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Modelling and Control of Permanent-Magnet-Assisted Synchronous Reluctance Motor for Enhanced Performance in Electric Vehicles

Abstract: - This paper propose an advanced control system for permanent-magnet-assisted synchronous reluctance motor (PMaSynRM) for electric vehicles. The enhanced design aims to improve the dynamic response and operational stability of the motor, crucial for optimizing performance in electric vehicle applications. We introduce a comprehensive control framework that includes proportional-integral (PI) controllers for the inner loop focusing on current control, and a sophisticated outer loop controller designed to manage speed and torque seamlessly. Simulation results demonstrate the effectiveness of the dual-loop control in maintaining high efficiency and minimal torque ripple under varying load conditions. This integration not only refines motor performance but also ensures robustness and reliability, achieving an overall system efficiency of 95%. The study provides a detailed analysis of the modeling and control strategy implementation, its impact on motor performance, and the associated enhancements in efficiency and torque handling capabilities.

Keywords: Electric Vehicles, Synchronous Reluctance Motor, Permanent-Magnet Motors, Dual-Loop Control Systems

1. INTRODUCTION

Fossil fuels becoming less and less available as sources of alternative energy become more and more urgent [1].The automobile industry, which is one of the biggest consumers of fossil fuel, is taking giant strides in the EV and hybrid vehicle (HEV) lines to combat conventional vehicles that run on petroleum [2]. Better electric motor performance coupled with low and drop of costs has been a great drive for the industry toward the research on EV [3]. A good electric motor for electric vehicles should have the ability to generate a high value of torque at a low speed for starting or hill climbing and at the same time, be capable of delivering high powers at a high speed during the cruising [4]. Mutiple type of motors have been used of the EVs and HEVs such us : Induction Motors (IM), BLDC, Synchrounous Reluctance Motor (SRM), and IPMs (Interior Permanent Magnets) [5]. In addition to the aforementioned benefits—rapid torque response, high power density, an extensive speed range, high efficiency, dependability, and cost—these attributes are maximised in the montionned motors. Permanent Magnet Synchronous Motors (PMSMs) with PMs have high energy density, but this is also what sets them apart; they come at a price [6]. IMs for traction applications are chosen depending on their durability and low-maintenance case, while on the other hand, due to the high starting currents, the disadvantages include lower efficiency, power coefficient and battery duration [7]. SRMs offer high efficiency, cost-effectiveness, and simple and robust design but are normally accompanied with high levels of noise, vibration, and ripples in the torque [8]. BLDC motors provide a high efficiency with an increased power density, but the fixed power range limits the extended speed capability of the drive [9].

The Permanent-Magnet-Assisted Synchronous Reluctance Motor (PmaSynRM) has garnered significant research interest, primarily due to its widespread use in marine applications [10]. Following its adoption in Tesla's electric vehicle (EV) systems, there has been a surge in research aimed at enhancing system efficiency through optimized design and control

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mechanisms. Numerous researchers have explored the optimization of design and control for this type of motor. In this paper, the authors specifically delve into advanced control strategies for Permanent-Magnet-Assisted Synchronous Reluctance Motors (PmaSynRMs) in electric vehicle applications, with a particular focus on flux weakening techniques [11]. Flux weakening is crucial for extending the speed range of electric motors beyond their base speed, allowing EVs to maintain high torque at lower speeds and transition smoothly to high-speed operations without sacrificing power output or efficiency.

Researchers have explored using ferrite permanent magnets, which are more cost-effective than rare-earth magnets, in synchronous reluctance machines. This study [12] aims to show that ferrite PMs can deliver high performance and energy efficiency in electric vehicles (EVs), thus lowering the overall costs of EV powertrains. Further research [13] focuses on integrating ferrite PMs into motor designs for EVs, emphasizing both affordability and efficiency. This paper likely details a specific motor design that meets the operational demands of EVs, assessing factors such as torque density, power efficiency, and thermal properties. Similar to [12], another study [14] introduces a ferrite-based PMaSynRM, comparing it to established designs like the Prius motor. It aims to highlight the cost-effectiveness and performance, supported by detailed simulation and experimental results to validate the design against industry standards. The authors in [15] provide a comprehensive performance analysis of PMaSynRMs under various conditions, comparing different motor designs and configurations. The study examines design variations that optimize efficiency, reduce losses, and enhance EV drivability. Research in [16] presents a novel approach to the parametric design of PMaSynRMs with ferrite magnets to optimize key performance indicators like torque and efficiency affordably. This might include theoretical modeling and finite element analysis of various design configurations. The focus of [17] is on robust control algorithms that enhance the field weakening capabilities of PMaSynRMs. It discusses the integration of these control strategies into real-world EV applications to ensure compatibility with existing systems.

