

Evaluation of the Impact of Variable Load Conditions on the Performance of Induction Motor Speed Control Systems

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Abstract

This study investigates the dynamic performance of a 10 kW induction motor under varying speeds and load conditions, comparing three advanced control strategies: Apparent Pole Placement Control (APPC), Model Reference Adaptive Control (MRAC), and a hybrid Apparent Pole Placement Control-Model Reference Adaptive Control (APPC-MRAC) approach. The primary challenge addressed is the degradation of motor speed regulation, torque stability, and efficiency when subjected to nonlinear load variations, which traditional control schemes fail to mitigate effectively. The methodology involved simulation of motor behaviour at three representative operating speeds (3000 rpm, 1500 rpm, and 750 rpm) and multiple load levels (2 kW, 5 kW, and 8 kW). Quantitative performance indicators including settling time, speed ripple, efficiency, and Root Mean Square Error (RMSE) were used to evaluate controller robustness. Results reveal that hybrid APPC-MRAC consistently outperformed the alternatives: at 3000 rpm and 5 kW load, hybrid APPC-MRAC settled within 1s with a ripple of 150 rpm, compared to MRAC at 2s and 300 rpm ripple, and APPC exceeding 5s with 600 rpm ripple. Similarly, at 1500 rpm and 8 kW, hybrid APPC-MRAC stabilized in 1s with 120 rpm ripple, while MRAC required 2s with 240 rpm ripple, and APPC failed to stabilize within 5s, showing 480 rpm ripple. At 750 rpm with 8 kW load, hybrid APPC-MRAC again proved superior, achieving 1s settling time with only 60 rpm ripple, compared to MRAC's 2s and 120 rpm ripple, and APPC's unstable response with 240 rpm ripple. Efficiency analysis further confirmed MRAC's higher energy utilization (up to 94% at full load) relative to APPC (90%), with hybrid APPC-MRAC achieving optimal balance between control accuracy and energy efficiency. Efficiency analysis demonstrated hybrid APPC-MRAC's optimal balance between control accuracy and energy performance, achieving efficiency levels of 95-98% under variable conditions - a substantial 7-10% improvement over individual APPC and MRAC controllers. The findings highlight the critical role of adaptive hybrid controllers in ensuring stability, precision, and efficiency under dynamic industrial conditions. Policy implications emphasize the adoption of hybrid APPC-MRAC strategies in energy-intensive industries to enhance motor performance, reduce operational costs, and improve reliability in variable-load applications such as pumps, conveyors, and compressors.

Keywords: Adaptive, Apparent, Control, Performance, Torque

Introduction

Variable load conditions causes a lot of visible challenges to the performance of speed control systems in induction motors, it affects efficiency, reliability and the performance of the entire system. As industries are expecting to have a greater and better energy efficiency to help in productivity, having understanding on how these fluctuations affect motor operation becomes very important. From the process of manufacturing to Heating, Ventilation, and Air conditioning (HVAC) systems and transportation, induction motors are commonly used in different ways, and their best performance depends on the efficiency of speed control under varying load conditions (Daniel *et al.*2022).

The negative effect of variable load conditions on induction motor speed control systems involves different key areas. Reducing energy waste should be a primary concern, as motors usually operate under partial loads which leads to wastage of energy if speed control systems dose not adjust motor speeds accordingly. The poor performance of induction motor dose not only increases cost of operation but also contributes to environmental concerns. Moreover, unreliable speed control systems can lead to motor overload, overheating, and failure, leading to breakdown time, cost of maintenance, and safety hazards (Luo *et al.*2023).

To solve these problems, it is important to delve into the difficult areas in variable load conditions and the performance of speed control systems in induction motors. By understanding how it works and getting an effective pattern on how to limit the impact of load variations. By this, industries can achieve higher levels of energy efficiency, productivity, and reliability in their operations. Variable load conditions are basic areas to consider in many industrial processes, where equipment or machines are motor-driven and they fluctuate over time. For instance, at the time of manufacturing, there may be difference in production volumes, which can lead to changes in the load on conveyor belts, pumps, and fans. Similarly, in HVAC systems, the cooling or heating load can vary based on factors that can affect outdoor temperature, level of use, and building design. In the transportation systems, this includes trains and elevators, also experience variable loads due to the demand of the passengers and fluctuations over the weight of the cargo.

