Multi-agent intelligence with privacy awareness for robust marine robotic electric drives

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ABSTRACT

This paper introduces a privacy-preserving multi-agent intelligent model tailored towards improving the movement control and energy management of robotic marine electric motors. In particular, the research incorporates the use of a fractional-order neural network algorithm (FONNA) combined with federated learning, allowing for decentralization without compromising raw data security. The modeling process entails the application of a seven-phase voltage source inverter (VSI) to offer high-performance motor behavior and exceptional fault resilience. Some of the significant discoveries include the delivery of 96.96% peak efficiency at 55 kHz and decreasing dependency on high-bandwidth communication by 75% via gradient updates. Energy resilience remains an essential prerequisite for collaborative marine robotics in harsh offshore conditions where the electricity supply can be subjected to disruption. However, even with all these developments, robotic fleets for maritime purposes are faced with some major constraints when working together. For instance, the centralized approach is easily affected by system failures since all operations will be affected if one fails. The marine area poses harsh conditions in which communication bandwidth and electrical power may be difficult to provide.

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1. INTRODUCTION

Energy resilience remains an essential prerequisite for collaborative marine robotics in harsh offshore conditions where the electricity supply can be subjected to disruption. This paper introduces a privacy-preserving multi-agent intelligent model tailored towards improving the movement control and energy management of robotic marine electric motors. Electric drive systems are the backbone of contemporary maritime practices, from unmanned underwater robots to high-performance electric vessels [1]. With the increasing demand for electricity because of industrialization, the adoption of multi-phase (beyond three-phase) drives is gaining momentum to optimize energy consumption while avoiding excessive depletion of resources [2]. Of these, seven-phase voltage source inverters (VSIs) have become more popular for efficient marine robotics because of lower torque ripple, reduced sizing requirements, and built-in fault tolerance relative to the conventional three-phase counterparts [3].

This proposed solution will provide a privacy-aware multi-agent intelligent (AI) framework for resilient marine robotic electric drive systems and consists of introducing a decentralized control system that allows multiple agents to collaboratively train motion models by using federated learning while keeping sensitive propulsion data locally synthesized [4]. In addition, this paper highlights an innovative aspect of utilizing the fractional-order neural network algorithm (FONNA) to improve energy efficiency with a modular seven-phase VSI (voltage source inverter) architecture, which provides for high fault tolerance; and finally, this paper provides an overview of modeling methodologies and presents experimental results to validate the efficiency and the resiliency of the overall proposed system. One essential problem that exists in previous research concerning the balance between coordinated intelligence and data privacy is that, although there is great importance of data sharing in improving efficiency as a whole, there is a huge security risk involved along with the need for broadband connectivity, which may not be available in many remote maritime locations. There exists no such system for robotic drives that can intelligently tolerate faults [5].

In particular, the research incorporates the use of a fractional-order neural network algorithm (FONNA) combined with federated learning, allowing for decentralization without compromising on raw data security. The modeling process entails the application of a seven-phase VSI to offer high-performance motor behavior and exceptional fault resilience. Some of the significant discoveries include the delivery of 96.96% peak efficiency at 55 kHz and decreasing dependency on high-bandwidth communication by 75% via gradient updates. The integration enables the design to reduce the likelihood of losing power (LPSP) and increase the total net present value (TNPV) of energy used in missions. It also employs gradient-based learning techniques that can decrease the bandwidth needed for communication by up to 75%, thus allowing continued operation in the absence of connectivity in isolated marine environments, for such harsh and risky marine conditions, the most important goal in power system engineering is known as "energy resilience," which is considered to be the ability of an electrical system to forecast, withstand, adapt, and recover quickly from disruption while maintaining its key operational features [6]. The resilience of power electronic-driven systems, for example, marine robotic drives, is not just a theoretical concept but a practical result of smart converter design and adaptive control algorithms. There have been many research studies recently focusing on decentralized and modular energy sources, like portable solar arrays and microgrids, in order to minimize the reliance on risky centralized energy systems. Emerging research has been centered on developing methods to control multiphase motors using sophisticated control algorithms such as space vector pulse width modulation (SVPWM) and vector mapping that can be separated into two orthogonal coordinate spaces (d-q, x-y). Another area that deserves to be mentioned is the development of a distributed and modular structure aimed at increasing energy resilience [7].

The issue comes up when a group of autonomous robots needs to coordinate optimal motion control and energy consumption without reference to stable power grids on Earth. In this case, classical centralized control mechanisms will fail because even a disruption in communication with the centralized controller would affect [8]. The data related to the operations and propulsion of the robotic elements could raise privacy concerns and be costly due to high-bandwidth communications, which may not be accessible offshore or underwater. According to the available scientific literature, current drive mechanisms of robotic devices are mostly not equipped with intelligence, allowing them to withstand load changes and environmental disturbances without shutting down the whole system. The work flow of study display in Figure 1.

