Nonlinear Sliding Mode Based Speed and Torque Control of Induction Motor Drive

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Author's Declaration

We, hereby declare that this thesis, titled “Nonlinear Sliding Mode Based Speed and Torque Control of Induction Motor Drive” is the result of our original research work and has not been submitted elsewhere for any degree or examination. We affirm that the sources of information used in this thesis have been duly acknowledged. We express our sincere gratitude to our supervisor Dr. Shafaat Ullah for their invaluable guidance, support, and expertise throughout the research process. Each member of the group has contributed significantly to the research, data collection, analysis, and writing of this thesis. We jointly take responsibility for the content presented in this thesis and affirm its accuracy and authenticity.

Abstract

There are many electromechanical systems where it is important to precisely control their torque, speed, and position. Many of these, such as elevators in high-rise buildings, we use on daily basis. Many others operate behind the scene, such as mechanical robots in automated factories, which are crucial for industrial competitiveness. Even in general-purpose applications of adjustable-speed drives, such as pumps and compressors systems, it is possible to control adjustable-speed drives in a way to increase their energy efficiency. Advanced electric drives are also needed in wind-electric systems to generate electricity at variable speed. Hybrid-electric and electric vehicles represent an important application of advanced electric drives in the immediate future. In most of these applications, increasing efficiency requires producing maximum torque per ampere, it also requires controlling the electromagnetic toque, as quickly and as precisely as possible, where the load torque TLoad may take a step-jump in time, in response to which the electromagnetic torque produced by the machine Tem must also take a step-jump if the speed ωm of the load is to remain constant.

In this thesis, a novel method for Nonlinear Sliding Mode Based Speed and Torque Control of Induction Motor Drive is suggested. The sliding mode control approach is renowned for its resistance to changes in parameters variation and outside disturbances. The suggested solution overcomes the constraints of linear control approaches and offers improved tracking performance across a wide variety of applications by combining it with nonlinear control strategies.

Induction motors, the ubiquitous workhorses of industry, possess remarkable power but are hampered by inherent non-linearities. This complexity presents a challenge in achieving precise control over their speed and torque. This abstract delves into the application of non-linear sliding mode control (SMC) as a powerful technique to conquer these hurdles.

Controlling the speed and torque of induction motor drives with a high level of precision is vital for multiple industrial applications. The nonlinear design of the controller is based on taking into consideration the known nonlinearities of the induction motor model, making the resulting closed-loop system more robust to parameter variations and external disturbances. The sliding mode control concept provides certainty that the system trajectories will converge to a known switching surface, realizing a desired speed and torque tracking performance. The main emphasis is made on the design of the nonlinear sliding surface, the development of the control law, and the stability analysis of the closed-loop system. The final part of the project

describes the simulation setting, based on which the efficiency of the proposed control solution can be evaluated and potentially compared to the existing method.
Extensive simulations and experimental validation are used to assess the efficacy of the suggested technique.

Overall, this research helps standalone PV systems be optimized, making it easier for them to be used in more off-grid applications and lowering dependency on traditional energy sources. With enhanced performance and dependability for standalone PV systems in varied climatic circumstances, the suggested nonlinear sliding mode control approach offers a potential development in the field of MPPT algorithms.

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All praise and thanks to Allah Almighty, the most merciful and the most gracious, who endowed me with will, strength and means to complete this Thesis. Without his bounty, grace, and mercy this work would have never been accomplished. Peace and blessing upon Holy Prophet Muhammad (PBUH) for whom the whole universe is created, His families, His companions, His followers. He (PBUH) brought us out of darkness and enlightened the way of heaven.

