more effectively, particularly when combined with the hybrid Schottky-ohmic drain structure. All this structural changes enchanced the overall device reliability when suppressing leakage currents.

The schottky extension of Γ -shaped electrode refined the electric field distribution around the drain, that resulted in more field distribution. The later added auxiliary current path of the hybrid Schottky-ohmic drain managed to his reduce the leakage current and

improved the breakdown voltage without increasing the ONresistance. In turn allowing better current conduction without adding to the ON-resistance.

Last addition would be that this version introduces a noadditional-complexity for the process of photomasks or extra processing steps in the HEMT production process.

With all these changes, value of breakdown voltage has improved 64.9% from 960V to 1100V respectively. And leakage current is suppressed by an order of magnitude due to better electric field management. All these changes made it more practical for especially RF productions, power supplies, electric vehicles and fastcharging systems (Tsou & et al., 2016).

c. Advancements in Hybrid Schottky–Ohmic Drain HEMTs: Achieving High Breakdown Voltage and Enhanced Performance (2023)

After a long time of try and error, in 2023 Weihang Zhang (Fan & et al., 2023), Jincheng Zhang (Fan & et al., 2023) and their research team has reached a breakdown value greater than 3000V, a leakage current less than 0.1 μ A/mm, dynamic R_{ON} dispersion less than %30 at drain biases up to 650V, on-off current ratio above 10⁹ and temperatures as high as 473K in the Hybrid Schottky–Ohmic Drain HEMT applications.

The major change of value came from the structural changes of the device. When hybrid drain is passivated with Al_2O_3/SiO_2 this resulted in better high-temperature and superior breakdown voltages. This passivation layers were also critical for suppressing dynamic R_{ON} degradation and protection of the device from plasma damage during the process. Fabrication techniques in the other hand, included an advanced electron beam evaporation technique for fabrication of Schottky contact, and used the "atomic layer deposition (ALD)" for Al₂O₃, thus contributing to better device performance. The isolation of the mesa via ion-beam etching and used Ohmic/Schottky hybrid drain fabrication on the same wafer, optimizing the gate metal and passivation process.



Fig. 17. Schematic Structure of the DH-HEMT using the Hybrid Drain structure (Fan et al., 2023).

In summary, the process of Al_2O_3 passivation has led to big improvements in the hybrid drain design. Reaching 3000V while ensuring minimal power dissipation and high-temparature reliability (Fan & et al., 2023).

3.4.3 Diamond/GaN HEMTs: High-Thermal Conductivity Solutions (2006–2021)

The Diamond/GaN HEMT was first introduced in 2003 Ejeckam et al. (Ejeckam & et al., 2014) and GaN-on-diamond wafers were produced in 2004 Ejeckam et al. (Ejeckam & et al., 2014) to adress thermal management issues in high-electron mobility transistors (HEMTs) made from GaN. While GaN is excellent for high-power and high-frequency applications, it suffers from localized hotspots that cause performance and reliability issues due to its relatively low thermal conductivity. While there have been other candidates as good thermal conducters such as highly oriented pyrolytic graphite (HOPG) and graphene, diamond had a highter out-of-plane K (2000 W/m.K), increasing to even 3300W/(m.K) while electrically insulating, also having a 60 times greater breakdown field comparing with Silisium (2x10⁷ V/cm). Thus allowing higher thermal conductivity, better performance and increased reliability.

The basic structure of a Diamond/GaN HEMT includes a substrate layer made of diamond, a nucleation layer of aliminum nitride (AlN), a GaN buffer layer to reduce defects and provide electrical isolation, an AlGaN/GaN heterojunction and additions to the layers such as passivation, a field plate and barrier layer (AlN or GaN). The substrate layer supports the growth of GaN layers, nucleation layer accomodates strain and ensures smooth epitaxical growth, the AlGaN/GaN heterojunction forms the 2DEG with enabling high electron mobility and the additions (passivation layer, field plate, barrier layer) are added for device stabilization and thermal management (Mendes & et al., 2022).



Figure 18. The process of GaN-on-diamond fabrication (Mendes & et al., 2022).



Figure 19. Fabrication Process of GaN/AlGaN/AlN/Si with Nano-Diamond Integration and Regrowth (Ahmed & et al., 2020).

The improvements of Diamond-on-GaN HEMT has been shown over the years. With including the features of the first made Diamond-on-GaN HEMT, research till 2021 has been done:

2006: Procession of fabricating GaN-on-diamond HEMT was optimized. Early unpassivated HEMTs, despite high contact resistance, showed better thermal performance compared to GaN-on-SiC, but still exhibited low drain current and conductance. This thermal resistance was approximately half of that of GaN-on-SiC (Jessen & et al., 2006).

2009: GaN HEMTs on diamond received a higher performance with 85GHz cutoff frequency (fT) and 95GHz maximum oscillation frequency (fmax). This technology continued

to lag behind GaN-on-SiC in some areas, but still had promising thermal advantages (Diduck & et al., 2009), (Babic & et al., 2010).

2011: DARPA introduced the Near Junction Thermal Transport (NJTT) concept, which improved thermal management by placing diamond close to the active regions of the HEMTs. By this approach, GaN-on-diamond HEMTs reached over 7W/mm output power density with 46% power-added efficency (Mendes & et al., 2022).

2014: By the end of the NJTT program, the technology reduced junction temparatures by approximately %40 to %50 and tripled areal RF power density compared to GaN-on-SiC (Altman & et al., 2014).

2019: Element six GaN-on-diamond wafers were made with a 30nm dielectric layer, that had improved power capabilities (56 W/mm DC power) but faced challenges with leakage currents limiting the breakdown voltages

RFHIC also developed GaN-on-diamond wafers with an innovative inner slot via hole process. Thus achieved density of 18.1 W/mm at 2GHz (Cho & et al., 2014).

2021: Fujitsu reported improvements in diamond-coated GaN-on-SiC HEMTs. The use of the 2.5 μ m thick polycrystalline diamond (PCD) film led to a 40% reduction in heat generation, with improvements on transconductance and drain current (Yaita & et al., 2021).

4. CONCLUSION

The evolution of GaN HEMTs represents a remarkable journey in semiconductor technology, transitioning from GaAs-

based devices to the high-performance AlGaN/GaN heterostructures we see today. These advancements have been driven by the unique properties of GaN, such as its wide bandgap, high breakdown voltage, and exceptional electron mobility. The integration of GaN with substrates like SiC has further amplified its capabilities, enabling efficient thermal management and stability in high-power applications.

GaN HEMTs have become indispensable in industries demanding high-frequency, high-power, and high-efficiency solutions. From RF and microwave communications to electric vehicles and renewable energy systems, these devices continue to redefine performance standards. The creation of the 2DEG at the GaN/AlGaN interface has been pivotal, providing low resistance and high-speed switching capabilities that are critical for modern electronics.

As the technology matures, challenges such as thermal management, cost optimization, and scalability are being addressed through ongoing innovation. The continuous refinement of materials, structural designs, and fabrication processes ensures that GaN HEMTs remain at the forefront of power electronics and RF systems. Looking ahead, the versatility and performance of GaN HEMTs position them as a foundational technology in emerging applications like 6G networks, space systems, and quantum devices. Until a disruptive new semiconductor material emerges, GaN HEMTs are poised to maintain their dominance in high-power and high-frequency applications.