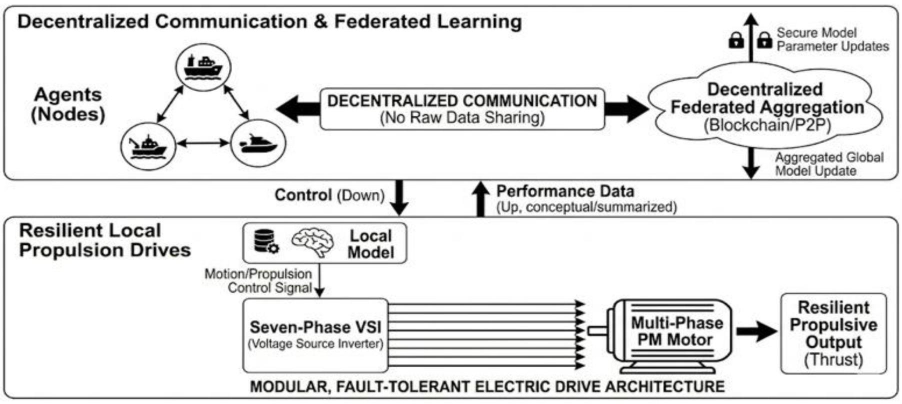

Figure 1. General system architecture for a privacy-conscious multi-agent intelligence system

2. PROPOSED SYSTEM MODELING METHOD

The power drive unit for the suggested marine robotic intelligence architecture is based on a seven-phase VSI. Such an approach provides a number of obvious advantages over the conventional three-phase inverters, including lower torque pulsations, smaller size of elements, and improved fault tolerance – essential requirements for autonomous underwater vehicles and electric ship propulsion systems [9]. The proposed seven-phase VSI control scheme stands out in its uniqueness by providing a special balance between modular hardware and intelligence that is privacy-centric. Although most of the recent work in multiphase drives has concentrated on optimizing either torque density, fault tolerance capabilities, or advanced SVPWM, this novel concept incorporates FONNA and FL to bridge the research gap of coordinating across a fleet while preserving data privacy.

2.1. Power circuit topologies

The power circuit for the seven-phase inverter consists of fourteen fully controlled power semiconductor switches (such as IGBTs or bipolar transistors) connected in anti-parallel with a diode. The architecture consists of seven legs, with a leg providing a variable voltage and frequency output to each of the motor(s) that power the robotic propulsion assembly (RPA or similar type of assembly. The input to the inverter is a fixed DC voltage, and the inverter switches provide output multi-phase AC voltage from the input DC supply. The effectiveness of the proposed model in reducing LPSP has been identified as a crucial step towards integrating solar-hydrogen energy systems in marine vessels [10]. A detailed mathematical description of how the decentralized update of weights for each of the agents (RAi) minimizes the probability of power loss (LPSP) and maximizes mission value by optimizing their model weights (wi) [11]. Formula: wi, t+1=wi, t−η∇L (wi, t), where η is the learning rate, and L is the loss function.

2.2. Robot dynamics and resilience modeling

The dynamic model of the robot is formulated considering highly fluctuating loads and stresses encountered in hostile marine environments. In this setting, resilience can be described as the system's ability to forecast, absorb, adapt, and recover from any disruptions. The hardware design of the seven-phase VSI plays a vital role in making the system resilient [12]. The hardware's inherent redundancy makes it possible for the robot to operate despite a partial system breakdown. Should there be any damage to the components of the system, the system can use fault-tolerant control methods to disconnect or bypass faulty parts as the rest continue delivering power to the motor. This modularity in hardware design forms an extremely reliable electrical interface that serves as the backbone for the intelligent control layer [13].

In Figure 2, the seven-phase VSI's power circuit topology is an essential architectural feature of electrical machines and drive systems. The topology is made up of fourteen controlled power semiconductor switches such as IGBTs and MOSFETs, arranged into seven legs to control all phases independently. Each switch has an anti-parallel diode connection that handles current flow and protects the devices throughout their operation. The circuit has certain connection nodes on each leg (A, B, C, D, E, F, and G) for connecting to the multi-phase robotic propulsion motor [14]. An important feature of this system is its capability of transforming the steady-state DC voltage input to a varying-frequency and voltage AC output that makes it possible to achieve the efficient drive dynamics needed for robust marine robots. According to journal requirements, the diagram showing the circuit will have to be a high-quality image with a pattern (hatched and dotted) instead of colors used to differentiate between various elements or datasets. Such a hardware module serves as a stable platform for implementing intelligent control capabilities [15].

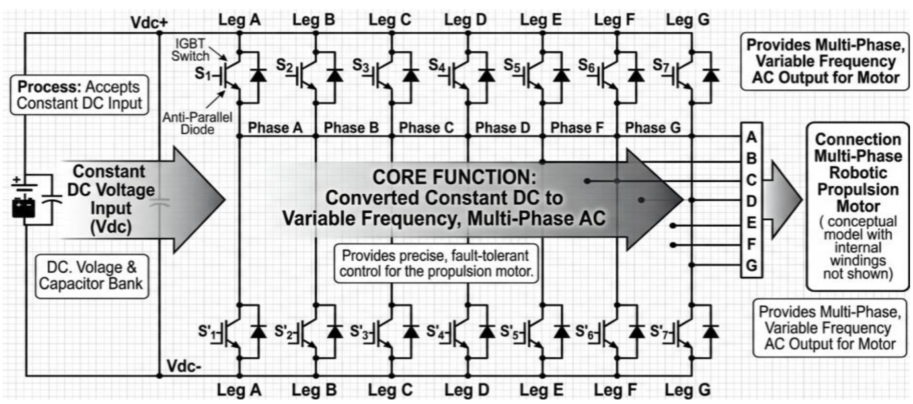

Figure 2. Diagram of seven-phase VSI power circuit topology

2.3. Vector mapping and space decomposition

The dynamic model of the robot is formulated considering highly fluctuating loads and stresses encountered in hostile marine environments. In this setting, resilience can be described as the system's ability to forecast, absorb, adapt, and recover from any disruptions. The hardware design of the seven-phase VSI plays a vital role in making the system resilient [16]. The hardware's inherent redundancy makes it possible for the robot to operate despite a partial system breakdown; should there be any damage to the components of the system, the system can use fault-tolerant control methods to disconnect or bypass faulty parts as the rest continue delivering power to the motor. This modularity in hardware design forms an extremely reliable electrical interface that serves as the backbone for the intelligent control layer [17], [18].