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NOTATION

Variables that are functions of time v, i, λ

2. Peak values (of time-varying variables) ˆV , ˆ I , ˆλ

3. Phasors V =Vˆ_θv, I = Iˆ_θi

4. Space vectors

_H

(t),

_B

(t),

–

$F(t)$,

–

$v(t)$=Vˆ$ej\theta$,

–

i (t)= Iˆ$ej\theta$,

–

_(t)=_ˆej_

For space vectors, the exponential notion is used where,

$ej\theta$ =1_θ=cosθ+ j sin$\theta ej\theta$ =1_θ=cosθ+ j sinθ.

Note that both phasors and space vectors, two distinct quantities, have their peak values indicated by “□.”

List of Acronyms

Stator phases a, b, c
Rotor phases A, B, C

dq windings d, q

Stator s

Rotor r

Magnetizing m

Mechanical m (as in θm or ωm)

Mechanical $mech$ (as in $\theta mech$ or $\omega mech$)

Leakage

p Number of poles ($p \geq 2$, even number)

θ All angles, such as θm and the axes orientation (for example,

$ej2\pi/3$), are in electrical radians (electrical radians equal $p/2$

times the mechanical radians).

ω All speeds, such as ωsyn, ωd, ωdA, ωm, and ωslip (except for $\omega mech$),

are in electrical radians per second.

ωmech The rotor speed is in actual (mechanical) radians per second:

$\omega\mathrm{mech} = (2/p)\omega m$.

θmech The rotor angle is in actual (mechanical) radians per second:

$\theta\mathrm{mech} = (2/p)\theta m$.

fl Flux linkages are represented by *fl* in MATLAB and

Simulink

Chapter 1

Introduction

Chapter 1 of the thesis gives an introduction to the thesis. In this chapter, Section 1.1 contain an overview about IM i.e. nonlinear behavior of IM. Section 1.2 describes sliding mode control i.e. algorithm used speed and torque and for fast dynamic response and high efficiency Section 1.3 describes problem statement, while Section 1.4 describes objectives.

1.1 Overview

Induction motor is an AC motor in which the rotating part (rotor) receives electrical energy *inductively* (i.e., by means of mutual induction) from stator.

The simulation will be done for the rotor-oriented induction motor with various operating conditions to validate the control method.

The proposed method in this paper is to apply nonlinear sliding mode control with a predefined reaching law to induction motor speed and torque control. This is to achieve easy implementation and control tuning, which was an issue in conventional sliding mode control. Desired speed and torque response can be achieved by applying the control to produce the variable stator voltage and frequency command.

But when it comes to the induction motor, there has been an issue on how to apply sliding mode control which was originally designed for linear systems with no difficulty in extension to nonlinear systems in achieving good dynamic response and torque tracking due to its complex and strong coupling motor model.

Due to these reasons, a high-performance and robust control algorithm for the nonlinear and strong coupling induction motor model is still an unsolved problem. Sliding mode control is one of the robust control methods which has invariance property to parameter variation and disturbances. Due to its robustness, it has been widely applied to various nonlinear systems.

Other control methods like vector control give a much better dynamic response, but it is also a complex and costly solution for industries. In conventional control techniques, it may have good performance at a particular operating region, but it still has various constraints in achieving good dynamic and robust response in a wide speed range.

The vast majority of AC drives in the industry today use the v/f control strategy, which gives a simple and low-cost solution for speed control of the induction motor. But due to the complexity of the motor model, wide operating range, and strong nonlinear coupling between the motor variables, the v/f control method may have various constraints in achieving good dynamic response in a wide speed range.

One of the important aspects in any electric drive is its ability to produce the desired torque and speed response under various operating conditions. Speed control of the induction motor drive has been a topic of interest for researchers because it is inherently difficult due to its complex model and nonlinearity.

Induction motor has been the first choice for industries for its robustness, reliability, and efficiency when compared to other types of electrical motors. It has been extensively used in various industrial applications like conveyors, pumps, and compressors due to its various advantages.