A paper [18] explores optimizing motor designs to achieve peak energy efficiency along the typical torque-speed curve of EVs. The methodology could combine design modifications and control strategy improvements to surpass performance benchmarks. Focused on maximizing power density, research [19] explores innovative design tweaks in PMaSynRMs using ferrite magnets to enhance electromagnetic torque without significantly increasing material costs. Another study [20] examines the effects of pole shifting on torque production and ripple in PMaSynRMs, offering insights into how pole shifting impacts motor performance and acoustic characteristics, crucial for improving the passenger experience in EVs. In contrast to [21], which implements an outer loop control system for propulsion speed management demonstrating satisfactory but improvable performance, [22] introduces an inner loop for current control, creating a dual-loop system that significantly enhances control efficiency and robustness. This dual-loop configuration ensures a stable output by quickly adjusting to changes in load and speed demands, providing a more refined control of motor dynamics essential for precision-critical applications. Although these advancements in control systems offer improved performance and precision, they introduce increased complexity, particularly affecting real-world implementation and maintenance.

The principal contribution of this paper is the development and integration of an advanced dual-loop control system, which enhances the foundational concepts presented in [11] and [12]. Our design introduces a more streamlined version of this system, maintaining the robust performance of earlier models while simplifying the complexities typically associated with their implementation. This simplification is accomplished by employing PI controllers, which effectively reduce system overhead and improve usability. This approach ensures high-quality control without compromising the system’s operational integrity.

The remainder of this paper is organized as follows: Section 2 provides a technical description of the Permanent-Magnet-Assisted Synchronous Reluctance Motor (PmaSynRM). Section 3 details the control systems implemented, emphasizing the dual-loop configuration. Section 4 presents the results and discussion, highlighting the effectiveness of the proposed design and control approach. Finally, the conclusion in Section 5 summarizes the key findings and outlines potential future work to advance this research further.

2. DESCRIPTION OF THE PM-ASSISTED SYNCHRONOUS RELUCTANCE MACHINE (PMASYNRM)

The PM-Assisted Synchronous Reluctance Machine (PmaSynRM) combines the principles of permanent magnet (PM) and synchronous reluctance machine technologies. This hybrid design aims to harness the benefits of both technologies to enhance overall motor performance, particularly in electric vehicles (EVs). A PmaSynRM is characterized by the incorporation of permanent magnets in the rotor, which is designed to align with the reluctance paths. These magnets assist in maintaining a constant magnetic flux in the rotor, thereby enhancing the motor's efficiency and power output. The presence of PMs helps improve the torque density and power factor of the machine compared to a pure synchronous reluctance machine. The rotor structure as shown in Figure 1 is typically designed to optimize the flux barriers, which maximize the torque production while minimizing losses. This design not only improves the reluctance torque but also allows for better utilization of the magnets' field, contributing to a more efficient operation across a wide range of speeds and loads.

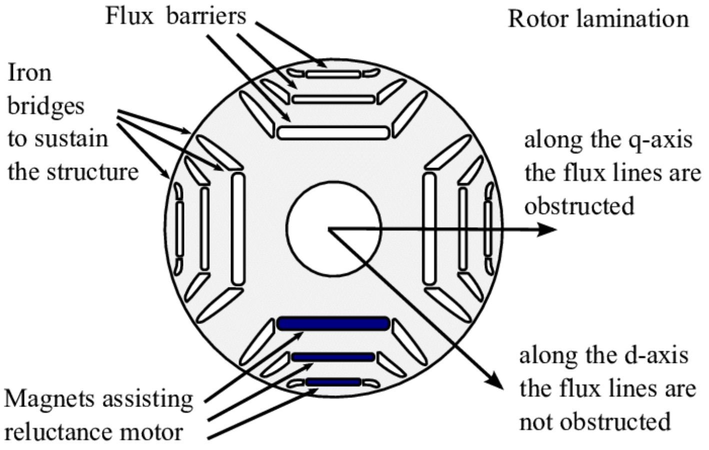

Figure 1: Rotor Structure of PmaSynRM

The PM-Assisted Synchronous Reluctance Machine (PmaSynRM) combines characteristics of both permanent magnet and reluctance machines to enhance performance in electric vehicle applications. Below, we describe the dynamic behavior and torque production through comprehensive mathematical equations.