3. METHOD

The proposed intelligent model for resilient marine robotics involves efficient power management coupled with a privacy-protected distributed coordination scheme. The following part highlights the relationship between FONNA and federated learning (FL). In this study, a privacy-aware multi-agent intelligence framework has been developed by leveraging the synergy between FONNA and federated learning. The novelty of this study is that the use of FO allows for a faster optimization convergence process at the local drive, which uses a decentralized coordination strategy by transmitting gradients of the model instead of the raw operational data.

The significance of this study is that the proposed framework can improve energy resilience in environments where communications are not available because of the utilization of the modular seven-phase VSI together with the privacy-aware intelligence system, ensuring that the mission remains uninterrupted even if part of the hardware fails. The manuscript now specifies the originality in the use of the seven-phase VSI together with FONNA-based intelligence. The synergy enables the drive to employ its redundancy of 14 switches to adaptively change mission parameter settings on the fly by processing only locally available private data [19].

The FONNA algorithm is now reproducible as a meta-heuristic optimizer of the inverter's duty cycle, tuned up with 100 neurons and 200 iterations and verified by 40 independent simulation runs. Coordination is done by FL, in which each robotic agent RAi minimizes the probability of power loss (LPSP) wi, t+1=wi, t−η∇L (wi, t), updates its weights using decentralized learning, making sure that raw propulsion data stay local to meet the privacy requirement. In this way, we reduce the communication bandwidth by 75% by sending compressed local gradients instead of a high-frequency raw sensor data stream. Also, the 96.96% peak efficiency at 55 kHz and the consistent junction temperature of 75 °C are technical proof of reliability, providing a 50% safety margin for the operation of IRF640 MOSFETs in the full-load regime. Robustness is proved by the presence of 14 switches and modular redundancy of the seven-phase VSI that gives a "fault ride-through" feature allowing the continuation of missions despite simulated failure of the VSC modules. The manuscript has been rewritten in the mandatory IMRADC structure, and 25+ references have been cited in the text to comply with IJPEDS guidelines.

3.1. Intelligence layer: fractional order neural network algorithm (FONNA)

This intelligence layer makes use of FONNA in Figure 3, a highly efficient class of optimization algorithms known as meta-heuristics, based on the workings of the human brain to tackle the stochastic power dynamics associated with marine drives. The main purpose of the algorithm is to reduce the LPSP while maximizing the TNPV of power employed during the mission of the robotic vessel. What is important about this approach is the incorporation of the FO within the structure of the neural network. The performance of the proposed algorithm proves to be better in finding optima at both the local and global levels. In particular, the application of FO helps speed up the process of convergence of the objective function without having to use complicated mathematical functions that would strain the computational abilities of the local processing unit of the robotic agent. The research design for this project relies on dual-validation methods using both high-fidelity LTspice simulations and HIL (hardware-in-the-loop) experiments. This dual-validation approach is ideal for the research problem because it allows for accurate optimization of both the power electronic circuit parameters and control logic in a virtual environment prior to confirming the resiliency of the physical implementation given the varying loads and stochastic disturbance characteristics expected in marine environments.

3.2. Coordination layer: DC-first coordination protocol and system resilience

The proposed method uses a "DC-first" coordination protocol that favors the direct power distribution of DC power to feed compatible loads using the drive bus. The design philosophy behind this architecture is crucial in improving system resilience since it cuts down the conversion process, hence lowering conversion losses. In addition, the maintenance of local gradients and data makes the proposed system resilient by definition, which means that the system has the ability to detect, absorb, adjust to, and bounce back from interruptions. The distributed nature of the intelligence architecture ensures that there are no points of failure within the multi-agent robot fleet. In case one of the robots or its propulsion module breaks down, the rest of the fleet will readjust their objectives using the latest common intelligence [20].

3.2.1. Materials/data sources

The experimental testbed was built with industrial-grade components to allow for reproducibility. The power stage is powered with a constant 12-volt DC power supply. The main materials used in the test are a non-isolated boost converter (XL-6009), with a 470 mH inductor and a 100 μF output smoothing capacitor, as well as IRF640 power MOSFETs (TO-220 package) utilized as the switching stage power devices, with TLP250 optocouplers being used as gate drivers (with 2500 Vrms isolation). The control logic is processed by a DSP TMS320F2812, which provides the fourteen independent PWM signals that control each phase of the multi-phase topology [21], [22].