Induction motors are widely used in industry, and control of their speed and torque is very important. Initially, scalar control techniques were used for induction motor drives, including V/Hz control, Volts per hertz Control, and Vector control. With the increasing usage of power electronics drives and control, Vector control has become the most popular control strategy for induction motor drives in high-performance drive systems. It has the capability to control motor torque and flux directly and independently, producing the best dynamic performance of the motor. Vector control has various features and advantages for vector-controlled induction motors. It is an application system that controls the torque and rotor flux of the induction motor by using vector signal computation. This method has proven to produce the best dynamic performance of the motor and has several features and advantages compared to other speed control methods. It can produce a rated flux and torque at start-up, allowing the motor to have a constant torque characteristic and a good product life. However, the motor's performance under variable speed and load torque conditions drops significantly compared to the performance at rated conditions. This is due to the difficulty of achieving the best performance at more than one operating point and the existence of stator and rotor resistance that affects the torque performance. Therefore, the development of the control method for induction motor drives, especially for speed and torque control, is very necessary.

1.2 Sliding Mode Control

Sliding Mode Control (SMC) is a vigorous control procedure broadly utilized in different designing applications. Uncertainties, disturbances, and parameter changes that can have an impact on a control system's performance all benefit from its use. A powerful framework for designing controllers that can guarantee stability and robustness in the face of these uncertainties is provided by SMC.

The idea of a sliding surface, which is a hyperplane in the state space, is at the heart of SMC. SMC's goal is to steer the system's state trajectory onto this sliding surface and maintain its position there. The sliding surface is planned with the end goal that the framework elements show positive way of behaving when it is reached. High speed convergence, lack of sensitivity to disturbances, and reduced sensitivity to model uncertainties are typical features of this behavior.

The development of a control law that causes motion along the sliding surface is the central concept of SMC. By creating a discontinuous control signal that responds to the system's position in relation to the sliding surface, this can be accomplished. Adaptive control actions are possible thanks to the formulation of the control law as a function of the sliding surface and its derivative. One of the huge benefits of SMC is its power. Even though the control law is designed to be insensitive to uncertainties and disturbances, it can still force the system to follow a desired path. The system's stable operation near the sliding surface is ensured by the control signal's discontinuity.

The selection of the sliding surface, the design of the control law, and the selection of switching control actions are just a few of the design parameters that must be taken into consideration before SMC can be implemented. These boundaries not entirely settled through a mix of scientific examination, reproductions, and trial approval.

In conclusion, uncertainties and disturbances in control systems can be effectively dealt with using the robust control method of sliding mode control. It is suitable for a wide range of applications, including automotive control, power systems, and robotics, due to its ability to provide stability and robustness. The plan and execution of sliding mode control require cautious thought of framework elements and control targets; however, it offers a useful asset for accomplishing solid and hearty control execution.

1.2.1 SMC Applications

The phase portrait of sliding mode control is shown in Figure 2. The first step in the process involves selecting a carefully designed function known as the sliding variable, which we'll refer to as 's'. When this sliding variable reaches zero, it establishes what is called the sliding manifold or sliding surface. The goal is to guide and control the system's state trajectory so that it reaches this sliding manifold and remains on it thereafter.

There are two distinct phases involved in this approach. The first phase is known as the reaching phase, where the system's state trajectory is directed towards the sliding surface. The sliding surface is carefully chosen based on the desired behavior of the system.

Once the system's state trajectory reaches the sliding surface, the second phase, called the sliding phase, begins. During this phase, the system's state trajectory moves towards the origin along the sliding surface. This sliding surface serves as a reference or a guide for the system's behavior, and the control mechanisms are employed to ensure that the trajectory stays on this surface.

The overall idea behind this method is to dynamically steer the system's state trajectory towards a specific desired behavior, represented by the sliding manifold or surface. By carefully selecting the sliding variable and defining the sliding manifold, the system's behavior can be controlled and maintained within desired bounds. This approach is particularly useful for achieving precise control and stabilization of complex systems.