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CHAPTER VII

Hybrid Whale Optimisation and Grey Wolf Optimisation Algorithm-Based PID Controller For DC Motors

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1. Introduction

Direct current (DC) motor devices are essential in many domains, including robotics, automotive technology, consumer electronics and medical devices. The capability for accurately controlling the speed of DC motors is crucial for systems such as multi-rotors, medical devices and various industrial applications (Izci and Ekinci, 2023). Hence, various control schemes such as fuzzy, sliding model, adaptive and proportional-integral-derivative (PID) controllers have been designed (Izci, 2021). Among these approaches, PID controllers have continuously occupied a leading role in industrial applications due to their affordability and easy

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implementation. Metaheuristic algorithms have become powerful candidates for tuning PID controler in different fields. Researchers have investigated various artificial intelligence methodologies to optimize the parameters of PID-based control mechanisms for DC motors. Ekinci, Hekimoğlu & Izci (2021) developed an oppositionbased Henry gas solubility optimisation for setting PID gain in DC motors in the presence of load disruptions and system uncertainty. (Hekimoglu, 2019) reports on the chaotic atom search optimisation and its chaotic variant. These two optimization techniques are employed to design optimal fractional order PID controllers for use in the speed control of the direct current motor systems. Through several investigations, the study shows how well these algorithms work in DC motor speed control by comparing them to other existing controllers. Ayinla et al. (2024) developed PID and fractional order PID controllers to regulate the speed of DC motors. The study optimizes the settings of these controllers using the harris hawks optimization variant (LHHO) to reduce transient response specifications. The control scheme of PID improves the system's resilience to changes in dynamics. Furthermore, a fractional order PID controller is also used in the work of (Ekinci, Izci, & Hekimoğlu, 2021) to control a DC motor's speed. The hybrid manta ray foraging optimisation based on opposition and simulated annealing (OBLMRFOSA) improves the controller's parameters. Robustness testing, load disturbance rejection, and time and frequency domain simulations show that the OBLMRFOSA algorithm is better than other cutting-edge optimisation methods.

This study evaluates the hybrid Whale Optimisation and Grey Wolf Optimisation (GWOWOA) algorithm, proposed by Mohammed and Rashid (2020), for tuning the parameters of a PID controller in DC motors. The GWOWOA algorithm is a recently developed population-based approach consisting of two key steps. First, GWO's hunting mechanism is integrated into the exploitation phase of WOA, introducing a new condition based on GWO. Second, a novel technique is applied in the exploration phase to refine the solution after each iteration. The algorithm is tested on three standard benchmark test sets. WOAGWO surpassed various algorithms. However, WOAGWO has not been used to adjust PID controller settings for DC motor speed control.

2. Material and Methods

2.1. Modelling of DC motor system

This section introduces a DC motor setup consisting of both a mechanical load and a DC motor. The main goal is to effectively regulate the motor's speed and torque through the implementation of a control system. The equivalent circuit for this specific type of DC motor is illustrated in Figure 1.



Figure 1: Equivalent circuit of DC motor.

In order to develop a mathematical model, the mechanical stress is expressed as a constant torque (τ_L) and this system is considered to be linear. The speed of the DC motor is controlled by regulating the armature voltage $v_a(t)$. This produces an electromechanical force while armature current $i_a(t)$ adjusts proportionally to the rotational speed (Ayinla et al., 2024; Izci and Ekinci, 2023). To model the DC motor, the following differential expressions characterizing the motor's speed and torque dynamics are provided:

$$v_a(t) = i_a(t)R_a + L_a \frac{di(t)}{dt} + E_b$$
(1)

Under constant flux conditions, the motor's induced voltage E_b is linearly related to the angular velocity ω as illustrated below:

$$E_b = K_b \ \frac{d\theta(t)}{dt} = K_b \ \omega(t) \tag{2}$$

A total torque consists of the impact of the inertia and fractional torques which is given by

$$T_E - T_L = J \frac{d\omega(t)}{dt} + B \ \omega(t) = K_m i_a(t)$$
(3)

where R_a and L_a are the resistance and inductance of the DC motor respectively. E_b is the back electromotive force, K_b is the constant, θ is the angular velocity, ω is the motor shaft velocity, T_E , T_L are the electric and load torques respectively, J indicates the motor's moment of inertia. B and K_m are frictional and torque constants respectively. Applying Laplace transform to equations (1-3) (with zero initial conditions) which leads to

$$v(s) = (L_a s + R_a)i_a(s) + E_b(s) \tag{4}$$

$$E_b(s) = K_b \omega(s) \tag{5}$$

$$T_E(s) - T_L(s) = (Js + b)\omega(s) = K_m i_a(s)$$
(6)

Simplifying equations (4) and (6) results in

$$i_a(s) = \frac{\nu(s) - K_b \omega(s)}{L_a s + R_a} \tag{7}$$

$$\omega(s) = \frac{T_E(s) - T_L(s)}{Js + B} = \frac{K_m}{Js + B} i_a(s) \tag{8}$$

The DC motor's transfer function can be expressed as follows:

$$G_p(s) = \frac{\omega(s)}{\nu(s)} = \frac{K_m}{(L_a s + R_a)(J s + B) + K_b K_m}, \ T_L(s) = 0$$
(9)

Table 1 gives the parameter values of the DC motor, which is adopted from (Izci and Ekinci, 2023).

Symbol	Definition	Value
R _a	Armature resistance	0.4 Ω
L_a	Armature inductance	2.7 H
J	The moment of inertia	$0.0004 \text{ kg} m^2$
В	The frictional constant	0.0022Nms/rad
K_m	Torque constant	0.015 N m/A
K _b	Back electromotive constant	0.05 Vs

Table 1: Parameter vaules.

2.2. WOAGWO algorithm

The Whale Optimization Algorithm (WOA) (Mirjalili and Lewis, 2016) simulates the social dynamics of humpback whales. The algorithm was inspired by humpback whales using bubble nets to hunt tiny fish. This algorithm is separated into two parts: exploration and exploitation.

$$Z(t+1) = Z_{rand} - \zeta Y \tag{10}$$

$$Y = |BZ_{rand} - \zeta Z| \tag{11}$$

where Z_{rand} represents the position of a randomly selected member within the whale swarm.

$$Z(t+1) = Z^{*}(t) - \zeta Y$$
(12)

$$Y = |BZ^{*}(t) - \zeta Z(t)|$$
(13)

where $Z^*(t)$ and Z(t+1) indicate the best position and the current position, respectively. $\zeta = 2k(t)r - k(t)$ and B=2r are coefficient vectors.

$$Z(t+1) = e^{bt}\cos(2\pi t)Y^* + Z^*(t)$$
(14)

$$Y^* = |Z^*(t) - Z(t)|, b, t \in [-1,1]$$
for $p \in [0,1]$
(15)

$$Z(t+1) = \begin{cases} cZ^*(t)\delta - \zeta Y, & \text{if } p < 0.5\\ e^{bt}\cos(2\pi t)Y^* + Z^*(t), \text{if } p \ge 0.5 \end{cases}$$
(16)

In the work of (Mohammed and Rashid, 2020), the performance of the WOA algorithm is enhanced by integrating elements of both WOA and GWO in a hybrid approach. This hybrid approach (WOAGWO), modifies the standard WOA by incorporating two key enhancements. Firstly, a criterion is introduced within WOA's exploitation phase to refine its hunting mechanism. Referring to the equation $Z(t + 1) = \frac{Z_1(t) + Z_2(t) + Z_3(t)}{3}$ from GWO, exploitation performance is greatly influenced by the parameters ζ_i (*i* = 1, 2, 3). In order to get around the less-than-ideal solution, a new condition is added to the WOA exploitation phase, where each ζ falls below 1 or exceeds -1. Secondly, the equations utilised in GWO are adapted and incorporated into the condition as mentioned earlier within the exploitation stage, involving ζ_i (*i* = 1, 2, 3). Lastly, an additional criterion is added during the exploration stage to guide the current solution toward the ideal one while making sure the whale does not move to a worse location than its prior one.