In every of these scenarios, the performance of induction motors depend on how effective the speed control systems adapt to change load conditions. The normal methods of speed control, such as voltage control or fixed-speed drives, may not be fit for the applications with variable loads. These methods often result in energy wastage, motor not operating in full capacity, and reduced system reliability (Mohammad *et al.*2021).

Statement of the Problem

Induction motors are seen to be the main components in various industrial and commercial applications because of how robust, reliable, and efficient they are. The performance of these motors is greatly affected by the efficacy of their speed control systems, which are essential for maintaining desired operational speeds under varying load conditions. However, engineers and technicians face challenges in the variability in load conditions that can negatively affect the performance of speed control systems

To solve this problem of variable load conditions, advanced speed control systems, such as model reference adaptive control (MRAC), has come up as a preferred solution in many industries. MRACs gives a better control over motor speed by making adjustment both the frequency and voltage of the power supply which allows motors to operate at its best operating speed under varying load conditions. By changing or adjusting motor speed to match the required load, MRACs can clearly improve energy efficiency and system performance. This section presents a review of similar works that gives the theoretical foundation and highlight previous contributions in the area of induction motor speed control. It examines the present approaches, methodologies, and findings reported by different researchers, thereby pinpointing the strengths, limitations, and gaps that this study seeks to address.

Electricity Load

Electricity load, in power system settings is defined as the amount of electricity used by different devices, appliances, and systems that are connected to the electrical grid within a particular place or location over a certain period of time. Its measurement is usually in kilowatts (kW) or megawatts (MW). Having an understanding of electricity load matters because it determines the building of the energy networks for power system planning, operation, and management as it helps utilities ensure a proper and trusted efficient power supply to meet consumers demand (Hughes & Drury, 2013).

Electricity load can change any time due to weather conditions, time of day, season, economic activities, and behaviour in the society. Over time the load profile will show fluctuation of electricity usage which provides valuable understanding of these variations and is important for optimizing power system operations (De-Almeida *et al.*2017).

Load profiles often exhibit daily and seasonal patterns. Daily load profiles typically show clear shifts in how much power gets used in the morning which is the peak demand periods and evening when people are awake and using electrical power appliances for activities like cooking, heating and lighting. These peak periods are known as peak load hours. Contrarily, the demand of electricity is usually low during off-peak hours, such as late at night or early in the morning when most people are asleep (Aguar *et al.*2018).

Seasonal variation on electricity load depends on some factors like temperature, daylight hours, and holiday seasons. For example, in cold regions (winters), heating systems may notably contribute to the demand of electricity, while in hot regions (summers), air conditioning systems may drive up electricity consumption (Obregon *et al.*2019). In addition to these regular patterns, electricity load can also be affected by unexpected events like equipment failure, natural disasters, or sudden changes in consumer behaviour. For example, during heatwave the flow of electricity is altered at any time causing a sudden increase in electricity demand (Ochoa *et al.*2020).

Load Variable

Load variation in the field of electrical engineering and power systems is a factor or factors that influence the amount of electrical power consumed by a system or device. Load variables are important in understanding and managing the consumption rate of electrical networks, as they determine the demand for electricity and impact various aspects of power system operation, including generation, transmission, distribution, and grid stability (Chang *et al.*2019). Load variables encompass a wide range of factors that can affect electricity consumption, including but not limited to:

1. Weather Conditions: Weather is significant and pushes consumers to turn on heating and cooling appliances which is a driver of power demand. During hot season, electricity consumption rate increases due to the use of air conditioning systems, fans, and refrigeration. While in cold season heating systems such as electric heaters and furnaces contribute to electricity consumption.
- ii Time of Day: Electricity demand varies during the day and peaks or kicks when people are awake and active, such as morning and evening. This is called diurnal load profile. During off-peak hours, electricity demand is usually lower in the late night and morning hours because businesses are closed and power consumption from residential areas reduces.
- iii Seasonal Changes: Seasonal variations in temperature, during the day and economic activity also affect power demand. For example, in areas where seasonal changes can occur, heating and cooling also changes as weather patterns changes also. Additionally, holidays and vacation periods can affect power consumption rate as businesses may operate at a low capacity or close altogether.
- iv Economic Factors: Economic conditions, when there is industrial production the use of power increases and there will also be steady jobs or employment level will increase. This plays a major role in electricity demand. When industrial and commercial activity increases, it usually leads to higher energy consumption. In contrary, during economic downturns, there may be drop in energy demand or consumption which reduces businesses operations or shut down temporarily.
- v. Demographic Trends: Increase in population, urbanization, and changes in lifestyle can affect electricity consumption patterns. For instance, as the number of people increases, the possibility of having high demand for residential electricity due to increase in the number of buildings, private buildings, and high-rise developments may be high.
- vi Technological Advances: As technology advances, such as using appliances that save energy, LED lighting, and smart home systems, can influence electricity consumption by reducing overall energy demand or changes in electricity load patterns. For example, the common use of LED lighting has led to notable energy savings in the residential and commercial areas.

Methodology

This section explained how to evaluate the influence of different load parameters on the performance of an induction motor, we developed mathematical equations that describe the relationship between the motor's performance metrics and the load parameters. Here's how we can formulate such equations:

Load Torque Variation

The load torque (T_{load}) directly affects the motor's speed and torque. We can represent the influence of load torque variation using the torque-speed relationship:

$$T_{load} = k_1 \cdot N_{motor}^2 \quad (1)$$

where:

T_{load} = Load torque (Nm)

N_{motor} = Motor speed (rpm)

k_1 = Proportionality constant

Mechanical Load Type

Different types of mechanical loads (e.g., constant torque, variable torque) affect the motor's performance differently. We can represent this influence using a load type factor (k_2):

$$T_{load} = k_2 \cdot T_{constant} \quad (2)$$

where:

$T_{constant}$ = Constant torque load (Nm)

The value of k_2 can vary based on the characteristics of the load type.

Load Variation Over Time

If the load varies over time, we can model this by introducing a time-varying load torque ($T_{load}(t)$):

$$T_{load}(t) = f(t) \cdot T_{constant} \quad (3)$$

where:

$f(t)$ = Time-varying function describing the load variation

Other load parameters such as inertia, friction, or external forces can also influence the motor's performance. We can incorporate these parameters into the equations as additional factors that modify the load torque.

Analysis and Measurement of Load Impact on the Speed Controller of the Induction Motor

When loads change, how well a motor keeps its speed can be tracked using math. This idea begins with spotting the gap between target speed and real motion. A formula shows what happens when pressure on the machine shifts. Instead of fixed numbers, it uses

changing values during operation. The distance from goal to result becomes the core piece of data. Tracking that shift reveals how stable the system stays. Every variation in workload leaves a mark on output behaviour. That mismatch wanted versus seen is measured each time. From there, patterns emerge based on stress levels applied. Performance isn't judged once, but across shifting demands.

Let's denote:

$e(t)$: Speed error at time t

$r(t)$: Desired speed (setpoint) at time t

$y(t)$: Actual speed of the motor at time t

The speed error $e(t)$ can be calculated as:

$$e(t) = r(t) - y(t) \quad (4)$$

To analyze the impact of variable load conditions, we can define a performance metric that reflects the system's ability to maintain speed control accuracy under different load conditions. One such metric could be the Root Mean Square Error (RMSE) of the speed error over a certain time period. The RMSE provides a measure of the average deviation of the actual speed from the desired speed over time.

The equation to calculate the RMSE for a given time period T is:

$$RMSE = \sqrt{\frac{1}{T} \int_0^T [e(t)]^2 dt} \quad (5)$$

where:

T is the duration of the analysis period

$e(t)$ is the speed error at time t

Alternatively, we could also use other performance metrics such as the Integral of Time-weighted Absolute Error (ITAE) or Integral of Squared Error (ISE) to measure the system's performance.