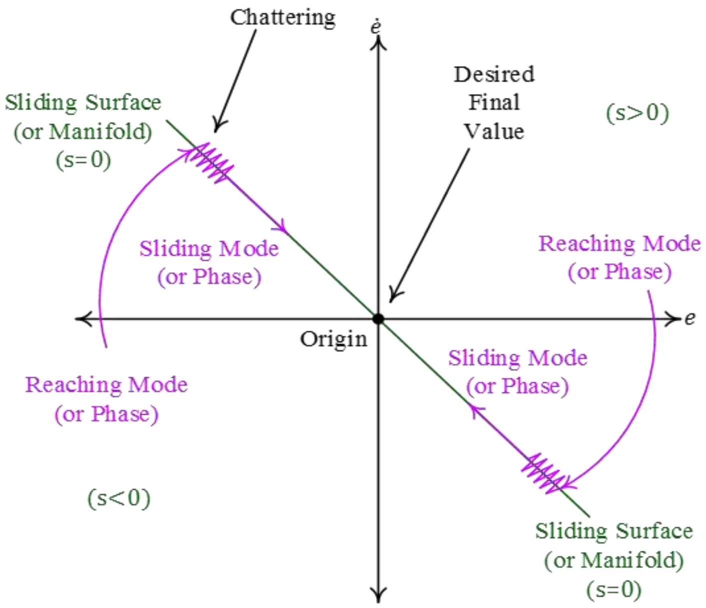

Figure 1: Phase portrait of sliding mode control concept

1.2.2 Main Features of SMC

The following are the main features of the SMC.

- **Robustness:** SMC is well-known for its resistance to a variety of uncertainties, disturbances, and system modeling errors. It is built to effectively deal with parametric and non-parametric uncertainties, such as system parameter variations and external disturbances.
- **Harshness toward Demonstrating Exactness:** Compared to other control methods, SMC is less sensitive to modeling accuracy. It is suitable for controlling complex systems with uncertain dynamics because it can accommodate differences between the mathematical model used for control design and the system's actual behavior.
- **Quick Reaction and High Precision:** SMC can give quick and exact control reactions. It achieves precise control by driving the system's trajectory toward the desired state or reference trajectory using a sliding manifold or surface.
- **Chattering Phenomenon:** The term "chattering" refers to high frequency switching control actions that have the potential to cause actuator mechanical wear and audible noise. Various methods like reaching law design, boundary layer control, and continuous sliding mode control are used by SMC to reduce chattering.
- **Tolerance for Faults:** The ability to tolerate faults is built into SMC. By continuously adjusting the control law to compensate for the fault, it can deal with actuator failures or faults. This property makes it appropriate for applications where unwavering quality and adaptation to internal failure are basic.
- **Simple Concept and Execution:** When compared to other advanced control techniques, SMC provides a control design procedure that is relatively straightforward. It is easier to put into practice because it is based on the idea of sliding mode and the design of a suitable sliding surface.
- **Possibility of Wide Use:** SMC has been effectively applied to an extensive variety of control issues in different enterprises, including aviation, mechanical technology, power frameworks, car, and cycle control. Controlling nonlinear, uncertain, and time-varying systems has demonstrated its efficacy.

- **Capabilities of Adaptation:** SMC can improve control performance by incorporating adaptive mechanisms. Versatile SMC procedures adaptively change control boundaries in view of online framework estimations, permitting the regulator to adjust to changing framework elements and vulnerabilities.

Overall, SMC offers a powerful method for controlling systems that is robust, quick to respond, accurate, and tolerant of faults. Its effortlessness and wide pertinence go with it a well-known decision in many control designing applications.

1.3 Problem Statement

"Nonlinear sliding mode based speed and torque control of induction motor" is to design and implement a nonlinear sliding mode controller for an induction motor that can achieve high accuracy and robustness in the presence of disturbances and uncertainties.

induction motors are widely used in industrial applications, such as electric vehicles, robotics, and machine tools. However, the control of induction motors is challenging due to their nonlinear dynamics and sensitivity to disturbances.