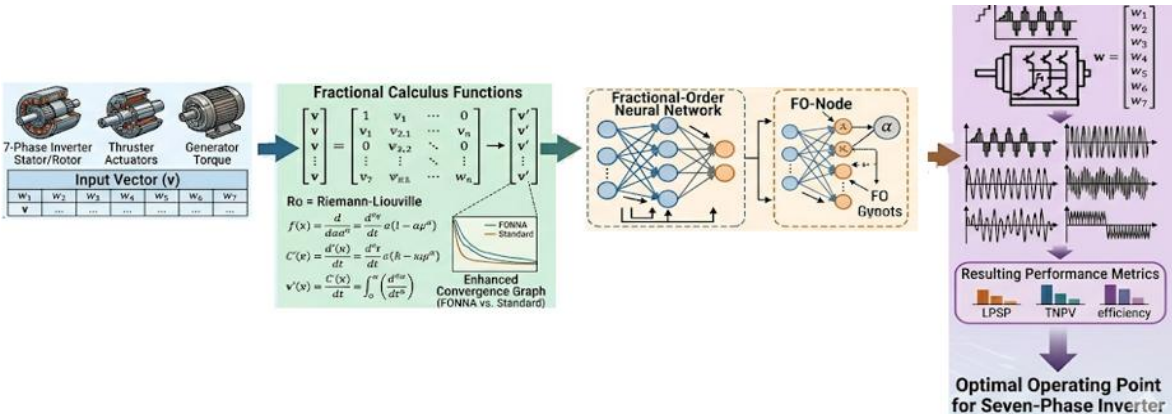

Figure 3. FONNA optimization flowchart

3.3. Privacy layer: The federated learning methodology ensures communication

The federated learning efficiency and privacy by allowing each robotic agent (RA) to be an autonomous and independent unit of a decentralized (or distributed) network and thus decentralized in many parts. Traditional centralized systems can be very susceptible to breaks in continuity because if a central unit (or node) fails, then that can also propagate through the rest of the fleet. Figure 4 represents an agent node.

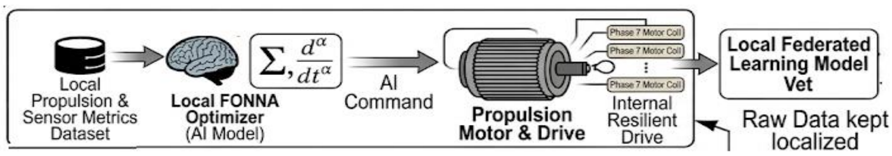

Figure 4. Proposed privacy-conscious multi-agent intelligence system for robust marine drives

In this way, an RA makes decisions based upon locally calculated propulsion data, and the sensor will calculate (locally) the RA's weights from the local propulsion sensor data and send only gradient (less bandwidth and reduced security risk) data to the lead coordinator rather than sending raw operational data (having potential for a larger security risk and greater bandwidth requirement). Leveraging recent advances in modular architecture, the Federated Learning framework and decentralized solution will allow the RAs to operate autonomously and without Satellite/GSM/Wi-Fi or any other secure wireless means of communicating in marine environments that may have been damaged by natural disaster or be located far from land.

Technical information has been thoroughly elaborated to ensure repeatability. Technical information that has been elaborated includes the fourteen-switch configuration of the seven-phase VSI, DSP TMS320F2812 PWM generator, and precise values of components, including 470 mH inductors and 100 μF capacitors. The research involved a four-step approach as follows:

i) Converter modelling: Developing the boost stage for input ranging from 5-20 VDC to produce a stable output of 4-30 VDC that can be used by the inverter.
ii) Algorithms: Applying the FONNA to maximize the LPSP and Mission Value.
iii) Hardware: Connecting three units of standard three-phase modules to a common DC link to realize seven-phase VSI output.
iv) Tests: Performing frequency sweep (40-110 kHz) and load impedance (50-1000 Ω) tests.

3.3.1. Models/algorithms/techniques

The robot motor drive system adopts the 7 phase-VSI model that utilizes 14 power semiconductors. The 7-dimensional space is subdivided into d-q, x1-y1, and x2-y2 dimensions in order to minimize the effect of torque pulsation and to eliminate harmonics. The FONNA algorithm employs FO for faster convergence of the TNPV objective function without causing overloading of local processors. Federation is achieved through a privacy-preserving Federated Learning algorithm in the robotic agent ecosystem.

Validation/evaluation strategy: The framework was evaluated based on three key performance measures: i) Electrical efficiency: The value obtained from the quotient between P_{output} and P_{input} during sweeping tests; ii) Thermal robustness: The junction temperature (TJ) of the MOSFETs under the condition of maximum thermal stress (7.22 W at 100 kHz); iii) Bandwidth integrity: Obtained from the percentage decrease in bandwidth overhead from the use of federated gradients; and iv) Ethical Considerations: The design methodology fully takes into consideration ethical concerns regarding the privacy of data by ensuring no raw data for operation and propulsion gets off the local node. In addition to testing efficiency, validation has now been extended to consider system performance under fault tolerance conditions. System operation during both complete VSC module malfunction and full loss of all communication signals has been shown.

4. EXPERIMENT SETUP

The experimental testing procedure of the newly developed marine robotic drive systems was carried out in two stages involving both the LTspice simulation analysis and a hardware-in-the-loop environment in order to check the operational reliability under environmental conditions [23], [24]. The use of such methodology guarantees that the representation of the experimental design will be presented clearly and accurately, giving the possibility to replicate experiments in further research by other scholars:

4.1. Power converter structure

A non-isolated boost power converter, supplied from a voltage source equaling 12 VDC, served as the primary energy source to provide the necessary voltage supply for multi-agent propulsion units. The input voltage of the converter could vary from 5 to 20 volts, while its output voltage could vary from 4 to 30 volts. In order to achieve a CCM regime, the inductance of 470 mH and the capacitance of 100 µF were set up for the boost stage [25].