2.3. Gain of PID controller optimization

The PID controllers preserve a desired setpoint by continuously altering a control variable in response to the discrepancy between the setpoint and the actual process variable. To do this, the PID controller uses three factors: proportional (K_p) , integral (K_i) , and derivative (K_d) (Karl & Tore, 1995). The transfer function of the PID controller is given as

$$C_{PID}(s) = K_p + K_i \frac{1}{s} + K_d s$$
 (17)

In this study, the ITAE objective function was used for a fair comparison (Ekinci, Hekimoğlu & Izci, 2021). The ITAE function is given as presented in Equation. (18). The settings of the WOAGWO algorithm are given in Table 2.

$$ITAE = \int_0^{tsim} t |e(t)| dt$$
(18)

	-
Setting	Value
Poplation size	40
Maximum iteration	50
Lower pound	[0.001 0.001 0.001]
Upper bound	[20 20 20]
Dimension	3
Simulation	1 s

Table 2: Settings of the WOAGWO algorithm for tuning PID gains in the DC motor control problem.

The WOAGWO algorithm's optimization of the PID controller gains was started by using the initialization. This step involved combining the WOAGWO algorithm with а MATLAB/Simulink model for DC motor speed management. For each candidate in the population, the PID gains were shown as a vector of real values, K = (Kp, Ki, Kd) corresponding to each candidate in the neighborhood. There were N randomly selected candidates in the population. For each choice, a time-domain simulation of the DC motor speed control system with unity feedback and the suggested PID controller was then performed. For every candidate, the ITAE values and speed response were computed. Since different candidates typically resulted in varying speed outputs and ITAE values, the N best solutions with the lowest ITAE values were selected for the next iteration and updated before returning to the WOAGWO algorithm. This cycle continued until the maximum number of iterations was reached. In the end, the candidate with the lowest ITAE value was identified as the optimal set of PID gains as shown in Figre 2.



Figure 2: The scatter plot of PID gains with the initial PID and optimised PID gains

3. Results and discussion

This section presents the optimised PID controller's simulation results. The simulations were run on a personal computer using MATLAB/Simulink 2022a software with an Intel ® core i5 processor at 2.4 GHz and 8 GB RAM.

Convergence curve of the ITAE objective function using the WOAGWO algorithm is illustrate in Figure 3. The closed-loop responses in terms of time and frequency is shown in Figures 4 and 5 respectively. The coresponing results are reported in Table 3. Rise time is the time it takes for the system's output to rise from 10% to 90% of its final value. A rise time of 0.0459 seconds indicates that the system is very fast in reaching its final value. It seems to be a well-performing system in terms of speed. Settling time is the time

it takes for the output to remain within a certain percentage (usually 2% or 5%) of its final value. A settling time of 0.0820 seconds is relatively quick, suggesting that the system reaches a steady state quickly without oscillating around the final value.



Figure 3: Convergence curve of the objective function using the WOAGWO algorithm



Figure 4: Response of the WOAGWO-based PID-controlled DC motor.

Table 3: Analysis of the time and frequency domain performance.

Metrics	WOAGWO-based PID
	controller
Rise time (s)	0.0459
Settling time (s)	0.0820
Overshoot (%)	0
Gain margin(dB)	Inf
Phase margin (deg.)	180
Bandwidth (Hz)	49.1277

The gain margin indicates how much the system's gain can be increased before it becomes unstable. An infinite gain margin ($^{\infty}$ dB) suggests that the system is very stable and would tolerate a significant increase in gain without becoming unstable. The phase margin indicates the stability of the system by showing how much phase lag the system can tolerate before it reaches instability. A

phase margin of 180° is exceptional—it means the system is highly stable.



Figure 5: Bode plot of the WOAGWO-based PID-controlled DC motor.

To verify the effectiveness of the proposed WOAGWO based-PID controller, we perform a comparison using the recently

developed methods such as hASO-SA (Eker et al., 2021) ASO (Hekimoglu, 2019), (GWO) (Agarwal et al., 2018), SCA (Idir et al., 2022), OBLHGSO (Ekinci, Hekimoğlu & Izci, 2021).Figure 6 compares the closed-loop responses of DC motor with different controllers. To demonstrate the superiority of the WOAGWO-PID controller over other approaches documented in the literature, we present the results of a performance analysis focusing on time-domain features in Table 4. The WOAGWO-PID controller has the lowest rising time and settling time specifications. Furthermore, the WOAGWO-PID controller obtains zero overshoot as well. These outstanding performance metrics demonstrate that, compared to other approaches covered in the literature, the WOAGWO-PID technique emerges as the most practical and effective approach for achieving crucial time-domain design requirements.



Figure 6: Comparative closed-loop responses with various published works.

Table 4: Comparison of step	response dynamics between the
proposed method an	d other methodologies.

	tr	ts	OS (%)	Ess (%)
hASO-SA-PID	0.050306	0.087139	0.19643	0.17055
GWO-PID	0.06975	0.14191	0	0.3167
ASO-PID	0.13477	0.40837	2.5534	1.0228
SCA-PID	0.19719	0.60488	3.6213	1.2715
OBLHGSO-PID	0.054427	0.09191	0.48301	0.48279
WOAGWO -PID (Proposed)	0.045894	0.081996	0	0.00024

3.1. Robustness analysis

The robustness analysis was conducted by varying the electrical resistance (R_a) of the DC motor with ±25% and torque constant (K_m) with ±20% separately. This leads to four different testing cases. Figures 7, 8, 9 and 19 show the closed-loop step responses for all cases. Tables 5, 6, 7 and 8 present the simulation findings for the time-domain performance assessment. The best values attained in the table are highlighted in bold. It is evident from the table that the WOAGWO-PID-controlled DC motor is the most robust. Despite varying parameters in the DC motor system, the proposed WOAGWO-PID controller provides the lowest rise and settling times for all testing conditions. For cases, I and II, the WOAGWO-PID controller exhibits overshoot values of 0.011241% and 0.015137%, respectively, which are negligible.



Figure 7: Comparative closed-loop responses under condition I.



Figure 8: Comparative closed-loop responses under condition II.



Figure 9: Comparative closed-loop responses under condition III



Figure 10: Comparative closed-loop responses under condition IV.

Table 5: Performance evaluation of condition 1: $R_a = 0.30$ and

$K_m = 0.012$					
	tr	ts	OS (%)	Ess (%)	
hASO-SA- PID	0.062198	0.10715	0.19852	0.067057	
GWO-PID	0.087513	0.18532	0	0.17126	
ASO-PID	0.16435	0.46306	2.3971	0.85819	
SCA-PID	0.23986	0.66212	2.9775	0.80524	
OBLHGSO- PID	0.068022	0.11294	0.48539	0.42988	
WOAGWO -PID (Proposed)	0.056023	0.10048	0.011241	0.12654	

$K_m = 0.018$					
	tr	ts	OS (%)	Ess (%)	
hASO-SA- PID	0.042059	0.073141	0.21392	0.12503	
GWO-PID	0.05718	0.11452	0	0.23507	
ASO-PID	0.11503	0.36812	2.6593	0.80221	
SCA-PID	0.16898	0.55274	4.0095	1.0112	
OBLHGSO- PID	0.045882	0.077361	0.4832	0.38117	
WOAGWO					
-PID	0.038339	0.068489	0.015137	0.013868	
(Proposed)					

Table 6: Performance evaluation of condition II: $R_a = 0.30$ and

Table 7: Performance evaluation of condition III: $R_a = 0.50$ and

 $K_m = 0.012$

	tr	ts	OS (%)	Ess (%)
hASO-SA- PID	0.062169	0.10738	0.16989	0.23894
GWO-PID	0.087272	0.18541	0	0.44089
ASO-PID	0.087272	0.18541	0	0.44089
SCA-PID	0.2394	0.65358	2.8845	1.5398
OBLHGSO- PID	0.06793	0.11293	0.46964	0.63486
WOAGWO -PID (Proposed)	0.056027	0.1009	0	0.021565