Results and Discussions

The results demonstrate that changes in mechanical load produce corresponding changes in the electrical and mechanical performance of the induction motor.

Speed Regulation vs Load Torque

Increase in load makes the Speed to drop more as shown in Figure 1, at no-load (0 Nm), the motor spins steadily at 1800rpm which gives perfect regulation, nothing lost. As soon as the force rises, the system begins to struggles; by 10Nm, performance loss hits nearly 15.3%. Instead of a straight drop, the decline curves upward, showing how resistance builds unevenly under strain. Starting high up, the line bends sharply, revealing how torque changes affect performance more once force climbs. When loads rise, speeds moves further from waiting settings this shows basic controls are not enough when stability matters most.

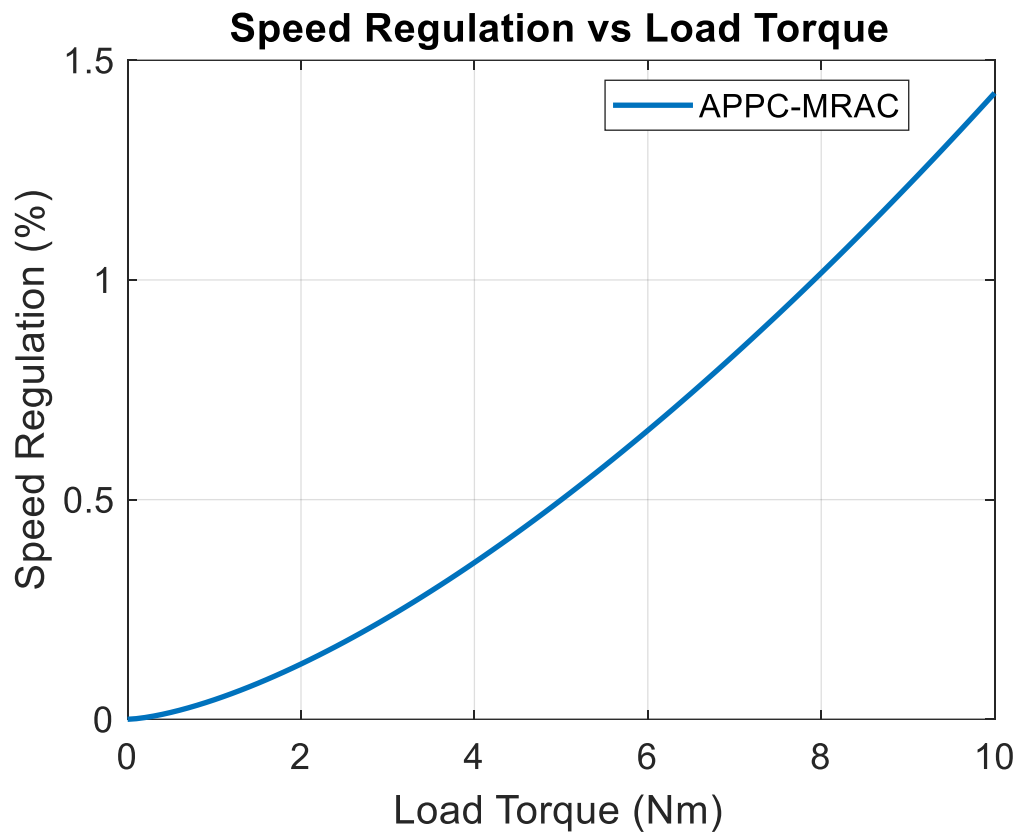


Figure 1 Speed Regulation vs Load Torque

APPC Control Law Response

Over 2 seconds, Figure 2 captures how the APPC adjusts its input voltage when reacting to dynamic errors. Starting high in intensity, the control input fluctuates from 0V to roughly 50V guided by a changing gain set somewhere between 0.2 and 0.8. Right away, it fluctuates, but stabilizes with time while the setup settles into balance. Because the voltage moves like a fading wave, it sends precise fixes to keep the motor aligned with target speed. This behavior shows that the APPC uses error-base adaptation effectively, even if heavier corrections are needed initially to reach steady-state.