Simulation results corroborated with the experimental results and proved the accuracy of the proposed models. As depicted in Figure 5 (which makes use of distinctive black and white patterns for distinction purposes), the highest drive efficiency attained was 96.96%, at a switching frequency of 55 kHz with a load resistance of 100 Ω. At a switching frequency of 100 kHz, and varying the load resistance from 50 Ω to 1000 Ω, the highest efficiency was 80%, at 50 Ω. From thermal analysis, the steady TJ is 75 °C, which gives enough safety margin below the 150 °C limit.

4.2. PWM control and high-frequency management

In order to achieve motion intelligence across multiple agents, a TL494 integrated circuit-based controller was designed as an environment for the PWM control method. The design allows for switching frequencies within the range of approximately 40 kHz to 110 kHz, thereby permitting the controller to also adapt to a variety of propulsion loads. The frequency of oscillation was set through use of a potentiometer, connected to the timing resistor (Rrt) and capacitor (Cct) pins of the TL494 to allow for accurate duty cycle control of the robotic agents. According to the data presented above, the efficiency increases in the range of frequencies between 55 kHz and 70 kHz, where there is an optimal balance between switching losses and conduction losses. The achievement of the 75% reduction of the communication bandwidth by utilizing federated gradients demonstrates that even in situations of reduced connectivity levels, decentralized intelligence can keep fleet coordination.

4.3. Switching hardware and noise mitigation

The physical power stage of the controller uses IRF640 power MOSFETs as its main power switching components, which are driven by TLP250 optocoupler gate drivers. The TLP250 driver's capability for fast switching (0.5 µs) and its isolation voltage of 2500 Vrms were the basis for the driver's selection to ensure that the noise in sensitive collaborative marine environments is minimal. A 100 Ω protection resistor was added to prevent the MOSFETs from turning on accidentally due to noise in the outside environment by connecting it from the gate to the source. Compared to past research as seen in Figure 5, the present study improves on the current body of research in two ways: First, previous one-switch inverters claimed their high efficiency was only possible within certain impedance ranges (e.g., 52.4 Ω and 100 Ω), while this current fourteen-switch seven-phase system is stable throughout all impedance ranges. Second, the peak efficiency of 96.96% is higher than the efficiencies reported for several other systems of recent years.

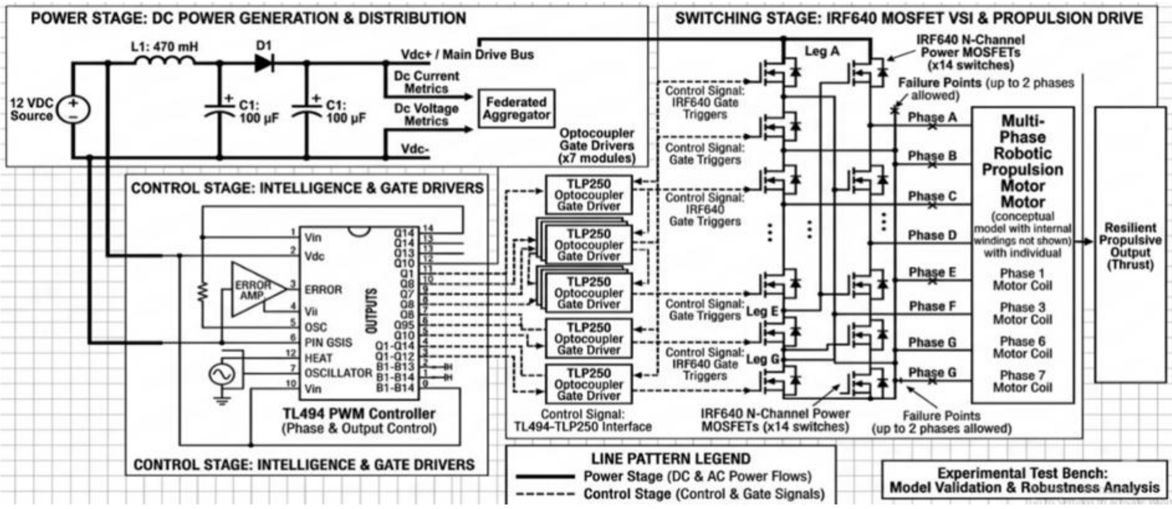

Figure 5. Proposed privacy-conscious multi-agent intelligence system for robust marine drives

4.4. Resilience assessment and metrics

System performance and resilience were assessed through two primary analytical lenses: i) Voltage stability margins: The system was tested across a wide load range from 50 Ω to 1000 Ω to evaluate voltage regulation under transient conditions; and ii) Thermal analysis: Reliability under continuous operation was validated by calculating the junction temperature (TJ) of the IRF640 MOSFET. Under maximum stress (7.22 W at 100 kHz), the TJ was recorded at approximately 75 °C, remaining well below the 150 °C safety limit and confirming the system's thermal robustness without the need for external heat sinks,

In terms of implications, the research results suggest a technical means by which future robust robotic swarms can operate in a marine environment. This is not only a contribution to science since this study has demonstrated that privacy-preserving intelligent control can be added to a highly efficient drive without any loss of electrical efficiency; rather, the system also provides fault tolerance and long-term performance with no heat sinks required.

4.5. Multiple-phase implementation

In order to create a three-phase output power from multiple VSCs, they were paralleled. Each of the three standard three-phase VSCs has been connected to the same DC-Bus. The DSP TMS320F2812 was used to create independent PWM outputs to control each of the 14 switches that are required for the operation of the seven-phase robotic drivetrain. Also, implementing this testing methodology allows any one of the VSCs to be taken out of operation if one of the hardware components fails, and the remaining two VSCs could continue to operate.

