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Optimization of Gearbox Ratio and Transient Behavior in Induction Motor-Driven Systems for Enhanced Performance

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Abstract: ***This paper examines the transient behaviour of an induction motor–gearbox–load system during startup and braking, focusing on the influence of key dynamic parameters, including inertia, torque, and gearbox ratio. A comprehensive mathematical formulation is developed to analyse the transient time, leading to the derivation of an optimal gearbox ratio that minimises acceleration and deceleration durations. Both analytical and graphical evaluations reveal that deviations from this optimal ratio significantly extend transient times, resulting in increased energy losses. The findings demonstrate that high-speed induction motors deliver superior transient performance while maintaining compact size and reduced weight. Moreover, the study indicates that optimisation calculations can be simplified without compromising accuracy, thereby improving computational efficiency. These insights contribute to the optimization of electromechanical drive systems, enhancing their dynamic response in real-world applications.***

Keywords: ***Transient Response, Optimization, Acceleration Time, Braking Time, Dynamic Performance, Energy Efficiency***

Abbreviations:
VFD: Variable Frequency Drive
J_M: Moment of inertia of the mechanical system ($kg{\cdot}m^2$).
J_m: Moment of inertia of the motor ($kg \cdot m^2$).
r: Gearbox ratio.
w_M: Angular velocity of the mechanical system (rad/s).
T_M: Resisting torque of the mechanical system ($N \cdot m$).
T_n: Rated torque of the induction motor ($N.m$).
δ: Coefficient accounting for the inertia contribution of the gearbox, t_{tran}: transient time

I. INTRODUCTION

The starting and braking performance of electromechanical systems based on asynchronous motors depends on several electrical and mechanical parameters that directly influence the duration and efficiency of the process. From an electrical perspective, factors such as supply voltage, frequency, control type, and starting method affect the initial torque, inrush current, and motor stability [1]. From a mechanical standpoint, elements such as load inertia, resisting torque, and friction influence the motor's dynamic response. A high inertia load requires greater torque to accelerate, thereby increasing the time needed for the vehicle to start up. Similarly, during braking, a load with significant inertia will take longer to stop unless controlled braking, either electrical or mechanical, is applied [2].

A high supply voltage directly influences the performance of an asynchronous motor during startup by increasing the initial torque available at the motor shaft. According to the relationship $T \propto V^2$, an increase in the applied voltage results in a quadratic increase in torque, enabling the machine to accelerate more rapidly and reducing the time required to reach the nominal speed [3]. This effect is particularly beneficial in applications that require a rapid ramp-up, such as lifting systems, compressors, and specific industrial processes that necessitate dynamic startup.

However, a high supply voltage also has significant drawbacks, particularly the occurrence of high inrush currents during startup. In the absence of current-limiting devices such as soft starters or variable frequency drives, the motor can draw a current up to 5 to 7 times its nominal value. This current surge imposes substantial thermal stress on the stator windings, accelerating their ageing and potentially damaging the insulation over time. Additionally, these sudden inrush currents can cause voltage drops in the electrical network, potentially affecting other connected equipment and leading to power supply disturbances [4].

From an electrical protection standpoint, excessive inrush current can also lead to the inadvertent tripping of protection devices such as circuit breakers and thermal relays, disrupting the continuity of system operation. In some cases, prolonged overcurrent can cause a rapid rise in motor temperature, increasing the risk of thermal overload and reducing the lifespan of the motor and its components [5].

Thus, while a high supply voltage can enhance startup performance by providing greater torque, it is crucial to consider the associated risks of inrush currents [6]. To mitigate these issues, several strategies can be employed, such as using star-delta starters, autotransformers, or variable frequency drives, which allow for gradual modulation of the voltage and help limit the electrical and thermal stresses on both the motor and the network [7].

By adjusting the supply frequency, it is possible to gradually control the motor speed, enabling precise control of both startup and braking. Unlike traditional starting methods (direct startup, star, delta

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autotransformer), the use of variable frequency drives (VFDs) helps avoid current spikes and mechanical jolts, thereby reducing stress on motor components and extending their lifespan [8].