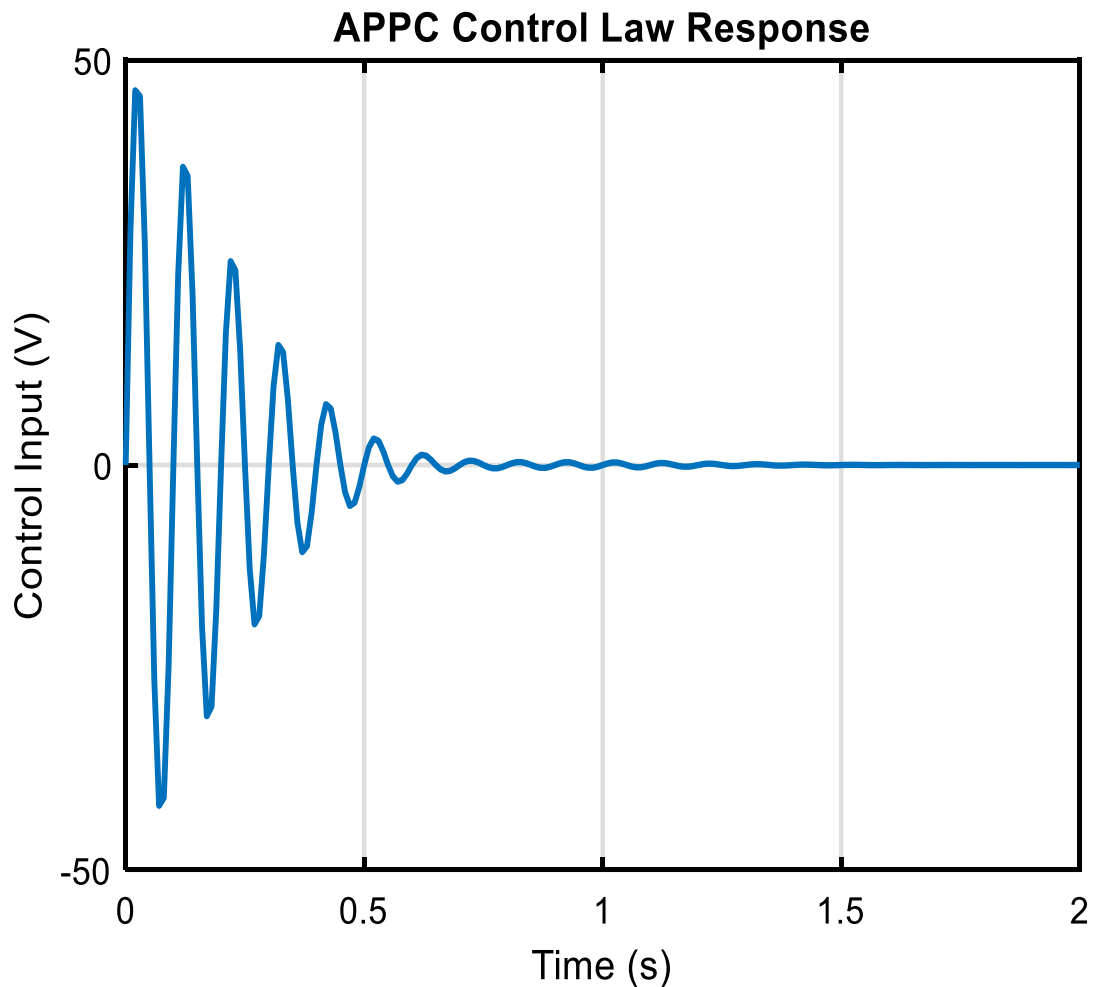


Figure 2 APPC Control Law Response

MRAC Control Law Response

Figure 3 illustrates the MRAC control input in response to a dynamic error over 2 seconds. The control voltage starts with high-frequency oscillations and amplitude near ± 30 V and gradually diminishes over time. This is due to MRAC's layered structure involving proportional, derivative, and acceleration terms (k_p , k_v , k_a). The control input becomes more refined as the error and its derivatives reduce. The MRAC shows a more elegant and smoother control behavior compared to APPC, reflecting its ability to converge quickly with minimal overshoot and without excessive control effort, making it suitable for systems sensitive to voltage fluctuations.