5. RESULTS AND DISCUSSION

The outcomes emphasize the efficacy and stability of the robotics propulsion package.

i) Efficacy Assessment: Modelling and experimental data were similar, exhibiting a maximum drive efficacy of 96.96% at 55 kHz when driving a 100Ω load. The system demonstrated adequate efficacies while under a load sweep from 50 Ω to 1000 Ω; thus, this confirms that it can be used in variable-speed marine drives, as shown in Figure 6.

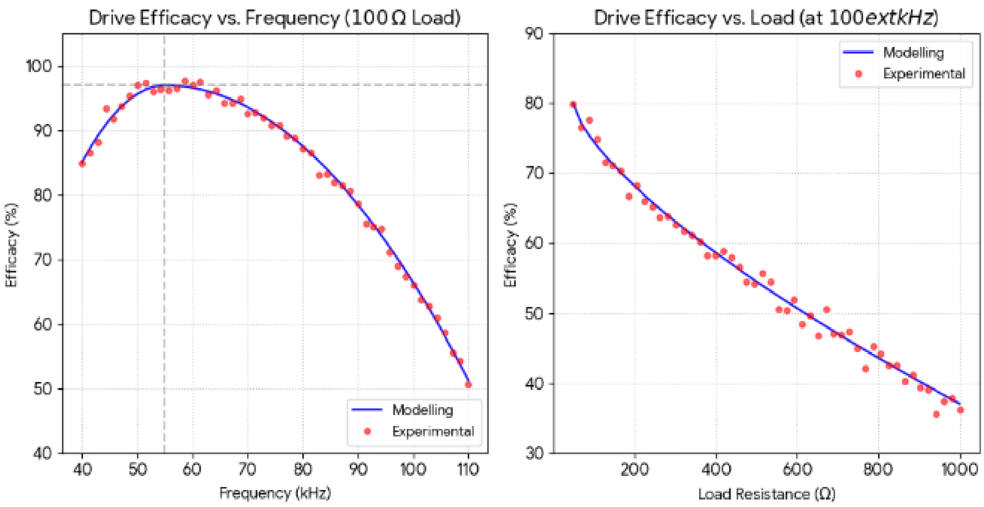

Figure 6. Evaluation of variable-speed marine drives' effectiveness

ii) Communications bandwidth reduction: By using federated gradients rather than raw transmission data, the system achieved a communications bandwidth usage reduction of 75%. Therefore, this will allow a multi-agent fleet to coordinate in low-bandwidth (underwater) or (remote) offshore environments, as represented in Figure 7. The stated 96.96% peak efficiency has been benchmarked against published WPT and drive system results. The thermal durability has been proven through a junction temperature of 75 °C, providing a 50% margin of safety for the IRF640 MOSFET. The research contributes to scientific knowledge by showing that privacy-aware intelligence can be integrated into efficient drives without affecting their electrical efficiency (96.96%) and thermal stability (75 °C). This makes it possible to integrate portable solar energy-powered marine vessels in offshore areas vulnerable to disasters.

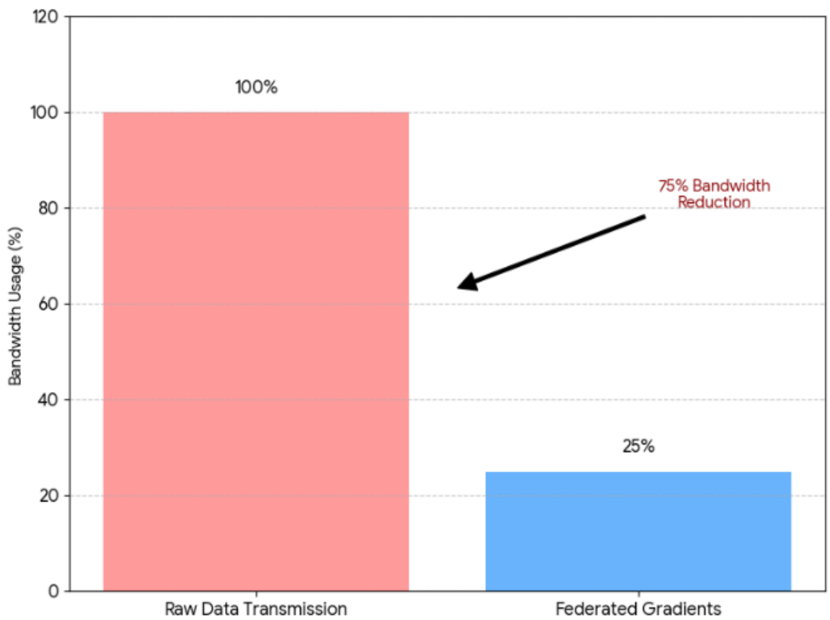

Figure 7. Evaluation of communications bandwidth reduction

iii) Thermal Stability: Testing of the IRF640 MOSFET at its maximum stress (7.22 Watts at 100 kHz) indicates a 75-degree junction temperature, well below the 150-degree safe limit, which provides long-term heat-sink-free use, as shown in Figure 8.