The variable frequency drive (VFD) reduces the inrush current by gradually increasing the voltage and frequency, thereby limiting the current surge and reducing thermal overload on the motor [9]. By adjusting the frequency and voltage in a synchronised manner, the VFD optimises the torque generated by the motor in response to the load. This is particularly beneficial for high-inertia loads, such as fans, pumps, and conveyors, where a sudden startup could lead to mechanical overloads. For braking, the VFD allows the motor speed to be gradually reduced by lowering the supply frequency and voltage, minimizing mechanical stress and extending the lifespan of components. Some VFDs incorporate a dynamic braking mode, where the motor's kinetic energy is dissipated as heat through a braking resistor. More advanced models even enable energy recovery by feeding this power back into the grid, thereby improving the overall system efficiency [10].

The choice of starting method depends on the specific requirements of the application. Direct startup is simple but can result in excessive currents. Star-delta starting is cost-effective but provides limited torque. Autotransformer starting offers more flexibility but is more expensive. For even more precise control of both startup and braking, the use of a variable frequency drive remains the most advanced and efficient solution [11].

High inertia complicates the startup and braking of electromechanical systems. The higher the inertia, the more torque is required to accelerate or decelerate the load, which directly impacts the dynamic performance of the system. An optimized design, incorporating a suitable motor, appropriate starting devices, and effective braking, is essential to ensure optimal performance and extend the system's lifespan [12].

The nature of the load plays a fundamental role in the design and selection of asynchronous motors, particularly regarding starting and braking torque [13]. The load may be constant, variable, or cyclic [14], each having a distinct impact on motor performance and control system requirements. A precise understanding of the load profile is therefore essential to ensure efficient operation and prevent issues such as overloads, mechanical shocks, or excessive energy consumption. The nature of the load directly influences the asynchronous motor's performance in terms of starting, braking, and energy efficiency. Accurate sizing, based on load profile analysis, is crucial to ensure reliable operation, optimise energy consumption, and prevent premature wear of mechanical and electrical components.

Among all these electrical and mechanical parameters, a critical component in transmitting mechanical power to the load is the gearbox. This article focuses on examining the influence of the gearbox on the startup and braking times of an electromechanical system-based asynchronous motor.

II. EXTRACTION OF DYNAMIC PARAMETERS AFFECTING TRANSIENT RESPONSE

The dynamic response of an electromechanical system during startup or braking is significantly influenced by various parameters, as discussed earlier. The time required for acceleration or deceleration is primarily governed by the motor's starting torque and the transmission ratio of the gearbox. Given the angular velocity (ω), the torque (T), and the moment of inertia (J) of the mechanical system, the transient time (t_{tran}) can be mathematically expressed as:

$$t_{tran} = (J_M + \delta . J_m . r^2) . \frac{\omega_M}{kT_n . r \pm T_M} \quad \dots \quad (1)$$

Where:

J_M - Moment of inertia of the mechanical system ($kg{\cdot}m^2$).

J_m - Moment of inertia of the motor ($kg \cdot m^2$).

r - Gearbox ratio.

w_M - Angular velocity of the mechanical system (rad/s).

T_M - Resisting torque of the mechanical system ($N \cdot m$).

T_n - Rated torque of the induction motor ($N.m$).

δ - Coefficient accounting for the inertia contribution of the gearbox, typically ranging from 1.1 to 1.3.

This equation describes the fundamental relationship between the dynamic parameters that influence transient behaviour, highlighting the crucial roles of inertia and torque in determining the system's acceleration or deceleration time. The positive sign (+) is used to indicate the starting phase, while the negative sign (−) corresponds to the braking phase.

The optimal gearbox speed ratio, r_{op}, which minimizes the starting or braking time, is determined by the following equation:

$$r_{op} = \pm \frac{T_M}{k.T_n} + \sqrt{\left(\frac{T_M}{k.T_n}\right)^2 + \frac{J_M}{\delta . J_m}} \quad \dots \quad (2)$$

This ratio is derived by optimizing the transient response of the system, considering the interplay between the motor's torque characteristics, the total moment of inertia reflected through the gearbox, and the resisting torque of the mechanical load. By selecting *the right option, the system achieves the shortest possible acceleration or deceleration time, thereby enhancing its* overall dynamic performance.

