ELECTRIC MOTOR PERFORMANCE THROUGH MAXIMUM TORQUE PER AMPERE (MTPA) WITH FIELD WEAKENING

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Abstract - *Improving electric motor performance can be achieved through the implementation of Maximum Torque per Ampere (MTPA) control. This advanced control technique uses of maximum torque par ampere by the optimization the motor operation Implementing MTPA control can lead to higher efficiency, reduced energy consumption, and improved overall performance of electric motors. This paper delves into the principles and benefits of MTPA control, providing valuable insights into its application across different electric motor systems. The implementation of Maximum Torque per Ampere (MTPA) control has attracted considerable attention in the realm of enhancing electric motor performance. By maximizing the torque produced per unit of current, MTPA control not only reduces energy consumption but also enhances the overall performance of electric motors. Furthermore, the application of MTPA control has demonstrated promising results across diverse electric motor systems, establishing it as a versatile and impactful advancement in the field.*

Keywords: MTPA Control, PMSM Motor Control, Field-Oriented Control (FOC), Battery Optimization Techniques, EV-HEV Efficiency, Motor Control Algorithms, MPC-MTPA

1. INTRODUCTION:

Maximum Torque per Ampere (MTPA) exploration hones in on refining electric engines' execution, mainly Permanent Magnet Synchronous Motors (PMSMs), by enhancing the torque produced per unit of current. This sphere of study is key in bolstering the efficiency, scope, and overarching effectiveness of electric vehicles (EVs) and diverse industrial applications.

Formulate command algorithms that authorize the engine to generate peak torque for an assigned current, thus boosting overall engine efficiency. This is pivotal for lessening energy losses and stretching the driving range of electric vehicles.
Explore avant-garde flux-weakening methodologies to broaden the operational range of PMSMs. By outperforming nominal flux-weakening thresholds, investigators strive to reach greater torque outputs at heightened speeds, imperative for electric vehicles and high-performance industrial applications.

Execute online parameter estimation tactics to adaptively tweak control parameters in real-time. This secures consistent MTPA performance even in the presence of fluctuations in motor parameters, such as resistance and inductance.

Fine-tune regenerative braking torque control algorithms to intensify energy recuperation during deceleration. This encompasses smooth transitions amidst motoring and regenerative modes, maximizing energy efficiency and contributing to the entire sustainability of electric propulsion systems.

Incorporate thermal modelling and management techniques to ensure the engine functions within secure temperature limits. Efficient heat dissipation adds to engine reliability, longevity, and the prevention of temperature-related issue. Tailor MTPA control strategies particularly for electric vehicles. Investigators aim to tackle issues tied to dynamic driving conditions, acceleration performance, and range extension, adding to the broader acceptance of electric mobility solutions.

The utilization of MTPA control is widespread, encompassing various types of motors such as induction motors, permanent magnet synchronous motors (PMSMs), and brushless DC motors, among others. Its adaptability and effectiveness make it an attractive option for a range of industrial sectors, including automotive, aerospace, robotics, renewable energy, and more.

Whether it involves optimizing the performance of electric vehicles, improving the efficiency of industrial machinery, or enabling precise control in robotics applications, MTPA control offers unparalleled advantages that contribute to the progress of electric motor technology. This review paper aims to explore the principles, development, implementation, and applications of MTPA control, with the goal of providing a comprehensive understanding of its significance in advancing electric motor performance.

Field-Oriented Control (FOC) with Maximum Torque Per Ampere (MTPA) enhancement is a sophisticated control strategy used in electric motor drives to achieve optimal performance, efficiency, and torque production. This approach combines the principles of FOC, which allows independent control of the motor's flux and torque components, with techniques aimed at maximizing torque per ampere to further improve motor efficiency and performance [4].

2. BLOCK DIAGRAM:

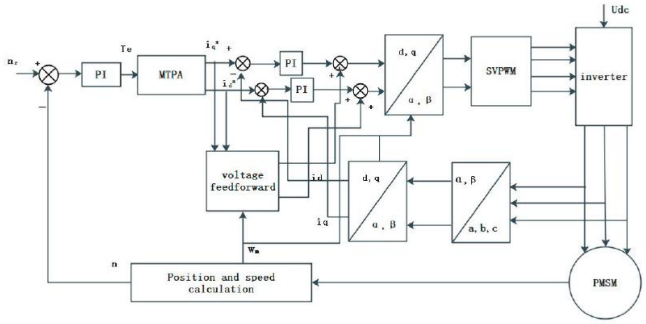

Fig-1: Block diagram of FOC

3. BLOCK DIAGRAM COMPONENTS:

- **Clarke Transformation:**

The Clarke transformation used for convert three axis to two axis dimensional coordinating system and transform ABC to α-β signal