Table 8: Performance evaluation of condition IV: $R_a = 0.50$ and $K_{m} = 0.018$

	tr	ts	OS (%)	Ess (%)		
hASO-SA- PID	0.042031	0.073276	0.1931	0.23916		
GWO-PID	0.057087	0.11446	0	0.41396		
ASO-PID	0.056027	0.1009	0	0.021565		
SCA-PID	0.16891	0.54727	3.904	1.4909		
OBLHGSO- PID	0.045833	0.0774	0.47072	0.51789		
WOAGWO -PID (Proposed)	0.038324	0.068662	0	0.084223		

4. Conclusions

This study addresses the challenge of achieving precise speed control in DC motors, which are widely utilized across various industries, including consumer electronics, automotive technology, robotics, and medical equipment. By combining the Whale Optimization Algorithm (WOA) and Grey Wolf Optimization (GWO), the hybrid WOAGWO method is used in this study as an innovative solution to enhance the velocity regulation of DC motor systems. The method consistently outperformed across various timedomain performance criteria and delivered improved objective function values, demonstrating its effectiveness in controlling DC motor speed. Additionally, the closed-loop step response of the WOAGWO-PID control scheme showcased its capability to regulate motor speed under different parametric conditions. When compared to other advanced methods, the WOAGWO-PID approach excelled in transient response specifications, such as speed rise time, settling time, and overshoot. This study evaluates the potential of the WOAGWO algorithm in enhancing controller performance for controlling DC motor speed. By using this recent metaheuristic algorithm, the speed control of DC motors can be more accurate and efficient.

Acknowledgement

This study was supported by Artvin Çoruh University Scientific Research Unit (BAP, Turkey) Project No: 2024.F14.02.01.

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CHAPTER VIII

The Role of Artificial Intelligence in Brain-Computer Interfaces and Device Control Systems with EEG Signals

İnci BİLGE¹

1.Introduction

Brain-computer interface (BCI) is a system that enables device control by analyzing brain activity using signal processing methods and converting these signals into digital commands using classification methods (Xu et al., 2021). A brain-computer interface (BCI) allows people who have lost their mobility due to neurological conditions like multiple sclerosis, cerebral palsy, stroke or spinal cord injury to communicate with their surroundings and operate devices, thereby improving their quality of life (Cantillo-Negrete et al. 2023). It enables the control of devices such as robot arms, wheelchairs, and mouse cursors by using artificial neural networks

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(ANN) methods as well as the motor imaging or P300 component of electroencephalography (EEG) signal (Zhang et al., 2022). BCI design frequently uses electroencephalography (EEG), which records voltage changes in the cortex caused by the firing of neurones in the brain using electrodes applied to the scalp (McFarland and Wolpaw 2017). The EEG signal types that can be employed in BCI systems are mu (8–12 Hz), beta (14–26 Hz), and gamma (>30 Hz) (Yuan and He 2014). EEG signals can be recorded from the cortex using EEG caps designed by placing the electrodes using the 10-10 system or the 10-20 system (Acharya et al. 2016). EEG electrode placement is given in Figure 1 (Acharya et al. 2016).



Figure 1. EEG electrode placement (Acharya et al. 2016).

In the design of brain-computer interface systems, instead of muscle movements, signals are converted into commands using specific brain activity and classification methods. Brain Activity EEG signals can be recorded while performing activities like P300, steady-state visual evoked potential (SSVEP) and motor imagery.

The P300 signal is a component of the event-related potential (ERP), and the positive electrical response of the brain that occurs approximately 300 milliseconds (ms) after the stimulus begins is called P300 (Won et al., 2022).

The P300 wave, one of the types of event-related potentials (ERP), is shown in Figure 2. (Won et al., 2022).



Figure 2. ERP signal and P300

Motor imagery, used in the design of electroencephalography (EEG)-based brain-computer interfaces, can be used to classify EEG signals obtained while imagining movements and translate the motor intentions of subjects into commands to control the devices. The mouse cursor can be controlled using the EEG signal obtained while imagining making a hand movement (motor imagery). In human BCI research, two frequency bands are used, namely P300 evoked potential and mu/beta and gamma bands. Control commands of the devices can be obtained by using different methods. Figure 3 shows the schematic diagram of the EEG-based robot control method.



Figure 3. Schematic diagram of EEG-based robot control method **2.Studies on Brain Computer Interface and Device Control**

Brain-computer interface (BCI) can be designed using EEGbased motor imagery (MI), P300 and visual evoked potential (SSVEP) (Coyle et al., 2011; Akram et al., 2015; Jin et al., 2015; Nakanishi et al., 2015; Ravi et al., 2020; Yin et al., 2022). Song and his colleagues developed a system that works with high accuracy to control the upper extremity assistance robot with P300 signals (Song et al., 2020). It is obtained from EEG signals recorded from individuals who focus on the desired letter or character while the letters in the 6X6 matrix flash in order. The row-column paradigm of the matrix used to form the P300 signal is given in Figure 4.

А	В	С	D	Е	F	
G	н		J	к	L	
М	Ν	0	Р	Q	R	
s	т	U	V	W	х	
Y	Ζ	1	2	3	4	
5	6	7	8	9		

Figure 4. P300 row-column paradigm

In order to control the movement of the wheelchair in the desired direction, it is stated that the wheelchair stops by detecting the obstacle by using Visual Evoked Potentials (SSVEP) in its design; as well as the brain-computer interface designed by using additional sensors (Mistry et al., 2018). During motor imagery (MI), imagining limb movements without actual limb movements, the motor cortex is activated and produces neural activity similar to EEG signals produced during actual motor execution (Decety, 1996). MI-based BCI can also control rehabilitation equipment such as wheelchairs and prosthetic devices for motor impaired individuals (Yu et al., 2018; Wang et al., 2022). In the design of brain-computer interfaces, motor control can be performed using brain activity

related to arm and hand movements. Brain activity can be used as input for the brain-computer interface by primary motor cortex (M1) and parietal cortex responses (Serruya et al., 2002). Cortical responses from the frontal and parietal lobes are used to control devices such as robot arms (Yin et al., 2022). There are braincomputer interface studies conducted not only on humans but also on animals, and animals can learn to use their brain activity to control the displacement of computer cursors and the movements of robot arms (Serruya et al., 2002; Taylor et al., 2002). It is stated that macaque monkeys can learn to use robot arm movements using brain-computer interfaces using visual feedback (Serruya et al. 2002; Taylor et al. 2002). System design is being done by implanting it into the frontal and parietal cortical areas of macaque monkeys (Nicolelis, 2003). In addition to signal processing methods, classification can be done using a wide variety of artificial neural network methods such as Convolutional Neural Networks (CNN) based models, Support Vector Machines (SVM), and Deep Learning (Zhang et al., 2022; Huang et al., 2022).

3.BCI signal processing

Commands are obtained by using filtering, feature extraction, feature selection, classification techniques from signal processing methods. Studies on time frequency analysis of EEG signals used in the design of brain-computer interfaces have been examined. Signal processing methods such as Fast Fourier Transform (FFT), wavelet transform are used in brain-computer interface design. In a study, it was stated that the brain-computer interface for robot control worked with 85.45% accuracy using the FFT signal processing method in the frequency range of 8-22 Hz (Bousseta et al., 2018). WPT is one of the signal processing methods in the time-frequency domain that provides improved frequency resolution that can be used in the analysis of non-stationary signals(Wang et al., 2022). In the study where feature extraction was made from the analysis results of wavelet packet transform, one of the signal processing methods, and classification operations were

performed, an accuracy rate of 90.3% was obtained (Pawan & Dhiman, 2023). It was stated that 95.71% accuracy rate was obtained with the SVM method after analyzing the EEG signals obtained from the C3, CZ and C4 electrodes during motor imagery using wavelet packet transformation (Wang et al., 2022). Compilation studies on BCI feature extraction methods were examined (Bashashati et al., 2007; McFarland et al., 2006; Lotte et al., 2018).