Voltage Equations

The dynamic performance of the PmaSynRM can be represented by its phase voltage equations. For the d-axis and q-axis, the voltage equations in a synchronous reference frame are as follows:

d-axis Voltage Equation:

$$Vd = Rs\ id + \frac{d}{dt}(Ld\ id) + \omega r(Lqiq + \Psi pm, q) \qquad (1)$$

q-axis Voltage Equation:

$$Vq = Rs\, iq + \frac{d}{dt}(Lq\, iq) + \omega r(Ld\, id - \Psi pm, d) \qquad (2)$$

Where:

- Vd and Vq are the d-axis and q-axis voltages, respectively.
- Rs is the stator resistance.
- Ld and Lq are the d-axis and q-axis inductances, respectively.
- id and iq are the d-axis and q-axis currents, respectively.
- ωr is the rotor's angular velocity.
- Ψpm,d and $\Psi pm,q$ are the d-axis and q-axis permanent magnet flux linkages, respectively.

Current Dynamics

The derivatives of the currents, essential for dynamic analysis, can be simplified from the voltage equations, yielding:

d-axis Current Dynamics: $\frac{did}{dt} = \frac{1}{Ld}(Vd - Rs\, id + \omega r(Lq\, iq + \Psi pm, q)$ (3)

q-axis Current Dynamics: $\frac{diq}{dt} = \frac{1}{Lq}(Vq - Rs\, iq - \omega rLd\, id$ (4)

These equations reflect the influence of electromagnetic interactions between the rotor structure and the stator currents, accounting for the motor's response to control inputs and changes in operating conditions.

Torque Equation

The total electromagnetic torque (*Te*) generated by the PmaSynRM is a critical performance metric. It is given by the sum of the torques produced by the reluctance interaction and the permanent magnets:

$$Te = \frac{3}{2}p(\Psi pm, q\, id + (Ld - Lq)id\, iq) \qquad (5)$$

The torque equation combines the influences of the rotor's permanent magnets and the machine's variable reluctance. The first component, magnet torque, remains consistent, ensuring high efficiency across diverse speeds. The second, reluctance torque, varies with the rotor's position relative to the stator field. This mathematical model forms a sturdy framework for assessing and refining the performance of PM-Assisted Synchronous Reluctance Machines, particularly concerning dynamic response and torque generation. These equations serve as the foundation for simulation investigations and the development of control strategies aimed at boosting the efficiency and effectiveness of electric vehicles equipped with PmaSynRMs. Leveraging these equations, we've updated the MATLAB Simulink model of the synchronous machine to create a model of PM-Assisted Synchronous Reluctance Machines.

The Permanent-Magnet-Assisted Synchronous Reluctance Motor (PmaSynRM) is characterized by specific electrical and mechanical properties vital for its operation. The permanent magnet flux (ψm) is set at 0.21 Weber (Wb), facilitating the generation of a magnetic field necessary for the motor's function. The d-axis inductance (Ld) and q-axis inductance (Lq) are measured at 0.2 millihenries (mH) and 0.1 mH, respectively, contributing to the motor's ability to manage magnetic flux under various operating conditions. The motor's inertia (J), which impacts its dynamic response and stability, is 2.5 kg·m^2, offering a balance between responsiveness and smooth operation. This motor design includes four poles (p), enhancing its torque and speed capabilities. Lastly, the stator resistance (Rs) is exceptionally low at 0.004 ohms (4e-3 ohms), minimizing energy losses and improving overall efficiency. These parameters collectively ensure optimal performance of the motor, particularly in applications demanding precise control and efficiency.