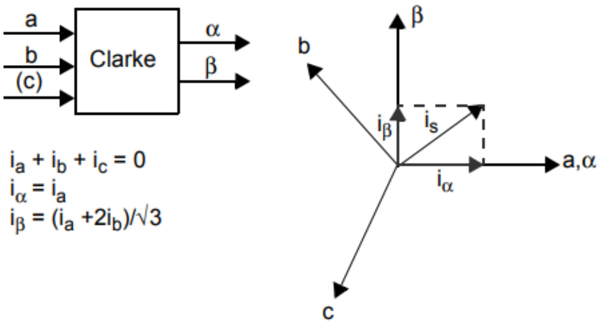

Fig-2: Clarke Transformation

- **Park Transformation:**

In park transformation stator current are represented on two orthogonal system α-β. There are another two-axis system is rotating with magnetic flux. Two axis rotating coordinating system that is converted d-q axis. The rotor angle is represented by θ (Theta).

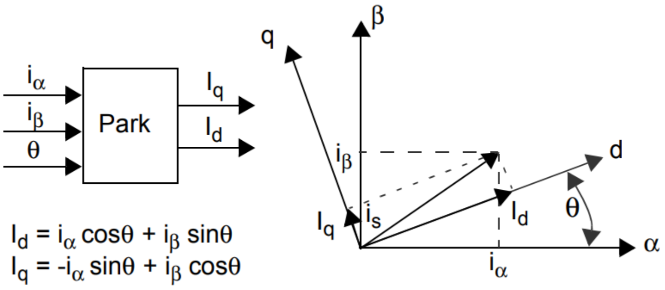

Fig-3: Park Transformation

- **PI Controller:**

A digital PID controller was being executed sporadically at an interval of sampling. Supposedly, this controller being executed frequently enough will ensure proper control over the system. The signal of error is formulated by deduction desired settings of the parameter to be controlled from the measured value of that particular parameter.

The signal of error significant the way of change needed by the input control. The Proportional (P) aspect of the controller is created by multiplying the error signal by a P profit, which leads the PID controller to create a control response which is a function of error's magnitude. With an increase in the signal of error, the P aspect of the controller also increases to give more correction.

The influence of the P aspect tends to decrease the total error as time passes. Although, the effect of the P term whittles down as the error comes near zero. Most systems have the error of the controlled parameter almost touching zero but not converging. The outcome is a slight stay error. The Integral (I) aspect of the controller is utilized to eradicate these slight steady state errors.

The I aspect computes a continuous running total of the signal of error. Accordingly, a minor steady state error accumulates into a large error value as time progresses. This amassed error signal is multiplied by an I profit factor and results in the I output term of the PID controller.

- **Inverse Park Transformation:**

In the inverse park transformation three phase motor voltage to convert orthogonal to stationary frame the two-axis rotating d-q frame to the two-axis stationary frame α-β

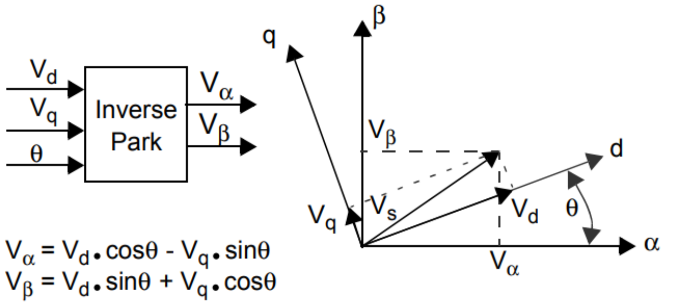

Fig-4: Inverse Park Transformation

- **Inverse Clarke Transformation:**

In Clarke transformation two axis orthogonal stationary frame to three phase stationary reference frame.