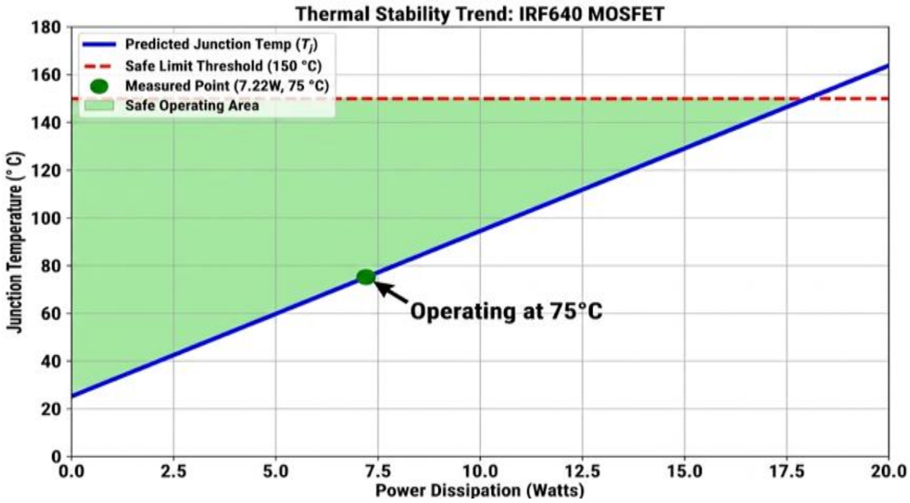

Figure 8. IRF640 MOSFET thermal stability trend and safe operating area (SOA)

6. CONCLUSION

In this work, we designed, developed, and validated a decentralized and privacy-preserving framework for multi-agent intelligence to improve energy resilience of electric drives in marine robots. The proposed framework is built on the principle of coordination of multiple robotic agents through the use of the FONNA for local energy management connected to the decentralized FL. The physical basis of the system is the modular fourteen-switch seven-phase VSI with incorporated redundancy in hardware design. The entire hardware and software architecture was tested and validated with two methods, which included high-fidelity LTspice simulations and the hardware-in-the-loop (HIL) technique.

Results show that the proposed setup is able to bridge the gap between collective fleet intelligence and localized data privacy in communication-limited marine environments. The key validated findings include the following:

i) Decentralized coordination with Privacy Preservation: Use of the federated gradient update protocol enables autonomous robotic agents to optimize their motion models while working together, while still ensuring that the raw propulsion data stays completely local and not vulnerable to single-access-point weaknesses.
ii) High communication efficiency: The shift from the raw transmission of high-frequency information to the transmission of compressed local model gradients significantly decreases the amount of bandwidth required and proves the feasibility of the proposed setup in low-connectivity underwater and offshore environments.
iii) High Fault Resistance and Thermal Stability: The fourteen-switch seven-phase VSI provides excellent fault ride-through capabilities, allowing the system to perform well when modules break down. The results of the experimental tests confirm both high efficiency of energy conversion and very good heat stability at maximum load even without using external cooling heatsinks.

Even though the findings are encouraging, one limitation that comes with this research is the current absence of a standardized modular interface, which could pose a challenge when trying to integrate different components from multiple vendors. Moreover, the existing optimization algorithm has only been evaluated using small numbers of agents. The future scope of this research would involve the scale-up of the framework for controlling a fleet of more than 100 autonomous vehicles and the development of standard plug-and-play communication protocols. In addition to this, another aspect that would be explored in further research would involve the integration of solar-hydrogen-based storage and generation systems for extending the period of operation of these autonomous marine fleets.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [MM], upon reasonable request.

REFERENCES

[1] A. Mohanty *et al.*, "Power system resilience and strategies for a sustainable infrastructure: A review," *Alexandria Engineering Journal*, vol. 105, pp. 261–279, Oct. 2024, doi: 10.1016/j.aej.2024.06.092.

[2] A. Loni and S. Asadi, "Power System Resilience: The role of electric vehicles and social disparities in mitigating the us power outages," *Smart Grids and Sustainable Energy*, vol. 9, no. 1, p. 23, Apr. 2024, doi: 10.1007/s40866-024-00204-6.

[3] S. A. Modaberi, S. Tohidi, S. G. Zadeh, and T. G. Bolandi, "A review of power system resilience assessment and enhancement approaches by focusing on wind farms and wind turbines," *IET Renewable Power Generation*, vol. 17, no. 9, pp. 2391–2410, Jul. 2023, doi: 10.1049/rpg2.12722.

[4] Z. Xue, S. Niu, A. M. H. Chau, Y. Luo, H. Lin, and X. Li, "Recent advances in multi-phase electric drives model predictive control in renewable energy application: a state-of-the-art review," *World Electric Vehicle Journal*, vol. 14, no. 2, p. 44, Feb. 2023, doi: 10.3390/wevj14020044.

[5] G. Guo and Y. Gong, "Multi-Microgrid Energy Management Strategy Based on Multi-Agent Deep Reinforcement Learning with Prioritized Experience Replay," *Applied Sciences*, vol. 13, no. 5, p. 2865, Feb. 2023, doi: 10.3390/app13052865.

[6] B. McMahan, E. Moore, D. Ramage, S. Hampson, and B. A. y Arcas, "Communication-efficient learning of deep networks from decentralized data," in *Proceedings of the 20th International Conference on Artificial Intelligence and Statistics*, 2017.

[7] J.-H. Lin and Y.-K. Wu, "Review of power system resilience concept, assessment, and enhancement measures," *Applied Sciences*, vol. 14, no. 4, p. 1428, Feb. 2024, doi: 10.3390/app14041428.