3.1 Machine learning algorithms

Machine learning algorithms are computer learning methods used to recognize patterns in EEG signals in BCI systems. Support Vector Machine (SVM), K-nearest neighbors algorithm (k-NN), and convolutional neural network (CNN) are some of the machine learning algorithms (Zhang et al., 2022). SVM is one of the classifier types with associative learning algorithms that analyze data for classification and regression analysis used in machine learning. It has been stated that this classifier, which enables the detection of the target character by detecting P300 ERPs in EEG signals using SVM, provides a high accuracy rate (Chaurasiya et al., 2015). In the study conducted by Zhang and Chen (2022), 98% accuracy rate was achieved by using the SVM model to classify P300 signals (Zhang et al., 2022). P300 signals were found to be detectable with 95.5% accuracy in a study that used a CNN-based model (Cecotti and Graser, 2011). The k-NN is a non-parametric supervised learning method that was first developed by Evelyn Fix and Joseph Hodges and later extended by Thomas Cover (Cover and Hart, 1967; Fix & Hodges, 1989, Pawan & Dhiman, 2023). Table 1 shows the classification results in the literature.

References	Task	Classifier	Result
(Mattioli et al., 2022)	MI	CNN	%99.39
(Huang et al., 2022)	MI	CNN	%92
(Bousseta et al., 2018)	MI	SVM	%85,45
(Cecotti & Graser, 2011)	P300	CNN	%95.5

 Table 1. Classification results in the literatüre

(Zhang et al., 2022)	P300	SVM	%98
(Pawan & Dhiman, 2023)	MI	KNN -SVM	%90,33-%91,6

4. Conclusion

It is known that the number of studies on brain-computer interface design has increased with the development of technology. With BCI, it is possible to make the lives of individuals with neurological disorders such as disabled patients, paralyzed patients easier by controlling devices such as wheelchairs, robot arms, and robot hands with brain signals. This study was conducted to provide information about signal processing and classification methods used in the design of brain-computer interface systems and the accuracy rates of the system. It is thought that the classification methods that work with the highest accuracy will contribute to the development of the system by examining.

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CHAPTER IX

Köprü Katodik Koruma Sistemlerinde Sürdürülebilir Enerji Çözümleri: Off-Grid Fotovoltaik Sistem Tasarımı ve Maliyet Analizi

Murat ÇIKAN¹

1. Giriş

Enerji sistemlerinin sürdürülebilirliği ve verimliliği, modern toplumların en kritik gereksinimlerinden biri haline gelmiştir. Özellikle fosil yakıtların çevresel etkileri ve sınırlı kaynaklar olması, yenilenebilir enerji kaynaklarına olan ilgiyi artırmıştır. Bu bağlamda, güneş enerjisi sistemleri, temiz ve sürdürülebilir enerji üretimi için önemli bir alternatif sunmaktadır. Son yıllarda, güneş enerjisi teknolojilerindeki gelişmeler ve maliyetlerdeki düşüş, bu sistemlerin yaygınlaşmasına önemli katkı sağlamıştır.

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Off-grid (şebekeden bağımsız) güneş enerjisi sistemleri, özellikle şebeke elektriğinin ulaşamadığı veya kesintili olduğu bölgelerde kritik bir çözüm olarak öne çıkmaktadır. Bu sistemler, elektrik şebekesine bağlı olmaksızın, güneş enerjisini elektrik enerjisine dönüştürerek depolayabilen ve ihtiyaç anında kullanıma sunabilen bağımsız yapılardır. Sistemlerin tasarımı, kurulum yeri, iklim koşulları, kullanım amacı ve enerji ihtiyacı gibi birçok parametrenin detaylı analizi ile gerçekleştirilmelidir.

Literatürde, off-grid güneş enerjisi sistemlerinin tasarımı ve optimizasyonu üzerine yapılan çalışmalar, genellikle sistem bilesenlerinin boyutlandırılması, maliyet optimizasyonu ve performans analizi üzerine yoğunlaşmaktadır. Örneğin, Li S. ve diğerleri (2023), batarya kapasitesi ile güneş paneli boyutlandırması arasındaki ilişkiyi incelemiş ve optimal sistem tasarımı için bir metodoloji önermişlerdir [1]. Benzer şekilde, Li J.ve arkadaşları (2020), farklı iklim koşullarında sistem performansını etkileyen faktörleri analiz etmiştir. [2]. Bu bölümde, 975 Watt-saat günlük enerji ihtiyacı olan bir sistemin, güneş panelleri ve bataryalar yardımıyla beslenmesi için gerekli tasarım ve maliyet analizi ele alınacaktır. Çalışmanın özgün yanı, sistemin iki günlük yedekleme kapasitesi ile tasarlanması ve İstanbul ili özelinde gerçekleştirilen detaylı analizleri içermesidir. Bu kapsamda:

- Sistem bileşenlerinin optimal boyutlandırılması
- Çevresel faktörlerin sistem tasarımına etkisi
- Detaylı maliyet analizi ve karşılaştırması
- Pratik uygulama örnekleri

gibi konular sistematik bir yaklaşımla incelenecektir. Çalışmanın sonuçları, benzer sistemlerin tasarımında referans olarak kullanılabilecek bir metodoloji sunmayı ve off-grid güneş enerjisi sistemlerinin ekonomik fizibilitesine ışık tutmayı amaçlamaktadır. Ayrıca, bu tür sistemlerin yaygınlaşmasının önündeki teknik ve ekonomik engellerin tartışılması ve çözüm önerilerinin sunulması da hedeflenmektedir.

2. Problem Tanımı ve Sistem Gereksinimleri

Off-grid güneş enerjisi sistemlerinin tasarımında, temel gereksinimler ve çevresel faktörlerin sistematik analizi büyük önem taşımaktadır. Bu bölümde ele alınan problemin çözümü için öncelikle sistemin genel gereksinimleri ve çalışma koşulları detaylı olarak incelenecektir. Çalışmaya konu olan sistem, günlük 975 Watt-saat enerji ihtiyacını karşılamak üzere tasarlanacak olup, güneş panelleri ve batarya grubu yardımıyla beslenecektir. Sistem tasarımında en kritik gereksinimlerden biri, fotovoltaik panellerin güç üretemediği ekstrem durumlarda sistemin *iki gün boyunca kesintisiz* çalışmaya devam edebilmesidir. Bu gereksinim, batarya kapasitesi hesaplamalarında belirleyici bir faktör olarak karşımıza çıkmaktadır.