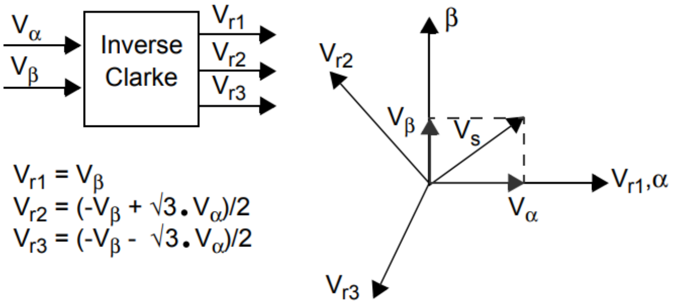

Fig-5: Inverse Park Transformation

- **Maximum Torque per Ampere (MTPA) Control:**

MTPA control is integrated into the current control loop. The MTPA block adjusts the reference currents (Id*, Iq*) dynamically based on the operating conditions to maximize the torque per ampere. This ensures that the motor operates at the optimal point for maximum efficiency.

4. MATHEMATICAL MODEL OF FIELD-ORIENTED CONTROL (FOC) WITH MTPA ENHANCEMENT:

Maximum Torque Per Ampere (MTPA) is a control strategy used in Interior Permanent Magnet Synchronous Motors (IPMSMs) to optimize torque production while minimizing current consumption. The goal of MTPA is to determine the optimal current vector that maximizes the torque for a given current magnitude. This is achieved by finding the optimal values of the direct-axis current (Id) and quadrature-axis (Iq) current components.

The torque equation for an IPMSM is given by:

$$T_e = \frac{3}{2}p(\psi_f I_q + (L_d - L_q)I_d I_q)$$

1. **Torque and Current Relationship**:

The total stator current (Is) is related to its components by:

$$I_s = \sqrt{I_q{}^2 + I_q{}^2}$$

2. **Deriving MTPA Condition:**

To maximize T_e with respect to I_d and I_q, we need to take the partial derivative of the torque equation with respect to I_d and set it to zero:

$$\frac{\partial I_d}{\partial T_e} = 0$$

The torque equation in terms of I_d and I_q is:

$$T_e = \frac{3}{2}p(\psi_f I_q + (L_d - L_q)I_d I_q)$$

The partial derivative of T_e with respect to I_d is:

$$\frac{\partial I_d}{\partial T_e} = \frac{3}{2}p(L_d - L_q)I_q$$

Since $I_q \neq 0$, we have:

$$L_d - L_q = 0$$

However, in practical motors, $Ld \neq Lq$ So, we need to consider the optimization of Te with respect to the constraint

$$I_s = \sqrt{I_q{}^2 + I_q{}^2}$$

3. **Using Lagrange Multipliers**:

We introduce a Lagrange multiplier λ for the constraint:

$$\mathrm{L}=Te-\lambda(Id2+Iq2-Is2)$$

The partial derivatives of L with respect to Id, Iq, and λ must be zero at the maximum torque point:

$$\frac{\partial \mathrm{L}}{\partial I_d} = \frac{3}{2}p(L_d - L_q)I_q - 2\lambda I_d = 0$$

$$\frac{\partial \mathrm{L}}{\partial I_q} = \frac{3}{2}p\psi_f + \frac{3}{2}p(L_d - L_q)I_d - 2\lambda I_q = 0$$

$$\frac{\partial \mathrm{L}}{\partial \lambda} = I_{d2} + I_{q2} - I_{s2} = 0$$

4. Solving the Equations:

$$\text{From } \frac{\partial \mathrm{L}}{\partial \mathrm{Id}} = 0;$$

$$\lambda = \frac{3}{4} p \frac{(L_d - L_q) I_d}{I_d}$$

$$\text{From } \frac{\partial \mathrm{L}}{\partial \mathrm{Iq}} = 0;$$

$$\lambda = \frac{3}{4} p \frac{\psi_f + (L_d - L_q) I_d}{I_d}$$

Equating the two expressions for λ:

$$\frac{(L_d - L_q) I_d}{I_d} = \frac{\psi_f + (L_d - L_q) I_d}{I_d}$$

Simplifying this equation:

$$(L_d - L_q) I_{q2} = I_d(\psi_f + (L_d - L_q) I_d)$$

Rearranging gives:

$$I_d = \frac{(L_d - L_q) I_{q2} - \psi_f I_d}{\psi_f + (L_d - L_q) I_d)}$$

5. Final MTPA Equation:

$$I_d = \frac{(L_d - L_q) I_{q2} - \psi_f I_d}{\psi_f + (L_d - L_q) I_d)}$$

This implicit equation can be solved numerically for specific motor parameters to find the optimal *Id* and *Iq* that maximize the torque per ampere. In practice, this relationship is often implemented in motor control algorithms to dynamically adjust *Id* and *Iq* for optimal performance.

