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Research

NEURAL NETWORK–DRIVEN EFFICIENCY OPTIMIZATION OF PMSM FOR ELECTRIC VEHICLE PROPULSION SYSTEMS

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ABSTRACT

Permanent Magnet Synchronous Motors (PMSMs) are widely adopted in electric vehicle (EV) propulsion systems due to their high-power density, fast dynamic response, and superior efficiency. However, maintaining optimal efficiency over wide speed–torque operating ranges and varying driving conditions remains a significant challenge. Conventional control techniques such as proportional–integral (PI) controllers and fixed-parameter field-oriented control (FOC) schemes fail to ensure optimal efficiency under dynamic load and speed variations. This paper proposes a **Neural Network (NN)–driven efficiency optimization strategy** for PMSM-based EV propulsion systems. The proposed NN controller adaptively optimizes control parameters to minimize motor losses and improve overall efficiency. The effectiveness of the proposed method is evaluated under various speed and torque conditions. Simulation results demonstrate improved efficiency, reduced losses, and enhanced dynamic performance compared to conventional control approaches, validating the suitability of the NN-based strategy for EV applications.

Index Terms— Permanent Magnet Synchronous Motor (PMSM), Electric Vehicles (EVs), Artificial Neural Network (ANN), efficiency optimization, loss minimization, intelligent motor control

I. INTRODUCTION

The rapid growth of electric vehicles has intensified the demand for high-efficiency and high-performance electric propulsion systems. Among various electric machines, the Permanent Magnet Synchronous Motor (PMSM) has emerged as a preferred choice for EV applications due to its compact size, high torque density, and excellent efficiency. Nevertheless, PMSM efficiency varies significantly with operating conditions such as speed, torque, temperature, and load dynamics encountered during real-world driving cycles.

Conventional PMSM control techniques, including field-oriented control (FOC) and direct torque control (DTC), typically rely on fixed-gain PI controllers. Although these methods offer satisfactory steady-state performance, they are unable to guarantee optimal efficiency across the entire operating range. Losses such as copper loss, iron loss, and inverter-related losses increase under non-optimal control conditions, reducing driving range and energy utilization efficiency.

Artificial intelligence-based control strategies, particularly Artificial Neural Networks (ANNs), have gained increasing attention for motor drive applications due to their learning capability, nonlinear mapping, and adaptability. ANN-based controllers can approximate complex nonlinear relationships between motor variables and efficiency metrics, enabling adaptive and intelligent control.

This paper presents an ANN-driven efficiency optimization framework for PMSM-based EV propulsion systems. The proposed approach dynamically adjusts control variables to minimize motor losses and maximize efficiency under varying operating conditions.

2. LITERATURE SURVEY

Permanent Magnet Synchronous Motors (PMSMs) have become a cornerstone of modern **electric vehicle (EV) propulsion systems** due to their **high efficiency, power density, and favourable dynamic performance** compared with other machine types. However, improving and maintaining high efficiency over wide operating ranges — particularly under varying speed, torque, and load conditions — continues to be a major research focus.

Traditional control strategies for PMSMs, such as **field-oriented control (FOC)** and **direct torque control (DTC)**, typically employ fixed-parameter **proportional–integral (PI)** controllers. While these approaches provide acceptable steady-state performance, they are sensitive to parameter changes, nonlinear dynamics, and load variations, which in turn can reduce system efficiency and dynamic performance. To handle these limitations, researchers have increasingly turned to **intelligent techniques** including artificial neural networks (ANNs), fuzzy logic, and hybrid methods to enhance control performance and efficiency.

A recent comprehensive review highlights the evolution of PMSM control methodologies from classical PID and FOC schemes to a range of **intelligent controllers** such as ANN, fuzzy logic control, and Adaptive Neuro-Fuzzy Inference System (ANFIS), along with optimization techniques applied to PMSM drives. The review emphasizes that intelligent controls offer improved robustness and adaptability in speed and torque regulation compared to traditional methods [3]. Journal of Electrical Systems

Artificial neural networks have been applied successfully in PMSM control to handle nonlinearities and provide adaptive responses. An ANN–based sensor less speed control scheme for a PMSM drive in EV applications demonstrated improved transient performance compared to conventional estimation methods. The ANN controller exhibited faster response times and reduced speed estimation errors relative to PI-based approaches [2][8]. MDPI+1

Other work has focused on optimizing PMSM performance through neural network integration with advanced control strategies. For example, a **neural network vector controller** was developed to overcome decoupling inaccuracies in conventional vector control methods, offering improved performance under dynamic conditions and in hardware-validated studies relevant to EV motors [5]. PubMed

In addition to classic speed or torque controllers, hybrid methods that combine ANNs with predictive or model-based control techniques have been explored. In EV drive systems employing a five-phase PMSM under fault conditions, a multi-layer perceptron ANN was used to *online tune PI controller gains*, demonstrating adaptability and reduced control errors compared with meta-heuristic based tuning techniques [9]. Nature