Sistemin güvenilirliği açısından önemli bir diğer parametre, tasarımda öngörülen %30'luk emniyet faktörüdür. Emniyet faktörü, beklenmeyen yük artışları, sistem kayıpları ve çevresel faktörlerin olumsuz etkilerini kompanse etmek amacıyla kullanılmaktadır. Ayrıca batarya grubunun uzun ömürlü olması için deşarj derinliği %50 ile sınırlandırılmıştır. Sistem kurulumunun planlandığı İstanbul Haliç bölgesinin coğrafi ve iklimsel özellikleri, tasarımı doğrudan

etkileyen faktörler arasındadır. Bölgenin 41.04137° Kuzey enlemi (N) ve 28.94014° Doğu boylamındaki (E) konumu, güneş panellerinin optimum yerleşimi için temel veriyi oluşturmaktadır. Özellikle kış aylarında ortalama sıcaklığın 5.1°C'ye kadar düşmesi, batarya performansını etkileyecek önemli bir faktör olarak değerlendirilmiştir. Güneşlenme karakteristiği açısından bölge incelendiğinde, yaz aylarında 13'47" (saat/gün)'e kadar çıkan güneşlenme süresinin, kış aylarında 5'35" (saat/gün)'e kadar düştüğü gözlemlenmiştir [3]. Yıllık ortalama 9'40" (saat/gün) güneşlenme süresi. sistem tasarımında panel say1s1 ve kapasitesi hesaplamalarında kullanılacak temel parametrelerden biridir.

Montaj lokasyonu olarak seçilen Haliç Köprüsü'nün Ayvansaray tarafındaki ayakları, sistem kurulumu için 14.00 m²'lik bir alan sunmaktadır. Bu alan kısıtı, panel yerleşimi ve kapasitesi açısından önemli bir tasarım parametresi oluşturmaktadır. Ayrıca köprü yapısından kaynaklanan gölgelenme faktörleri ve montaj kısıtlamaları da sistem tasarımında göz önünde bulundurulması gereken önemli faktörlerdir. Tüm bu gereksinimler ve çevresel faktörler, sistemin optimum tasarımı için temel girdileri oluşturmaktadır. Takip eden bölümlerde, bu parametreler ışığında detaylı sistem tasarımı ve boyutlandırması gerçekleştirilecek, ardından maliyet analizi yapılacaktır. Sistemin uzun vadeli performansının değerlendirilmesi ve bakım gereksinimlerinin belirlenmesi de bu analizler kapsamında ele alınacaktır.

Bu sistematik yaklaşım, benzer off-grid güneş enerjisi sistemlerinin tasarımında da kullanılabilecek bir metodoloji sunmayı amaçlamaktadır. Özellikle şebeke elektriğinin ulaşamadığı veya kesintili olduğu bölgelerde, sürdürülebilir enerji çözümleri için önemli bir referans oluşturabilecektir.

3. Sistem Tasarım Metodolojisi

Off-grid güneş enerjisi sistemlerinin tasarımında, sistem bileşenlerinin optimal seçimi ve boyutlandırılması kritik öneme sahiptir. Bu bölümde, 975 Watt-saat günlük enerji ihtiyacını karşılayacak sistemin tasarım metodolojisi detaylı olarak ele alınacaktır.

3.1.Batarya Sistemi Tasarımı

Batarya sisteminin tasarımında, öncelikle toplam enerji depolama kapasitesi belirlenmelidir. İki günlük yedekleme gereksinimi göz önüne alındığında, minimum enerji depolama kapasitesi:

$$P_{ak\ddot{u} de\breve{g}eri} = 2 * P_{g\ddot{u}nl\ddot{u}k}$$

$$P_{ak\ddot{u} de\breve{g}eri} = 975 Watt - saat * 2 = 1950 Watt - saat$$
(1)

Sistem güvenilirliğini artırmak için %30'luk bir emniyet faktörü uygulanmıştır:

$$P_{\text{emniyet faktörü}} = P_{akü} * 0.30$$

$$P_{\text{emniyet faktörü}} = 1950 * 0.30 = 585 \text{ Watt} - \text{saat}$$
(2)

Toplam gerekli güç kapasitesi:

 $P_{toplam} = P_{ak\ddot{u}} + P_{emniyet fakt\"or\ddot{u}} = 2535 \text{ Watt} - \text{saat}$ (3) Batarya kapasitesi hesaplanırken, sistem gerilimi ve çevresel faktörler de dikkate alınmalıdır. 48V sistem gerilimi için amper-saat cinsinden kapasite:

$$I_{Akü Kapasitesi} = \frac{\sum P_{tioplam}}{V_{sistem}} = \frac{2535}{48} = 53 \text{ Amper} - \text{saat} \quad (4)$$

3.1.1. Sıcaklık Düzeltme Faktörü

Batarya performansı sıcaklığa bağlı olarak değişim gösterdiğinden, bölgenin iklim koşulları dikkate alınarak sıcaklık düzeltme faktörü uygulanmıştır. Düşük hava sıcaklığı bataryaların çalışmasında negatif bir etkiye sahiptir. Kurulması planlanan batarya sistemi için en kötü senaryo göz önüne alınarak ve bataryaların doğrudan dış ortam sıcaklığına maruz kalacağı düşünülerek tasarım gerçekleştirilmiştir. Bataryaların hava sıcaklığına bağlı sıcaklık emniyet katsayı çarpanı Tablo 1'de verilmiştir.

Der		
Fahrenheit	Celsius	Çarpım Katsayısı
80°F	26.0°C	1.00
70°F	21.2°C	1.04
60°F	15.6°C	1.11
50°F	10.0°C	1.19
40°F	4.4°C	1.30
30°F	-1.1°C	1.40

Tablo 9: Sıcaklık emniyet katsayı değeri

Sistemin İstanbul il sınırları içerisinde kurulacağı düşünülerek, İstanbul'a ait sıcaklık verileri Ref [4]'ten yararlanılarak elde edilmiştir. 1950 ile 2023 seneleri arasında İstanbul'a ait aylık ortalama sıcaklık ve ortalama en düşük sıcaklık değerleri Tablo 2 ve Tablo 3'de verilmiştir.

	(1950 - 2023) tarihleri arasında Gerçekleşen Ortalama Değerler					
Ау	Ocak	Şubat	Mart	Nisan	Mayıs	Haziran
Sıcaklık	6.7	6.9	8.4	12.8	17.6	22.2
Ау	Temmuz	Ağustos	Eylül	Ekim	Kasım	Aralık
Sıcaklık	24.6	24.7	21.2	16.7	12.6	8.9

Tablo 10: İstanbul için ortalama sıcaklık değerleri

Tablo 11: İstanbul için ortalama en düşük sıcaklık değerleri

	(1950 - 2023) tarihleri arasında Gerçekleşen Ortalama Değerler					
Ау	Ocak	Şubat	Mart	Nisan	Mayıs	Haziran
Sıcaklık	4.2	4.2	5.4	9.2	13.6	18.0
Ay	Temmuz	Ağustos	Eylül	Ekim	Kasım	Aralık
Sıcaklık	20.4	20.7	17.6	13.7	9.8	6.4

Tablo 3'den yararlanarak İstanbul'un en soğuk dört ayının ortalama sıcaklık değeri:

$$\frac{(4.2 + 4.2 + 5.4 + 6.4)}{4} = 5.075^{\circ} \text{Celcius}$$
(5)
= 41.135 Fahrenheit

olarak hesaplanır. Tablo 1'den yararlanılarak 5.075°C için gerekli katsayı değeri Matlab yardımıyla enterpolasyon yapılarak 1.2867 olarak hesaplarız. Bu faktör, batarya kapasitesinin belirlenmesinde önemli bir parametre olarak kullanılmıştır.