Any deviation from the optimal gearbox speed ratio, r_{opt}, results in an increased transient time, thereby prolonging the acceleration or braking period. Consequently, this results in higher energy losses in the induction motor due to prolonged operation under transient conditions. In this context, Equation (2) can be reformulated as:

$$r_{op} = \sqrt{\mu^2 + r_0^2} \pm \mu \quad \dots \quad (3)$$

Where:

$$\mu = \frac{T_M}{k.T_n} \ and \ r_0 = \sqrt{\frac{J_M}{\delta . J_m}}$$

To simplify the equations, we introduce the mechanical torque, denoted as $T_{mech} = \frac{J_M . \omega_M}{T_M}$. Additionally, we define the optimal transient time ratio $t_{trans.opt}$ as the ratio of the operating speed r_{op} to the mechanical torque. Thus, we obtain:

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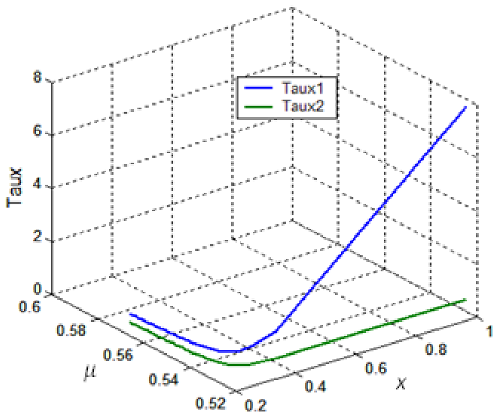
$$T_{aux} = \frac{t_{tran,rop}}{\frac{2.J_M.\omega_M}{T_M}} = \frac{t_{trans,rop}}{2.T_{mech}} \quad \dots \quad (4)$$

Consequently, the transient time of the electrical drive can be expressed in its relative form, as given by the following equation:

$$Taux = \sqrt{x(x+1)} \pm x \quad \dots \quad (5)$$

Where, $x = \left(\frac{\mu}{r_0}\right)^2$, this dimensionless parameter is fundamental to the transient dynamics of the induction motor-gearbox-load system, directly affecting both the starting and braking times.

The graphical representation of the relative transient time, as formulated in Equation (5), is illustrated in Figure 1. In this representation, T_{aux1} and T_{aux2} correspond to the minimum and maximum transient times, respectively. These values are determined based on the minimum and maximum data points calculated for motors ranging from 0.25 to 30 kW.



[Fig.1: Relative Transient Time of the Induction Motor-Gearbox-Load System]

For low power levels corresponding to the graphical representation of T_{aux1}, the influence of x is significant and considerably more pronounced compared to T_{aux2}, which remains relatively stable with no substantial variations. This indicates that at lower power levels, x plays a crucial role in affecting T_{aux1}, whereas its impact on T_{aux2} is minimal, suggesting that T_{aux2} is less sensitive to variations in x.

The analysis of Equation (5) and its graphical representation in Figure 1 demonstrate that the starting time (indicated by the positive sign) of the induction motor-gearbox-load system exhibits an almost directly proportional relationship with x. However, the braking time (indicated by the negative sign) in the range $0.75 \leq x < \infty$ shows a weak dependence on x.

In practical applications, achieving strict optimality conditions is challenging, primarily due to the difficulty in selecting a gearbox that precisely matches the required gear ratio dictated by the mechanical system. Consequently, deviations from the optimal gearbox ratio can significantly impact the transient time during both the starting and braking phases. A detailed study of these deviations and their effects on transient time can provide valuable insights into the system's dynamic performance and efficiency.

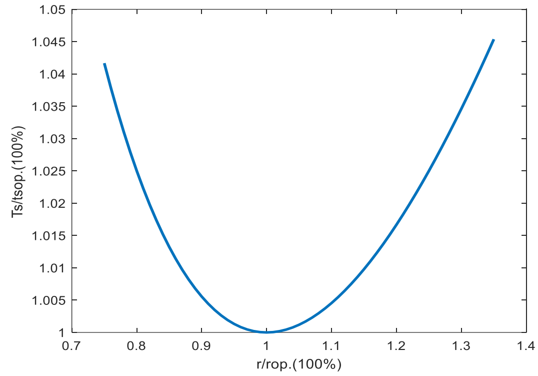
Let's put $v = \frac{t_{tran}}{t_{tran,rop}}$ and $z = \frac{r}{r_{op}}$

From equations (2), (3), (4), and (5), we obtain:

$$v = \frac{1}{2} \cdot \frac{1 + \left(\sqrt{x+1} \pm \sqrt{x}\right)^2 . z^2}{\left(\left(\sqrt{x+1} \pm \sqrt{x}\right).z \pm \sqrt{x}\right).\left(\sqrt{x+1} \pm \sqrt{x}\right)} \quad \dots \quad (6)$$

If $x \to 0$, $T_M \to 0$ and if $x \to \infty$, $J_M \to 0$.