The sliding mode control technique is a nonlinear control approach that is robust to disturbances and uncertainties. However, the design and implementation of a sliding mode controller for an induction motor is challenging due to the complexity of the motor's dynamics.[1]

The project proposal should address the following challenges:

• Design a nonlinear sliding mode controller for an induction motor that can achieve high accuracy and robustness in the presence of disturbances and uncertainties.

• Implement the controller on a real-time system and evaluate its performance.

1.4 • Compare the performance of the nonlinear sliding mode controller with other control techniques, such as proportional-integral(PI) control Objectives

- This project is aimed to overcome the limitations and improve the efficiency of the other techniques used for speed and torque control streatigy.
- To use the nonlinear sliding mode-based technique instead of PI and other techniques

Chapter 2

Literature Review

Control technique play a very important rule in enhancing the efficiency and performance of IM. There many control algorithms aims to extract high efficient , maximum power and fast dynamic response from IM. These algorithms continuously tracking and apply the different control technique to control the speed and torque of IM. For the purposes of fast dynamic response and high efficient. Over the year's researchers have explored different control techniques including conventional, linear and nonlinear approaches.

Direct speed and torque control (DTC) schemes, also known as bang-band controllers,were initially proposed for the IM by Takahashi and Noguchiin 1986 [3], and by Depenbrock in 1988,and are used extensively for high-performance AC drives for their simple decoupled topology. Ammar et al. [2] used an SM approach to design dual SMOs to estimate load torque, speed,and flux for space-vector-modulation-based DTC of the IMs. Wang et al. [2] proposed an SMO for linear IMs to estimate their online resistance, flux, and speed, while Kubota and Matsuse [3] theoretically showed that rotor resistance and speed can only be estimated simultaneously when the magnitude of the flux varies periodically, and not on a permanent basis.

The PI controller is one of the commonly implemented controllers in the outer loop for speed and torque regulation. Rodriguez et al. proposed a predictive controller formed by using a PI controller in the outer loop [3], while Miranda et al. presented a predictive IM torque control technique that utilizes the state-space model, along with the PI controller, to calculate a reference torque .Additionally, Habibullah et al. proposed a technique based purely on Finite-state model predictive control (MPC), using a PI control scheme [3], and Ahmad et al. developed a control scheme based on a state-tracking cost index, which utilized PI control in the inner loop.

Sliding mode control (SMC) is ultimately more robust and disturbance-resistant than PI control . Adaptive SMC techniques have recently been proposed to adapt to reduced gain, with respect to faults and disturbances,which reduced chattering.

Currently, a non linesr sliding mode control (SMC) technique has attracted significant attention, particularly for systems where the control law appears in the first derivative of the sliding variable. A comprehensive review of existing literature will be conducted to understand the current state of speed and torque control techniques for induction motors. This review will highlight the limitations of conventional control methods and the advantages of nonlinear sliding mode control.

Chapter 3

Proposed Methodology

- Induction motor is an AC motor in which the rotating part (rotor) receives electrical energy *inductively* (i.e., by means of mutual induction) from stator.A PV array which produces electrical energy form solar energy.
- It's a vector control technique.
- PI controller generate the error signal (speed error) we used the control laws to check its response.
- After that combined used of SMC and PI using control laws to check it comperative performance

But the main issue in IM is to obtain the fast dynamic response. Different techniques are used to obtain the maximum output and SMC is one of them. It involves the creation of a sliding surface and the design of a control law that drives the system states towards this surface. The control law is designed to force the system to track the sliding surface, which in turn will lead to tracking the error signal . Before control law derivation first we will find state space equations for it.