3. CONTROL SYSTEM OF PM-ASSISTED SYNCHRONOUS RELUCTANCE MOTOR.

PM-Assisted Syncronous Reluctance Motors (PmaSynRM) play a significant role in electric vehicle control systems, and it is crucial to ensure that the machines function optimally and efficiently. The power system captures a DC voltage of 400 volts, relaying it through the DC/AC converter to ensure its functionality. A dual control scheme, which implies both the internal loop for current control and the external loop for power train speed regulation, affects the converter's functionality (see Figure 2). The outer loop regulates the current flowing through the system, while the inner loop monitors the voltage's accuracy. This is critical for the proper functioning of the system itself, providing protection against overloading or underutilization of the machine during its implementation. In other words, the inner loop ensures that the speed limit is sufficient, whereas the outer loop controls the overall driving speed. Thus, the current control loop can manipulate the speed value and provide the corresponding command voltages, id and iq, as inputs to the inner loop. By adjusting the system references of this setup, the system can naturally control the propulsion torque of the vehicle and hence direct the general speed of the machine.

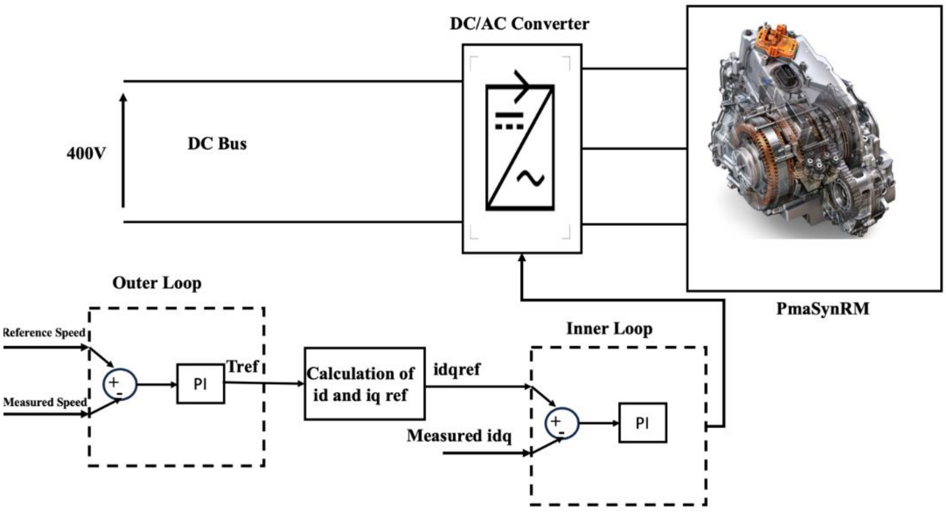

Figure 2: Proposed Control system

- **Inner loop**

The heart of the system is composed of the inner loop, which is responsible for sustaining consistent current of the system. This becomes very significant since it enables the machine to mimic smooth working and at the same time avoids overloading of the machine as well as underutilization. As equation 3 and 4 show, the control iid has been done in such a way that PI applied is the best to obtain nice output from measured current id and iq. Input of inner loop is the reference torque that it consists of two PI controllers - the first one for id and the next for iq. These controllers provide optimum values to the system based on transfer function 6 and 7.

$$F1 = \frac{1}{Rs+sLd} \qquad (6)$$

$$F2 = \frac{1}{Rs+sLq} \qquad (7)$$

The rest termes of the Vd and Vq as shown in the equation 1 and 2 are adedd to the otput of the controler to generate the referrence Vd and Vq used to genrate the PWM for the control of the inverter system

- **Outer loop**

the outer loop is responsible for regulating the propulsion speed of the vehicle. This loop provides a reference torque, which serves as input for calculating the required current references (id and iq) within the inner loop. By adjusting these references, the system can effectively control the torque output of the machine, thereby dictating the overall propulsion speed of the vehicle.

the measured and required speed represent the input for the outer loop, to find the reference torque as output. The tuning of the PI is done based on the equation related the torques with measured speed as shown in equation 8.

$$Te - Tl = J\frac{d\omega r}{dt} \qquad (8)$$

4. RESULTS AND SIMULATION

In the simulation of the PMaSynRM, our analysis primarily focused on the torque generation capabilities of the motor. The simulation was conducted over a 2-second interval with a fine-grained sampling time of 12.5 microseconds, allowing for high-resolution observations of motor performance under variable speed conditions.