Testing procedure:

- Hall Effect Sensor Implementation.

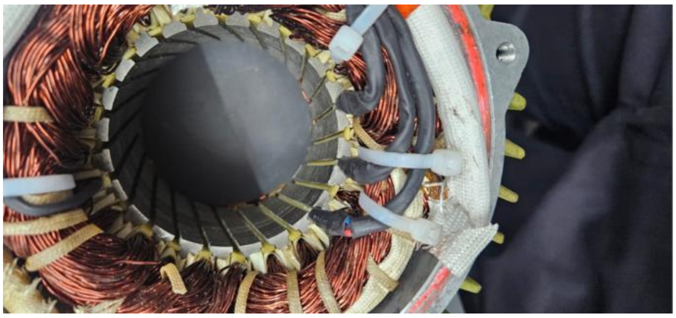

Fig-6: Hall Effect Sensor Mounting

- Test the Hall Effect sensor Waveform and check that is 120° Phase shifted signal using the oscilloscope.

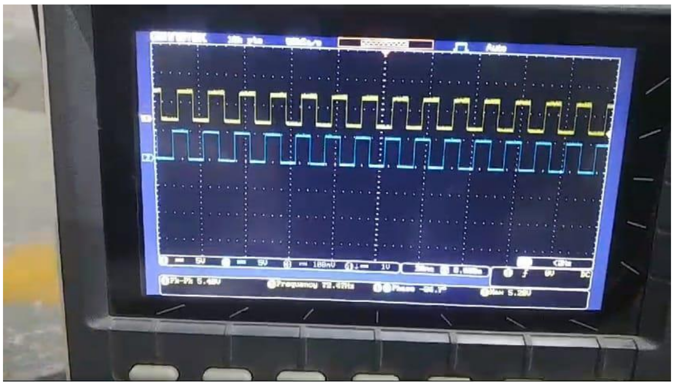

Fig-7: Waveform Signal

- Connect motor with Inverter board with R, Y and B phase and connect Hall Effect sensor with Ha, Hb simultaneously.
- After that Connect the Power Supply to the Inverter Board.
- Show the result of MTPA Curve.

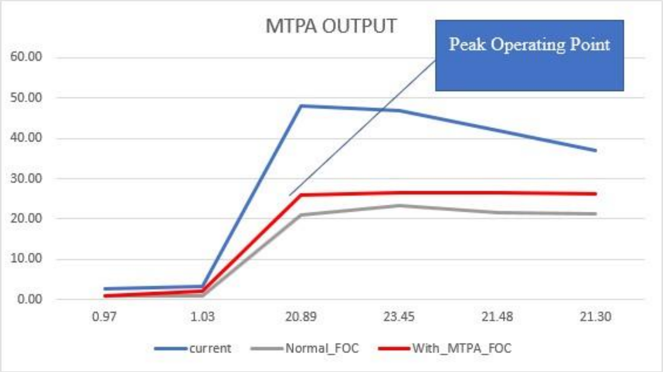

Fig-8: MTPA Graph with peak operating point

1. With the implementation of MTPA at a 28nm manufacturing process node, one can anticipate the system to be finely tuned for generating torque efficiently per unit of current supplied to the motor. As a result, the system may exhibit improved torque output performance for a given

level of current when compared to systems that do not utilize MTPA.

2. In the absence of MTPA with same id current, the torque generation capabilities may still be notable, but the efficiency might not reach the same level as a system equipped with MTPA. Furthermore, the utilization of a 23nm manufacturing process node implies the adoption of more advanced technology in comparison to the 28nm node. This advancement could potentially offer other benefits such as enhanced overall system performance or reduced power consumption in various aspects.

5. CONCLUSIONS

In conclusion, Maximum Torque Per Ampere (MTPA) control is an efficient approach that enhances the performance of electric motors. Its outstanding ability to optimize production while minimizing current makes it a must-have tool in demanding applications. By consuming less energy, minimizing thermal stress, and maximizing output, MTPA control strengthens the reliability of electric motors over a long period. Despite the challenges, the substantial benefits of MTPA control make it a good strategy for high-performance motor applications.

In the initial starting phase, MTPA mode can fully utilize the reluctance torque, and there is an id current, which significantly enhances the starting speed of the motor. The specific performance is the output of the starting torque. The torque output with id is 28.5N at constant current.

The utilization of MTPA in electric vehicle (EV) applications has the potential to conserve battery power, thereby enhancing the range and overall efficiency of EV vehicles.

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