3.1 Mathematical Modeling for error signal

Generally,

$$\frac{d\omega}{dt} = \dot{\omega} = \frac{1}{J_{eq}}(T_{em} - T_L) \quad \ldots\ldots\ldots\ldots\ldots\text{(a)}$$

$\omega^{\cdot}$: This term represents the angular acceleration of the motor. It's the rate of change of the angular velocity ($\omega\omega$) with respect to time (tt).

$\omega\omega$: This term represents the angular velocity of the motor. It's the rate of change of the angle through which the motor rotates per unit time. In simple terms, it's how fast the motor is spinning.

$J\mathrm{eq}Jeq$: This is the equivalent moment of inertia of the system. In a DC motor, it represents the combined inertia of the rotor and anything attached to it that resists changes in its rotational motion. Essentially, it's a measure of how difficult it is to change the speed of the motor.

$T\mathrm{em}Tem$: This is the electromagnetic torque produced by the motor. It's the torque generated by the interaction of the magnetic fields in the motor, which produces the rotational force.

$TLTL$: This represents the load torque. It's the external torque applied to the motor, which opposes the motion generated by the motor itself.

$$T_{em} = \frac{p}{2}\left[\lambda_{rq} i_{rd} - \lambda_{rd} i_{rq}\right] = \frac{p}{2}\left[0 - \lambda_{rd} i_{rq}\right] = \frac{p}{2}\left[0 - \lambda_{rd}\left(-\frac{L_m}{L_r} i_{sq}\right)\right] \text{.........(b)}$$

=p/2 L_m/L_r λ_rd i_sq

Tem: Electromagnetic torque produced by the motor

pp: Number of pole pairs in the motor

λrqλrq: Quadrature-axis component of the rotor flux linkage

irdird: Direct-axis component of the rotor current

λrdλrd: Direct-axis component of the rotor flux linkage

irqirq: Quadrature-axis component of the rotor current

p: This is a scaling factor that accounts for the number of pole pairs in the motor. It comes from the derivation of the torque expression for PMSMs.

$LmLr$LrLm: This term represents the ratio of the magnetizing inductance (LmLm) to the rotor inductance (LrLr). It shows the influence of the magnetizing effect compared to the rotor's own inductance.

λrdλrd: This is the direct-axis component of the rotor flux linkage. It represents the magnetic field generated by the rotor magnets or field windings.

isqisq: This is the quadrature-axis component of the stator current. It represents the current flowing through the stator windings in a direction perpendicular to the rotor magnetic field.

From Simulink Model, we have:

$$\begin{aligned} T_{em} = \frac{p}{2}\frac{L_m}{L_r}\lambda_{rd} i_{sq} &= \frac{p}{2}\frac{L_m}{L_r}(L_m i_{sd} + L_r i_{rd}) i_{sq} \\ &= \frac{p}{2}\frac{L_m}{L_r}(L_m i_{sd} + 0) i_{sq} \ldots in\ steady - state \end{aligned}$$

$$= \frac{p}{2}\frac{L_m^2}{Lr} i_{sd}\, i_{sq} \text{ ....(c)}$$

Starting with the equation:

$Tem=p2LmLr\lambda rdisqTem=2pLrLm\lambda rdisq$

We know that $\lambda rd=Lmisd+Lrird\lambda rd=Lmisd+Lrird$, where $isdisd$ is the direct-axis stator current and $irdird$ is the direct-axis rotor current. This is because the rotor flux ($\lambda rd\lambda rd$) in a permanent magnet synchronous motor (PMSM) is the sum of the magnetizing flux ($LmisdLmisd$) and the reluctance flux ($LrirdLrird$).