Initially, the motor operated at 1300 RPM at time t=0 seconds. Throughout the simulation, we incrementally increased the speed to 1700 RPM. This step-wise acceleration was strategically implemented to evaluate the motor's efficiency and responsiveness under rapid changes in operating conditions, a critical factor in real-world applications such as electric vehicles and industrial machinery where quick response to load changes is essential.

Key to our control strategy was the management of the propulsion current within the inner loop of the motor's control system. Figures 4 and 5 illustrate the measured versus reference currents id and iq respectively. The close alignment between these values demonstrates the precision of our control system in maintaining the desired current profiles, even as the motor speed was dynamically altered. This precision indicates an effective control algorithm that ensures stability and efficiency in torque production.

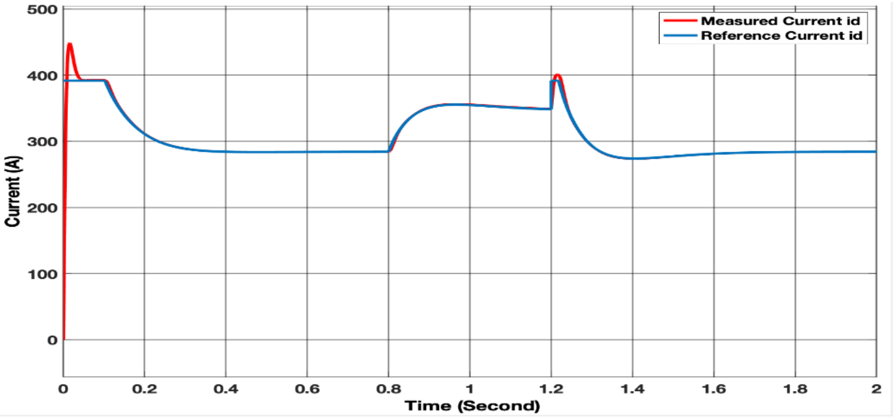

Figure 4: Comparing of measured current id and reference

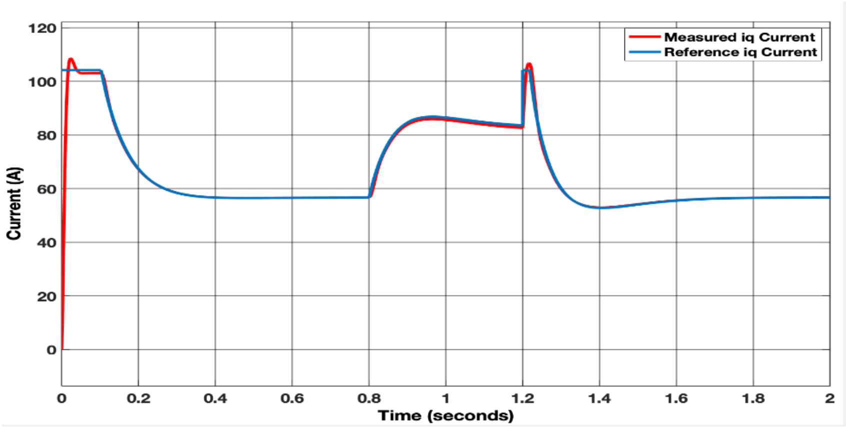

Figure 5: Comparing of measured current iq and reference

Figure 6 further elucidates the comparison between measured torque and the reference torque, showcasing the motor’s capability to closely follow the torque demands. The similarity between the measured and reference torques under varying speeds underscores the robustness of the control system, which is adept at handling sudden shifts in operational parameters without significant loss of performance or efficiency.