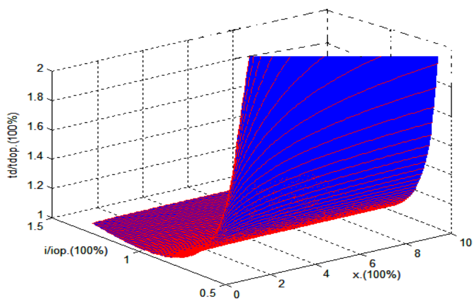
In practical applications, the moment of inertia of the rotor (J_m) is generally lower than that of the overall system (J_M), and the developed torque (T_M) remains below (k . T_n). Consequently, the variable x assumes relatively small values, allowing for an analytical approximation using the variations of v as $x \to 0$ to derive the necessary conclusions, as illustrated in Figure 2.



[Fig.2: Influence of High-Speed Induction Motor-Gearbox-Load on Transient Response Time and System Optimization]

The present study has demonstrated that within the range $z = 0.75$ to 1.35, the transient response time exhibits a deviation of no more than 5%. This observation underscores the advantage of utilizing high-speed induction machines with synchronous speeds $n_0 \geq 1200$ r/min, as they offer an optimal balance between minimal overall dimensions, reduced weight, and improved transient performance.

The analysis is extended to examine the system's transient behaviour across the two asymptotic limits of x, spanning from $x \to 0$ to $x \to \infty$. This approach aims to provide a comprehensive understanding of the direct influence of x on the system's dynamic response. Specifically, Figure 3 illustrates the transient regime as x approaches 0, whereas Figure 4 depicts the behaviour in the limiting case of x approaching ∞.



[Fig.3: Relative Starting Time Domain for x → 0]

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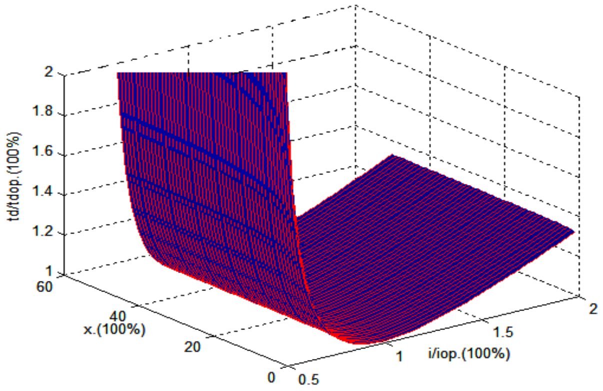

[Fig.4: Relative Starting Time Domain for $x \to \infty$]

By comparing the two figures, we observe a slight increase in the ratio i/i_{op} when x approaches infinity (Figure 4) compared to the case where x approaches zero (Figure 3). However, this variation remains marginal. This suggests that the factor x has a negligible influence on the results of the optimization calculations. Thus, in the context of performance analysis or system optimization, considering x does not lead to any significant changes in the overall conclusions. Therefore, it may be reasonable to simplify the calculations by neglecting the effect of x, which could reduce complexity without compromising the accuracy of the results.

III. CONCLUSION

This study presents a comprehensive analysis of the transient behaviour of an induction motor-gearbox-load system during both startup and braking phases. By deriving and evaluating the key equations governing transient time, we have demonstrated the critical influence of dynamic parameters such as inertia, torque, and gearbox ratio on system performance.

The transient time is directly influenced by the total moment of inertia, which includes both the motor and mechanical system components, as well as the resisting torque. The formulation of the optimal gearbox ratio ensures a minimised transient time by effectively balancing these factors.

Any deviation from the optimal gearbox ratio leads to increased transient time, resulting in higher energy losses due to prolonged operation in transient conditions. The study demonstrates that maintaining the gearbox ratio within the range $0.75 \leq z \leq 1.35$ results in a maximum transient time deviation of only 5%, making high-speed induction motors (with synchronous speeds exceeding 1200 r/min) particularly advantageous.

The study highlights the benefits of using high-speed induction motors in industrial applications, as they enable the minimisation of transient time while maintaining a compact size and high efficiency. Although achieving an exact optimal gearbox ratio may be challenging in practice, maintaining a ratio close to optimal ensures minimal impact on transient performance.

DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

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