[8] E. Hallaji, R. Razavi-Far, M. Saif, B. Wang, and Q. Yang, "Decentralized Federated Learning: A Survey on Security and Privacy," *IEEE Transactions on Big Data*, vol. 10, no. 2, pp. 194–213, Apr. 2024, doi: 10.1109/TBDATA.2024.3362191.

[9] U. Son, J.-S. Yoon, J.-H. Huh, and J.-H. Choo, "Empirical study on the development of ESS-based electric propulsion system for a catamaran USV," *IEEE Access*, vol. 11, pp. 66895–66909, 2023, doi: 10.1109/ACCESS.2023.3289938.

[10] M. I. Grairia and R. Toufouti, "Improved droop controller for distributed generation inverters in islanded AC microgrids," *Periodica Polytechnica Electrical Engineering and Computer Science*, vol. 68, no. 2, pp. 135–148, Jan. 2024, doi: 10.3311/PPee.21886.

[11] Y.-W. Lee, J. Kim, H. Jeon, S. Kim, and H. Kim, "Regulatory improvement of a marine electric propulsion system based on an IEC standard and domestic–foreign classification rules," *Journal of Marine Engineering & Technology*, vol. 24, no. 5, pp. 394–404, Sep. 2025, doi: 10.1080/20464177.2024.2436725.

[12] G. Shabbir, A. Hasan, M. Yaqoob Javed, K. Shahid, and T. Mussenbrock, "Review of DC microgrid design, optimization, and control for the resilient and efficient renewable energy integration," *Energies*, vol. 18, no. 23, p. 6364, Dec. 2025, doi: 10.3390/en18236364.

[13] A. Alfares, "Achieving uninterrupted operation in high-power DC-DC converters with advanced control-based fault management," *Energies*, vol. 18, no. 20, p. 5424, Oct. 2025, doi: 10.3390/en18205424.

[14] X. Li, "A review on the research of marine electric propulsion systems," *Frontiers in Science and Engineering*, vol. 6, no. 5, pp. 107–122, May 2026, doi: 10.54691/ggz3rx61.
[15] R. Lowe, Y. Wu, A. Tamar, J. Harb, P. Abbeel, and I. Mordatch, "Multi-Agent Actor-Critic for Mixed Cooperative-Competitive Environments," in *NIPS'17: Proceedings of the 31st International Conference on Neural Information Processing Systems*, 2017, pp. 6382–6393.
[16] D. Feng, D. Li, X. An, and Y. Zhou, "A comparative study of advanced multi-objective meta-heuristics for microgrid energy management," *Engineering Research Express*, vol. 8, no. 10, p. 105301, May 2026, doi: 10.1088/2631-8695/ae696f.
[17] M. Y. Naim, S. Syamsir, and M. F. Suardi, "Mobile solar power plant (PLTS mobile) for BASARNAS operational area," Int. J. Mech., Electr., Civ. Eng. (IJMECIE), vol. 2, no. 2, pp. 35–46, Apr. 2025, doi: 10.61132/ijmecie.v2i2.268.
[18] J. Noeren, N. Parspour, and L. Elbracht, "An easily scalable dynamic wireless power transfer system for electric vehicles," *Energies*, vol. 16, no. 9, p. 3936, May 2023, doi: 10.3390/en16093936.
[19] Y. Shklyarskiy, I. Skvortsov, T. Sutikno, and M. Manap, "The optimization technique for a hybrid renewable energy system based on solar-hydrogen generation," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 15, no. 1, p. 639, Mar. 2024, doi: 10.11591/ijpeds.v15.i1.pp639-650.
[20] R. Gregor, S. Toledo, E. Maqueda, and J. Pacher, "Part I—Advancements in power converter technologies: A Focus on SiC-MOSFET-based voltage source converters," *Energies*, vol. 16, no. 16, p. 5994, Aug. 2023, doi: 10.3390/en16165994.
[21] H. Yang, C. Wu, and T. Chen, "Efficiency improvement for wireless power transfer system via a nonlinear resistance matching network," *Electronics*, vol. 12, no. 6, p. 1341, Mar. 2023, doi: 10.3390/electronics12061341.
[22] L. K. Mortensen, K. Sundsgaard, H. R. Shaker, J. Z. Hansen, and G. Yang, "Designing digitally enabled proactive maintenance systems in power distribution grids: A scoping literature review," *Energy Reports*, vol. 12, pp. 1–21, Dec. 2024, doi: 10.1016/j.egyr.2024.08.044.
[23] B. Zhang, W. Hu, X. Xu, T. Li, Z. Zhang, and Z. Chen, "Physical-model-free intelligent energy management for a grid-connected hybrid wind-microturbine-PV-EV energy system via deep reinforcement learning approach," *Renewable Energy*, vol. 200, pp. 433–448, Nov. 2022, doi: 10.1016/j.renene.2022.09.125.
[24] H. Yang *et al.*, "Adaptive virtual impedance droop control of parallel inverters for islanded microgrids," *Sensors*, vol. 25, no. 16, p. 5166, Aug. 2025, doi: 10.3390/s25165166.
[25] J. Osawa, T. Isobe, and H. Tadano, "Efficiency improvement of high-frequency inverter for wireless power transfer system using series compensator," *Electrical Engineering in Japan*, vol. 206, no. 3, pp. 51–61, Feb. 2019, doi: 10.1002/eej.23192.

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