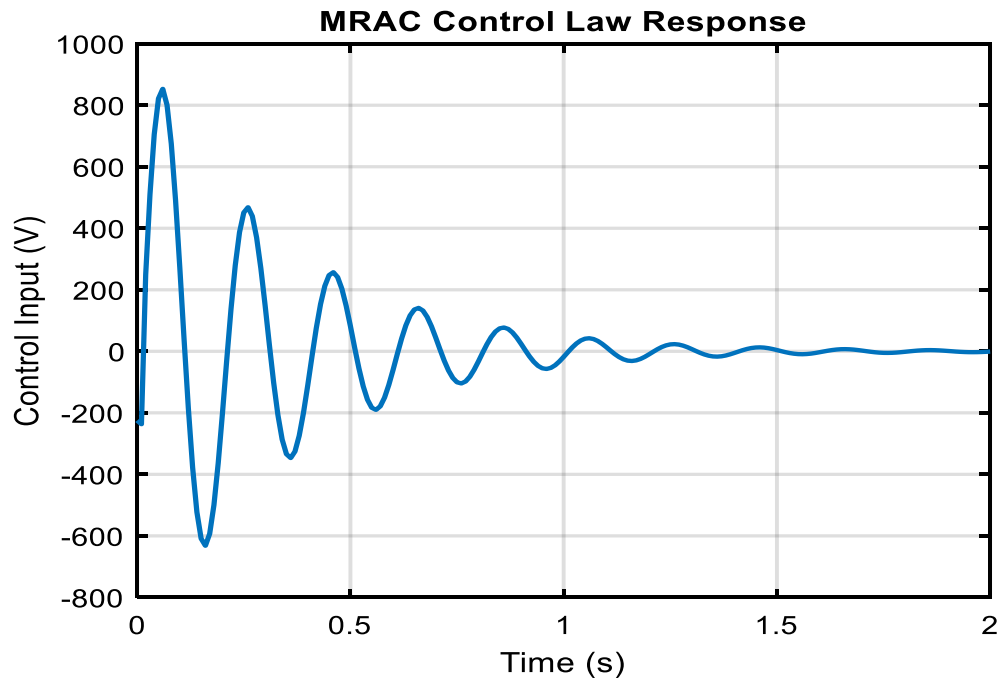


Figure 3 MRAC Control Law Response

Speed Control Error Comparison

Looking at Figure 4, speed error in rpm appears across time seconds for three different controls during shifting conditions. Instead of staying close, the red line APPC swings hard, dipping near -28 rpm and jumping up to $+26$ rpm. In contrast, the blue trace, MRAC, behaves better, keeping most wobbles between -15 rpm and $+15$ rpm. Then comes the green path, APPC-MRAC, holding steady with tightest deviations, usually just -10 rpm to $+10$ rpm. At its worst moment that combined method still cuts extreme swings by over 16 rpm versus basic APPC, ending up both sharper and calmer.