Beyond neural network control, research on PMSM efficiency optimization includes strategies based on detailed **loss modelling and energy balance**. Such approaches use analytical motor loss models to devise control laws that optimize efficiency across operating conditions. One study using energy balance control improved PMSM efficiency by up to 7 % compared with conventional loss minimization methods, highlighting the potential impact of model-based optimization for EV applications [4]. MDPI

Although not strictly ANN-based, efficiency improvement studies like the one by Wang and Wang applied **system loss models** to jointly optimize motor and inverter losses, achieving significant system efficiency gains compared with conventional methods. These approaches demonstrate the breadth of efficiency-focused research for PMSM drives, which can complement ANN-driven techniques [6]. MDPI

Gap and Motivation: While numerous works demonstrate **ANN control for speed estimation, torque control, and fault-tolerant performance**, fewer studies explicitly target **efficiency optimization of PMSM systems using ANN strategies** in the context of EV propulsion. Most existing efficiency studies rely on analytical loss modelling or optimization algorithms without leveraging the adaptive learning capability of neural networks. Integrating ANN frameworks with loss-aware control presents an opportunity to optimize efficiency dynamically under widely varying real-world EV drive conditions — a key motivation for the current research.

Summary:

The literature underscores the growing adoption of neural networks and intelligent control techniques for PMSM drives, particularly in speed and torque regulation for EV applications. Neural network methods demonstrate improved adaptability and dynamic performance compared with conventional controllers. Studies on efficiency, though promising, often rely on analytical or rule-based controllers rather than machine-learning-driven optimization. The proposed **neural network–driven efficiency optimization strategy** thus addresses an important gap by combining adaptive intelligence with targeted efficiency improvement in PMSM-based EV systems.

3. PMSM Modelling for EV Applications

The mathematical model of a PMSM in the synchronous rotating reference frame (d–q frame) is given by:

$$V_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q$$

$$V_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_e L_d i_d + \omega_e \psi_f$$

where V_d, V_q are d–q axis voltages, i_d, i_q are stator currents, R_s is stator resistance, L_d, L_q are inductances, ω_e is electrical angular speed, and ψ_f is permanent magnet flux linkage.

The electromagnetic torque is expressed as:

$$T_e = \frac{3}{2} p\left(\psi_f i_q + (L_d - L_q) i_d i_q\right)$$

The total motor losses consist of copper losses, iron losses, and inverter losses. Efficiency is defined as:

$$\eta = \frac{P_{out}}{P_{out} + P_{loss}}$$

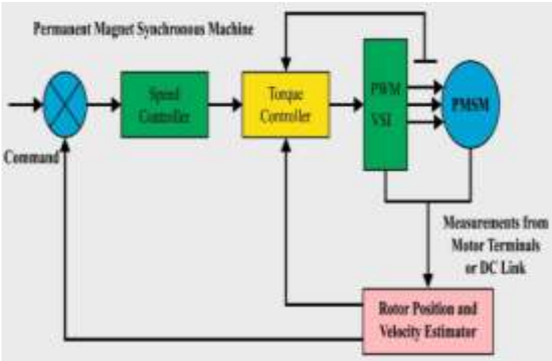

Fig 1. Model design architecture of ev controller with PMSM

4. Neural Network–Based Efficiency Optimization Strategy

A. ANN Architecture

The proposed ANN controller employs a multi-layer feedforward neural network trained using the backpropagation algorithm. The ANN inputs include:

- Motor speed
- Load torque
- Stator current components
- DC-link voltage

The output of the ANN is the optimized reference current (or control parameter) that minimizes losses and improves efficiency.

B. Training and Learning Process

The ANN is trained offline using data generated from PMSM simulations under various operating conditions. The training objective is to minimize the error between predicted optimal efficiency and actual efficiency. The trained network is then integrated into the real-time control loop.

C. Integration with Motor Control Scheme

The ANN is integrated with a conventional FOC scheme. While FOC ensures decoupled torque and flux control, the ANN dynamically optimizes reference currents to achieve loss minimization and efficiency enhancement.

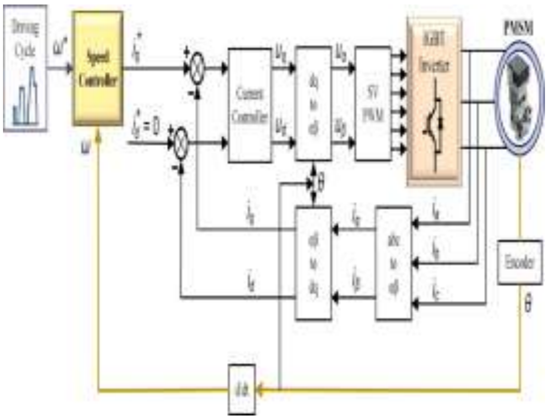

Fig 2. ANN control system for PMSM model

5. Efficiency Optimization Mechanism

The ANN-based controller continuously evaluates operating conditions and adjusts control parameters to:

- Reduce copper losses by optimizing current magnitude
- Minimize iron losses by regulating flux level
- Improve torque production efficiency

This adaptive optimization ensures high efficiency across low-speed, high-speed, and transient operating regions.