Substituting $\lambda rd=Lmisd+Lrird\lambda rd=Lmisd+Lrird$ into the equation:

$Tem=p2LmLr(Lmisd+Lrird)isqTem=2pLrLm(Lmisd+Lrird)isq$

In steady-state, the direct-axis rotor current irdird is usually zero, as there is no resistance in the rotor's direct-axis. So we simplify further:

Tem=p2LmLr(Lmisd+0)isqTem=2pLrLm(Lmisd+0)isq

Simplifying:

Tem=p2LmLr(Lmisd)isqTem=2pLrLm(Lmisd)isq

Further simplification:

Tem=p2(Lm2Lrisd)isqTem=2p(LrLm2isd)isq

Now let's discuss the meaning of this equation:

TemTem: This is still the electromagnetic torque produced by the motor.

p/2p/2: This scaling factor accounts for the number of pole pairs in the motor.

Lm2LrLrLm2: This term now represents the ratio of the square of the magnetizing inductance (LmLm) to the rotor inductance (LrLr). It still shows the influence of the magnetizing effect compared to the rotor's own inductance.

Sliding Mode Control Laws

$$\boxed{\lambda_{sd} = L_s i_{sd} + L_m i_{rd}} \qquad \boxed{\lambda_{rd} = L_r i_{rd} + L_m i_{sd}}$$

$$\boxed{\lambda_{sq} = L_s i_{sq} + L_m i_{rq},} \qquad \boxed{\lambda_{rq} = L_r i_{rq} + L_m i_{sq},}$$

$(Speed\ Error)\ e = \omega_{ref} - \omega$…………………………(1)

$(Sliding\ Surface)\ s = e + K_1 \int ed$………………….(2)

e is the speed error as defined in Equation (1).

K1K1 is a control gain.

∫e dt∫edt represents the integral of the speed error with respect to time

$\dot{s} \ = \dot{e} + K_1 e = K_1 e + \dot{e} = K_1 e + \left(\dot{\omega}_{ref} - \dot{\omega}\right).$

$\dot{s} \ = \dot{e} + K_1 e = K_1 e + \dot{e} = K_1 e + (0 - \dot{\omega}\ ).$

$\dot{s} \ = \dot{e} + K_1 e = K_1 e + \dot{e} = K_1 e - \dot{\omega}$…………………(3)

Equivalent Control,$\boldsymbol{u_{eq}}$

Now to obtain the equivalent control, u_{eq}, taking time-derivative of s, in Equation (19) and simplifying using Equations (17), Equation becomes:

$$\dot{s} = 0$$

$$K_1 e - \dot{\omega} = 0$$

$K_1 e - \frac{1}{J_{eq}}(T_{em} - T_L) \ = 0.$

$(T_{em} - T_L) = J_{eq} K_1 e$……….(4)

$$T_{em} = J_{eq} K_1 e + T_L$$

$$\boldsymbol{u_{eq}} = \boldsymbol{T_{ref1}} = T_{em} = J_{eq} K_1 e + T_L$$

Discontinuous Control,$\boldsymbol{u_{disc}}$

Similarly, to obtain the discontinuous control, u_{disc}, using:

$\boldsymbol{u_{disc}} = \boldsymbol{T_{ref2}} = -K_2 \text{sign}(s)$

Discontinuous Control Action:

The equation represents a form of discontinuous or sign-based control action.

$u$discudisc is the control input used for the system.

Tref2Tref2 is the reference torque for the motor.

Sign Function:

The function sign(s)sign(s) returns the sign of the input ss:

sign(s)=1sign(s)=1 if s>0s>0,

sign(s)=0sign(s)=0 if s=0s=0,

sign(s)=−1sign(s)=−1 if s<0s<0.

Total Control,$\boldsymbol{u_T}$

Now substituting values from Equation

Overall Control Law:

$$\boldsymbol{u_T} = \boldsymbol{u_{eq}} + \boldsymbol{u_{disc}} = \boldsymbol{T_{ref2}} = J_{eq} K_1 e + T_L - K_2 sign(s)$$

$$\boldsymbol{u_T} = \boldsymbol{u_{eq}} + \boldsymbol{u_{disc}} = \boldsymbol{T_{ref2}} = \underbrace{(J_{eq} K_1 e + T_L)}_{\boldsymbol{u_{eq}}} + \underbrace{(-K_2 \text{sign}(s))}_{\boldsymbol{u_{disc}}}$$