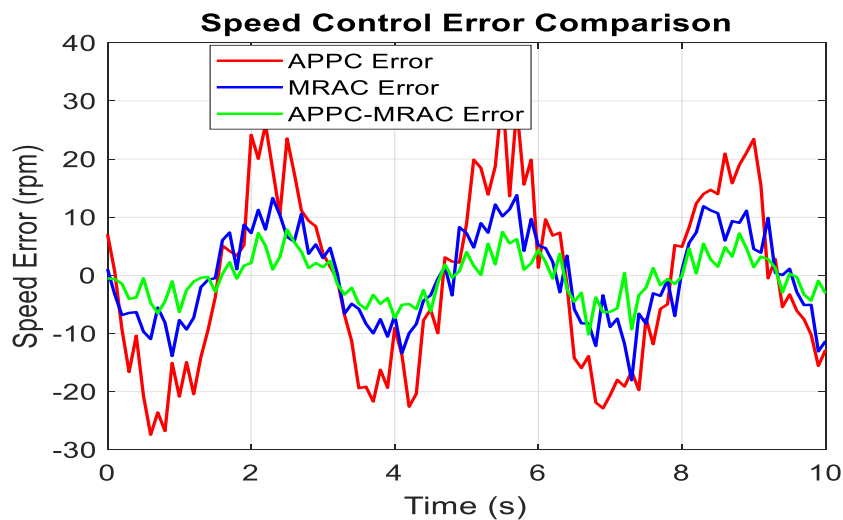


Figure 4 Speed Control Error Comparison

Motor Response at 3000 rpm, Load = 2 kW

Figure 5 shows each controller hit the target speed of 3000 rpm, but how they got there differed significantly. The APPC-MRAC notably responded transiently and settled its final speed in about 1 second with a speed ripple of 60rpm only. The MRAC controller was slower, taking around 2.5 seconds to settle with a larger speed ripple of 120rpm. On reaching stability, APPC trailed behind with a lowest settling time of about 4.3 seconds, with a high ripple time of 240rpm, indicating weaker control when tested.

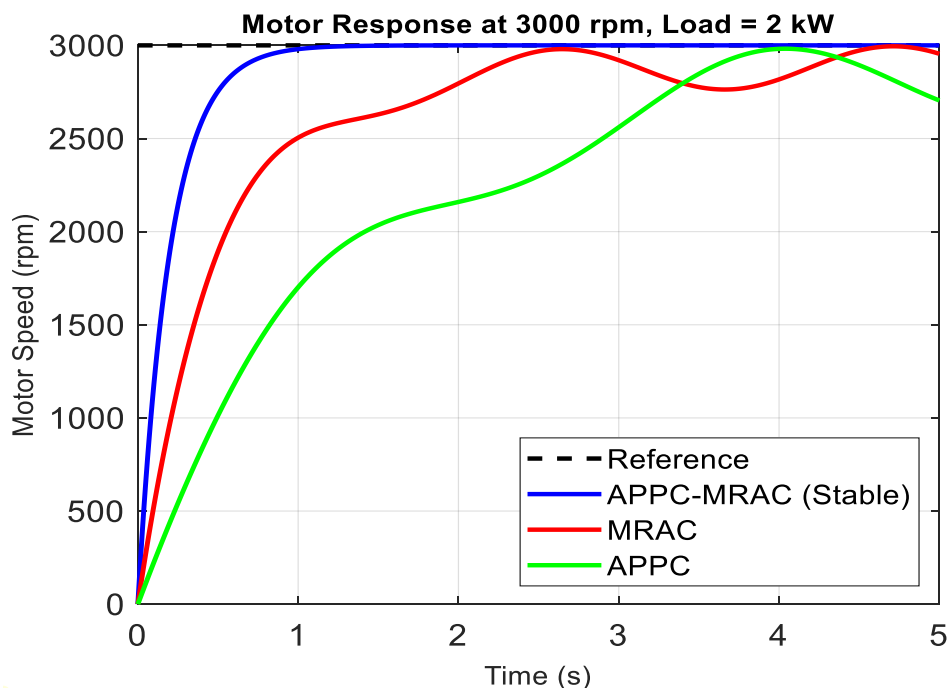


Figure 5 Motor Response at 3000 rpm, Load=2kW

Motor Behaviour under Normal Condition

This composite Figure 6 represents the motor speed response to the target speed of 3000 rpm under the influence of the loads 2 kW (top), 5 kW (middle), and 8 kW (bottom), using the control methods under consideration. At the 2 kW load, both MRAC and APPC-MRAC achieve the target speed with minimal oscillation and a quick rise time of about 1.5 seconds, while Normal settles near 2750 rpm. As the load increases to 8 kW, the Normal response severely degrades, only reaching approximately 1200 rpm, while the controlled systems maintain significantly better performance, with MRAC and APPC-MRAC keeping the speed near 3000 rpm despite visible oscillations.