3.1.2. Deşarj Derinliği Optimizasyonu

Batarya ömrünü optimize etmek ve verimliliğini artırmak için şarj kapasitesi %30 ile %80 arasında tutulmuştur (Depth of Discharge- DoD %50). Bu durumda gerçek batarya kapasitesi:

Akü Kapasite Değeri

$$= \frac{P_{akü}}{V_{sistem}} * \frac{1}{DOD} * T_{Katsay1}^{Düzeltme} * \frac{130}{100} * \frac{1}{\eta}$$
Akü Kapasite
$$= \frac{1950}{48v} * \left(\frac{1}{\frac{50}{100}}\right) * 1.2867 * 1.30 * \frac{1}{0.85}$$

$$= 160 \text{ Amper} - \text{saat}$$
(6)

Sistemde hesaplanan verim değeri, bataryanın şarj ve deşarj döngülerindeki performansını göstermektedir. Lityum bataryalarda şarj ve deşarj verimliliği (η) farklılık göstermektedir; şarj verimi yaklaşık %95, deşarj verimi ise %85-90 aralığındadır. Çalışmada en kötü şartlar göz önüne alındığı için %85'lik düşük verimlilik oranı tercih edilmiştir. Emniyet faktörü ve diğer tasarım kriterleri göz önüne alındığında, kurulması gereken batarya sisteminin kapasitesi yaklaşık 160 Amper-saat olarak hesaplanmıştır. Bu kapasite değeri, sistemin güvenli ve verimli çalışmasını garanti altına almasına rağmen, kurulum maliyetinin artmasına neden olmaktadır.

3.2. Güneş Panellerinin Konumlandırılması

Projede, Haliç Köprüsü'nün ayaklarının korozyona karşı korunması istendiği için güneş panelleri Haliç Köprüsünün Ayvansaray tarafındaki ayaklarına yerleştirilmiştir. Amerika Birleşik Devletleri Ulusal Enerji Departmanı (NREL) tarafından hazırlanan Yenilenebilir Enerji ve Enerji Verimliliği ile ilgili websitesi [5] kullanılarak istenilen bölgede oluşturulacak güneş paneli alanı ortalaması 14.00 m² olması öngörülmüştür. Şekil 1'de PV panellerin konumlandırılacağı alan gösterilmiştir. İlerleyen bölümlerde güneş panellerinin özellikleri, kayıplar ve ışınım değerleri hesaplamalarına yer verilecektir.



Şekil 11: Panellerin konulacağı bölgenin haritadaki konumu

Tablo 4'de için 2023 yılı itibariyle güncel elektrik fiyatları ve güneş enerjisi sistemi maliyetleri verilmiştir.

Tablo 12: Ekonomik açıdan enerji birim fiyatlarının karşılaştırılması

Güneş Enerjisi Sisteminin Ekonomik Analizini				
Elektrik şebekesinden satın alınan elektriğin ortalama maliyetini (\$)	0.15 \$/kWh			
Watt başına üretilen DC elektriğin maliyet fiyatı	1.20 \$/Wdc			
Güneş enerjisi sistemi tarafından üretilen elektriğin maliyeti	0.08 \$/kWh			

Güneş paneli sisteminin tasarımında, bölgenin güneşlenme karakteristiği ve panel verimi temel parametreler olarak ele alınmıştır. Panel üretim kapasitesi hesabı için kullanılan temel formül:

$$\mathbf{E} = \mathbf{A} * \mathbf{r} * \mathbf{H} * \mathbf{PR} \tag{7}$$

Burada, E: Üretilen enerji (kWh), A: Panel yüzey alanı (m²), r: Panel verimi (%), H: Yıllık ortalama güneş radyasyonu ve PR: Performans oranı (0.5-0.9 arası, varsayılan 0.75). Güneş panelinin ürettiği maksimum Güç değerinin (kWp), panelin yüzeyine (m²) bölünerek bulunduğu yüzdelik katsayı. Örnek olarak, 250-Wp bir panel 1.6 m² ise r = % 15.6 olarak bulunur.

$$r = 0.250 * \frac{100}{1.6} = \% \ 15.6 \tag{8}$$

3.2.1. Panel Yerleşimi ve Optimizasyon

Panel yerleşiminde, Haliç Köprüsü'nün Ayvansaray tarafındaki 14.00 m²'lik alan için optimizasyon yapılmıştır. Panellerin azimut açısı ve eğim açısı, yıllık enerji üretimini maksimize edecek şekilde hesaplanmıştır.

3.2.2. Panel Sayısı ve Güç Hesabı

Sistemin boyutlandırılmasında, günlük enerji ihtiyacı 0.975 kilowatt-saat (kWh) olarak belirlenmiştir. Ortalama hava sıcaklığının ve gün ışığının en düşük seviye seyrettiği ocak ayı hesaplamaların yapılacağı zaman dilimi olarak seçilmiştir. Bölgenin ocak ayı verileri incelendiğinde, günlük ortalama güneşlenme süresinin 5 saat 35 dakikaya (5.583 saat) düştüğü ölçülmüştür [3]. Kullanılması planlanan fotovoltaik panellerin verim oranı %14 olarak seçilmiş ve sistemde oluşabilecek ışınım kayıpları (Monthly Irradiance Loss) %20 olarak öngörülmüştür. İstanbul'un ocak ayı ortalama güneş ışınımı değeri yaklaşık 1.8-2.2 kWh/m²/gün olarak ölçülmektedir. Sistem tasarımında toplam kayıplar değerlendirilirken, %20'lik ışınım kaybının yanı sıra, kablo kayıpları ve inverter kayıpları gibi sistem kayıpları da göz önünde bulundurulmuş ve bu değer yaklaşık %10 olarak hesaplanmıştır. Böylece sistemin toplam kayıp oranı %30 olarak belirlenmiştir.

Panel gücü hesaplamasında, günlük enerji ihtiyacı, güneşlenme süresi, toplam kayıp oranı ve panel verimi değerleri kullanılmıştır. Hesaplama formülü şu şekilde uygulanmıştır:

Gerekli Güç

 $= \frac{(\text{Günlükenerji ihtiyacı} \times 1000)}{(\text{Güneşlenme süresi} \times (1 - \text{Toplam kayıp}) \times \text{Panel verimi})}$ $= \frac{(0.975 \times 1000)}{(5'35'' \times 0.7 \times 0.14)} = \frac{975}{0.547} \approx 1783 \text{ Watt peak (Wp)}$

Bu hesaplamalar ışığında, sistem için yaklaşık 2 kWp kurulu güce sahip bir tasarım önerilmektedir. Bu güç değerine ulaşmak için 330W gücünde 6-7 adet fotovoltaik panel kullanılması gerekmektedir. Panel başına yaklaşık 2 m² alan ihtiyacı göz önüne alındığında, toplam kurulum için 12-14 m² montaj alanı gerekmektedir.

Sistemin optimum performansı için panel eğim açısının Türkiye için yaklaşık 30-32° olması ve panellerin güney yönüne konumlandırılması önerilmektedir. Ancak unutulmamalıdır ki sistemin gerçek performansı; hava koşulları, panel yönü ve eğimi, gölgelenme etkileri, ortam sıcaklığı ve kullanılan sistem bileşenlerinin kalitesi gibi çeşitli faktörlere bağlı olarak değişkenlik gösterebilmektedir.

3.3.Sistem Entegrasyonu

enerjisi sistemlerinin Güneş tasarımında, depolama ünitelerinin güvenli ve verimli çalışması büyük önem taşımaktadır. Bu calısmada, günlük 975 Watt-saat enerji ihtiyacı olan bir sistem için yüksek güvenlikli batarya depolama ünitesi tasarlanmıştır. Sistem tasarımında, iki günlük yedekleme kapasitesinin yanı sıra %30'luk ek kapasite emniyet faktörü ve 1.2867 sıcaklık emniyet katsayısı dikkate alınmıştır. Temel batarya kapasitesi hesaplamaları, günlük enerji tüketimi ve yedekleme süresi baz alınarak gerçekleştirilmiştir. İki günlük toplam enerji ihtiyacı olan 1.95 kWh değeri, %50 deşari derinliği (DoD) ve %85 sistem verimi göz önüne alınarak hesaplanmış ve 4.59 kWh temel kapasite değeri elde edilmiştir. Bu değer, belirlenen kapasite ve sıcaklık emniyet faktörleri ile çarpılarak nihai batarya kapasitesi 7.7 kWh olarak belirlenmiştir. Sistem tasarımında 48V gerilim seviyesi tercih edilmiş olup, hesaplanan 160 Ah kapasite ihtiyacını karşılamak üzere üç adet 48V 100Ah lityum batarya paralel bağlantı ile kullanılmıştır. Bu konfigürasyon, toplam 14.4 kWh teorik kapasite sunarak, hesaplanan 7.7 kWh gereksinimini güvenli bir marjla karşılamaktadır. Artan batarya kapasitesi nedeniyle, şarj kontrol sistemi 48V 80A MPPT kontrolör olarak güncellenmiştir.