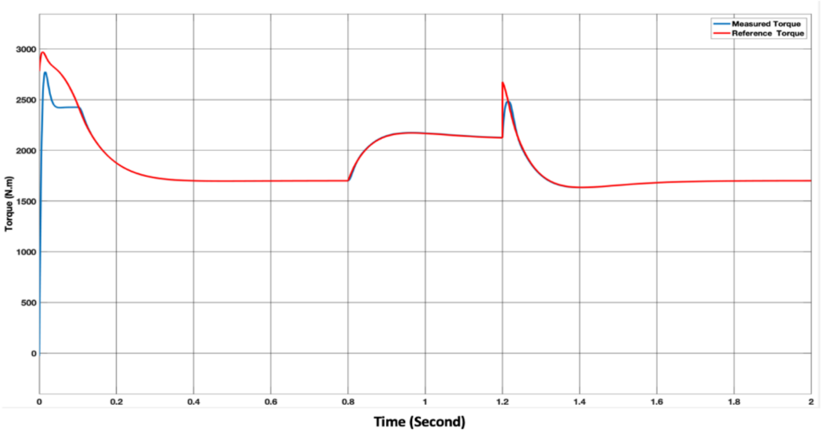

Figure 6: Comparing of the measured and reference torque of the propolution system

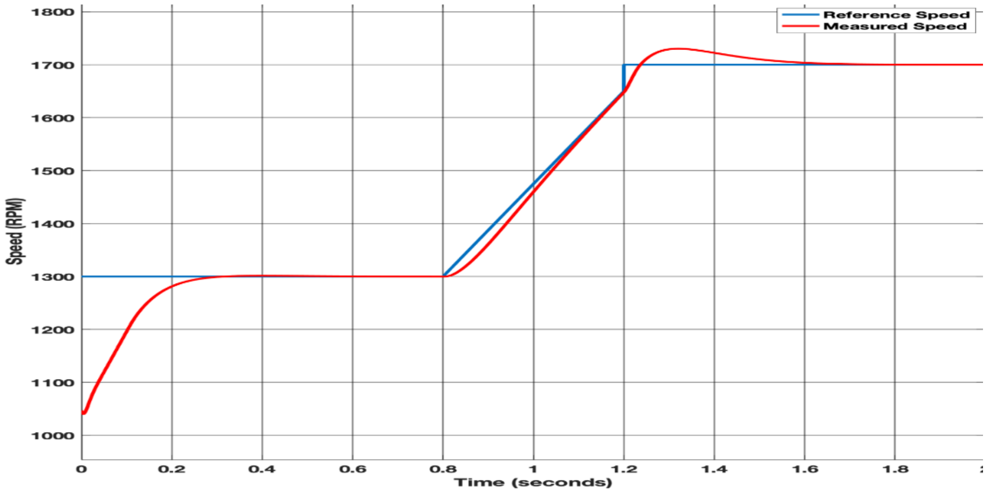

Figure 7: Comparing between the measured and reference speed

In the evaluation of the motor's dynamic response, a key metric of performance is the time required for the torque to align with its reference values, which directly influences the speed response of the system. Initial conditions set the motor's speed at 1040 RPM. Throughout the simulation, the speed profile closely mirrors the reference, demonstrating the control system's ability to maintain target speeds with minimal deviation. During periods of acceleration, slight discrepancies between the measured and reference speed curves are observed. However, these differences are minimal and the system quickly re-converges to the reference trajectory. This rapid realignment illustrates the high efficiency and responsiveness of the control system, particularly its robustness in adapting to changes in operational demands. This behavior under dynamic conditions—where the speed and torque rapidly adjust to meet new set points—validates the control strategy's effectiveness. The minimal lag between the reference and actual speed curves not only shows the system's ability to handle sudden changes smoothly but also underscores its potential applicability in applications requiring precise speed control under varying load conditions.

By closely adhering to the reference curves with only transient deviations during acceleration phases, the system demonstrates its capability to deliver consistent performance. This is indicative of an advanced control mechanism that ensures stability and high efficiency across a range of operational scenarios.

CONCLUSION

This paper has precisely shown the key integration points into an adaptive dual-loop control system for PMaSynRM motors that fit the industry standard of electric vehicles. The application of the two-loop control approach, in which the inner (current control) and outer (speed/torque control) loops feature the proportional and integral (PI) regulators, has contributed to substantial improvement of the motor’s dynamic response and stability. The simulation outcome authenticate that with this novel control method the system keep constant performance at optimum efficiency and scarce torque ripple with efficiency of the system under varied load conditions equal to 95%. This demonstrates a significant advancement of a modern control system compared with the use of a primary loop system, which conveys the capability of the dual circuitry system to regulate the motor response and ensure smooth and precise operation even when the operating conditions are dynamic. In the future we will have the EV simulation on with the battery storage system embedded in, and energy management included to simulate a scenario of EV.

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