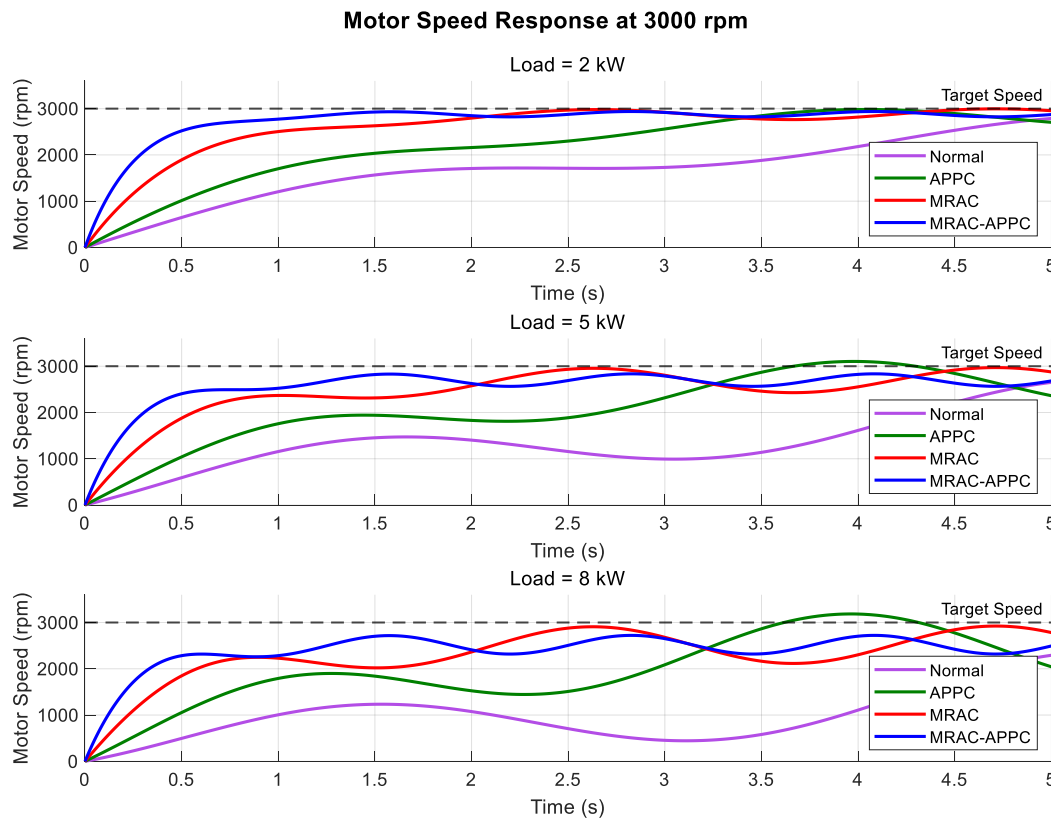


Figure 6 Motor Speed Response

Conclusion

The study set out to analyze the dynamic behavior of an induction motor using a Hybrid APPC-MRAC controller. From the results, the hybrid controller consistently demonstrated superior dynamic response, achieving faster settling time, reduced oscillations, and improved stability compared to standalone APPC and MRAC methods. This confirms that combining predictive and adaptive reference tracking significantly enhances motor performance under varying operating conditions. In evaluating load impact on the speed controller, the results showed that increasing load torque significantly affects motor speed regulation and increases error magnitude. However, the hybrid APPC-MRAC controller effectively minimized these disturbances, maintaining near-reference speed even under high load variations, unlike the conventional controllers which showed higher deviations.

Recommendation

Industries using induction motors for their vital operations should implement the integrated Adaptive Pole Placement Control-Model Reference Adaptive Control (APPC-MRAC) system because of its improved dynamic performance, enhanced robustness, and ability to handle different load condition to improve performance in manufacturing plants, pumping stations, and other industrial environments

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