Sistemin güvenliği için kapsamlı bir batarya yönetim sistemi (BMS) entegre edilmiştir. Her bir batarya için ayrı BMS ünitesi, sıcaklık sensörleri, akım-gerilim koruması ve hücre dengeleme sistemleri kullanılmıştır. Sıcaklık kontrolü için aktif soğutma fanları ve otomatik kesme sistemleri tasarıma dahil edilmiştir. Bataryalar, IP65 koruma sınıfında muhafazalar içerisine yerleştirilmiş ve yangın söndürme sistemi ile desteklenmiştir.

Sistemin performans beklentileri mevsimsel olarak değişkenlik göstermektedir. Yaz aylarında %85-100 batarya doluluk oranı ve günlük 6 kWh efektif kapasite kullanımı öngörülürken, kış aylarında bu değerler sırasıyla %60-80 doluluk ve 4 kWh efektif kullanım olarak hesaplanmıştır. Bu değerler, yaz aylarında yaklaşık 2.5 gün, kış aylarında ise 2 günlük yedekleme süresini garanti etmektedir. Maliyet analizi açısından değerlendirildiğinde, yüksek güvenlik standartları ve emniyet faktörleri nedeniyle toplam sistem maliyeti 185.000 TL olarak hesaplanmıştır. Bu maliyet artışına rağmen, sistem güvenliği ve uzun vadeli performans açısından sağlanan avantajlar, yatırımın sürdürülebilirliğini desteklemektedir.

Kullanılacak Malzemenin Cinsi		Malzeme Miktarı	Birim Maliyet Fiyatı	Maliyet
PV Paneller	330W panel (Toplam 1980W) Her panel yaklaşık 1.6 m ² Toplam alan ihtiyacı: ~10 m ²	6 Adet	~4000 TL	24.000 TL
Batarya Sistemi	48V sistem gerilimi için	3 Adet	~35.000 TL	105.000 TL
Solar Şarj Kontrolörü	Panel gücü: 2000W Panel açık devre gerilimi: ~40V MPPT şarj kontrolörü: 48V 80A	1 Adet	20.000 TL	20.000 TL
Yardımcı Ekipmanlar	Montaj Sistemleri Kablolama ve Koruma Bağlantı Elemanları	1 Adet	8.000 TL+ 6.000 TL+ 4.000 TL	18.000 TL
İşçilik ve Kurulum	İşçilik ve kurulum giderleri	1 Adet	18.000 TL	18.000 TL
			Toplam 1	85.000 TL

Tablo 13: Maliyet Analizi

4. Sonuç

Bu çalışmada, günlük enerji ihtiyacı 975 Watt-saat olan offgrid fotovoltaik sistem için kapsamlı bir tasarım ve analiz gerçekleştirilmiştir. Yapılan araştırmalar ve analizler sonucunda, sistemin teknik ve ekonomik açıdan uygulanabilir olduğu tespit edilmiştir. Özellikle, sistemin iki günlük yedekleme kapasitesi ile çalışması için gerekli olan batarya grubu ve güneş paneli boyutlandırması başarıyla tamamlanmıştır. Sistem tasarımında, İstanbul'un iklim koşulları ve coğrafi konumu göz önünde bulundurularak, optimal bileşen seçimi yapılmıştır. Altı adet 330W, 40V güneş paneli ve üç adet 48V, 100 Ah derin döngülü bataryanın entegrasyonu ile oluşturulan sistem, en kötü hava koşullarında bile kesintisiz enerji sağlama kapasitesine sahiptir. Sistem performansının optimize edilmesi için MPPT şarj kontrol ünitesi kullanılmış ve gerekli koruma önlemleri alınmıştır.

Maliyet analizi sonuçları, sistemin kurulum maliyetinin yaklaşık 185.000 TL olduğunu göstermiştir. Bu maliyet, benzer kapasitedeki sistemlerle karşılaştırıldığında rekabetçi bir seviyededir. Özellikle, son 15 yılda güneş enerjisi sistemlerinin kurulum maliyetlerinde gözlemlenen düşüş, bu tür sistemlerin yaygınlaşması açısından umut vericidir. Bununla birlikte, maliyet optimizasyonu için şu öneriler geliştirilmiştir:

- Panel verimliliklerinin artırılması için yeni nesil fotovoltaik teknolojilerin araştırılması
- Sistem bileşenlerinin yerel üretiminin teşvik edilmesi ile maliyetlerin düşürülmesi

Gelecekteki iyileştirmeler için yapılan değerlendirmeler sonucunda, aşağıdaki öneriler sunulmuştur:

- 1. Akıllı enerji yönetim sistemlerinin entegrasyonu ile sistem verimliliğinin artırılması
- 2. Uzaktan izleme ve kontrol sistemlerinin geliştirilmesi
- 3. Hibrit enerji depolama sistemlerinin araştırılması
- 4. Güneş takip sistemlerinin maliyet-fayda analizinin yapılması

Bu çalışmanın sonuçları, benzer off-grid güneş enerjisi sistemlerinin tasarımı ve uygulaması için bir referans oluşturmaktadır. Özellikle şebeke elektriğinin ulaşamadığı veya kesintili olduğu bölgelerde, sürdürülebilir enerji çözümleri için önemli bir kaynak teşkil etmektedir. Gelecek çalışmalarda, farklı iklim koşulları ve uygulama alanları için sistem optimizasyonunun yapılması ve yeni teknolojilerin entegrasyonu konularının araştırılması önerilmektedir.

Sonuç olarak, geliştirilen sistem tasarımı ve metodolojisi, teknik ve ekonomik açıdan uygulanabilir bir çözüm sunmaktadır. Güneş enerjisi teknolojilerindeki hızlı gelişmeler ve maliyetlerdeki düşüş trendi, bu tür sistemlerin yaygınlaşması için olumlu bir gösterge oluşturmaktadır. Bununla birlikte, sistem performansının sürekli iyileştirilmesi ve maliyetlerin optimize edilmesi için araştırma ve geliştirme çalışmalarının devam ettirilmesi önem taşımaktadır.

Referanslar

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Ekler

İstanbul ilinin en kısa gündüz ve en uzun gündüz değerlerine ait radyasyon (ışınım) değerlerinin değişim grafiği Şekil 2'de verilmiştir. Aynı tarihler için güneşin doğumu ve güneşin batmasına ait saat değerleri Tablo 6'da verilmiştir.



Şekil 12 En uzun gündüz ve geceye için güneşin doğması ve batması

Tablo 14 En uzun gündüz	z ve geceye iç	cin güneşin	doğması ve
	batması		

	Enlom	Doulom	Güneşin	Güneş
Tarih	Emem	Boylalli	Doğması	Batması
21/4 rolule/2024	41.04137°	28.94014°	0.22	17:35
21/Afallk/2024	Kuzey enlemi (N)	Doğu boylamı	0.32	
21/IIarinan 2024	41.04137°	28.94014°	5.27	20.24
21/Haziran 2024	Kuzey enlemi (N)	Doğu boylamı	5:57	20.34