6. Simulation Results and Discussion

The proposed NN-based PMSM drive is modeled in MATLAB/Simulink and tested under various EV driving scenarios, including:

- Constant speed operation
- Variable load torque
- Acceleration and deceleration cycles

Performance metrics analyzed include:

- Motor efficiency
- Energy consumption
- Torque ripple
- Speed response

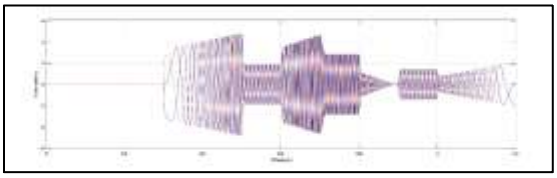

Fig 3. Time domain waveform of phase current in steady state Operation of PMSM with Variable control.

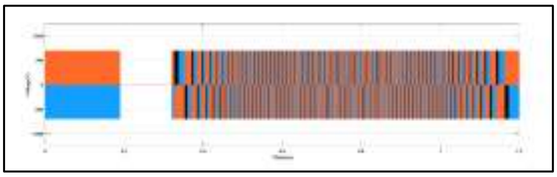

Fig 4. PMSM based switching voltage applied to the motor.

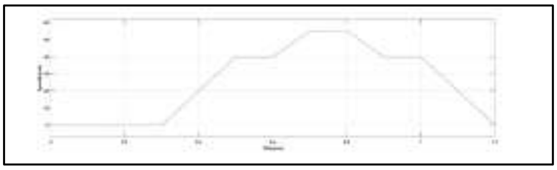

Fig 5. Reference **s**peed profile applied to the PMSM for performance evaluation.

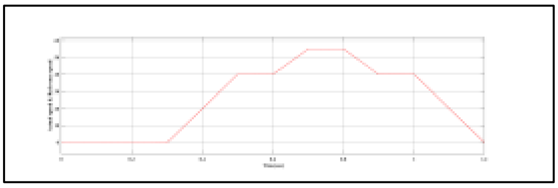

Fig 6. Speed response of the PMSM showing variation of actual speed with respect to reference speed over time.

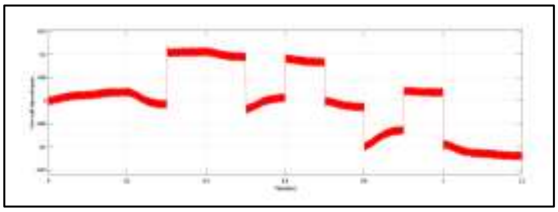

Fig 7. Overall speed of the PMSM under step changes in reference speed and load conditions.

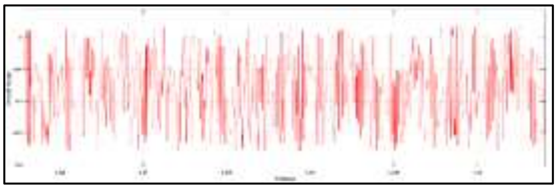

Fig 8. Torque response under transient condition.

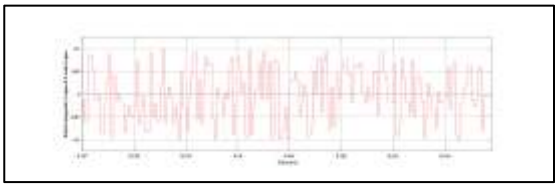

Fig 9. Response of electromagnetic torque and load torque of PMSM drive

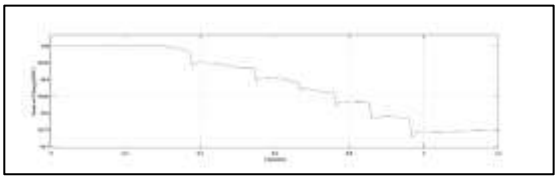

Fig 10. Battery state of charge variation with respect to time.

Simulation results show that the NN-driven approach achieves higher efficiency and reduced losses compared with conventional PI-based FOC, particularly under partial load and dynamic conditions.

7. Conclusion

This paper presented a **Neural Network–driven efficiency optimization strategy** for PMSM-based electric vehicle propulsion systems. By leveraging the learning and adaptive capabilities of ANN, the proposed method effectively minimizes motor losses and enhances overall efficiency across a wide operating range. Simulation results confirm the superiority of the proposed approach over conventional control techniques, making it a promising solution for next-generation EV propulsion systems.

Future Scope

Future work will focus on real-time hardware implementation using DSP/FPGA platforms, online ANN training, and integration with vehicle energy management systems to further improve driving range and system reliability.

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