Proposed SMC Of induction Motor drive Control Strategy

The Closed-loop operation of the proposed speed and torque control strategy shown below

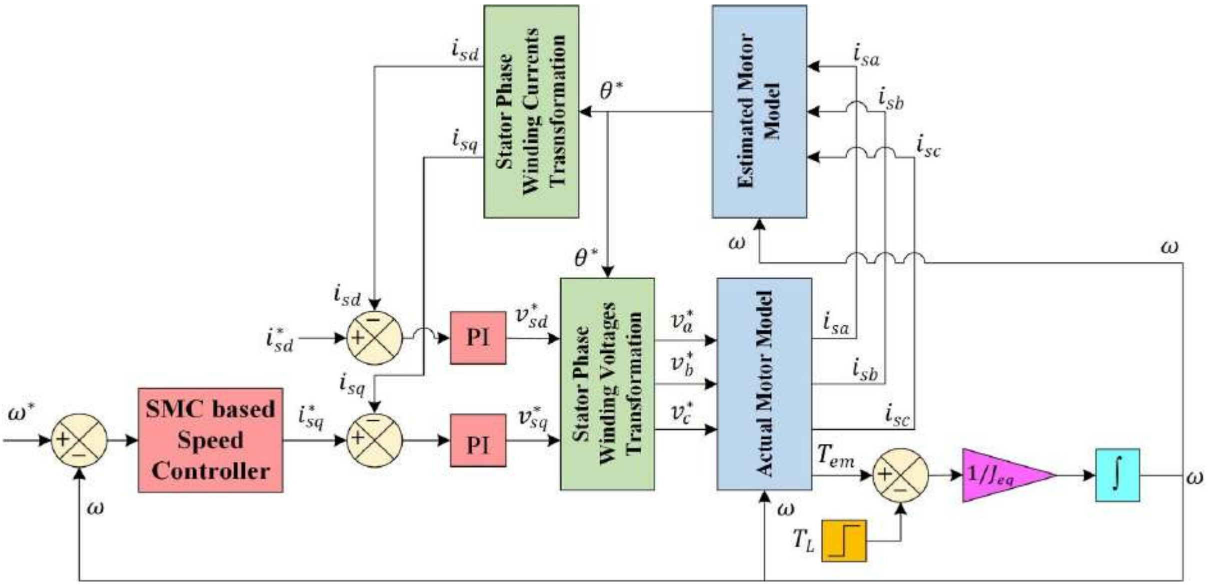

Figure 1: Closed-loop operation of the proposed speed and torque control strate

Reference Voltage Generation Through ANFIS

Table 1: Induction Motor Parameters

S.No.	**Names of Parameters**	**Values**
1	Operating Power	3 HP/2.24 kW
2	Operating Voltage (L-L, rms)	460 V
3	Operating Frequency	60 Hz
4	Number of Phases	3
5	Full-Load Current	4 A
6	Full-Load Speed	1750 rpm
7	Power Factor	0.80
8	Number of Poles	4
9	Full-Load Efficiency	88.50 %
10	Full-Load Slip	1.72 %
11	The Total Equivalent Moment of Inertia, J_{eq}	0.025 kg.m^2

12	Stator Circuit Resistance Per Phase, R_s	1.77 Ω
13	Rotor Circuit Resistance Per Phase, R_r	1.34 Ω
14	Stator Circuit Reactance Per Phase, $X_{\ell s}$	5.25 Ω
15	Rotor Circuit Reactance Per Phase, $X_{\ell r}$	4.57 Ω
16	Magnetizing Reactance of the Stator Winding, X_m	139 Ω

Results and Discussion

Performance Evaluation of the Proposed Technique

MATLAB/Simulink software is used for simulation purposes. This software enables us to simulate the circuit diagram of our proposed method.

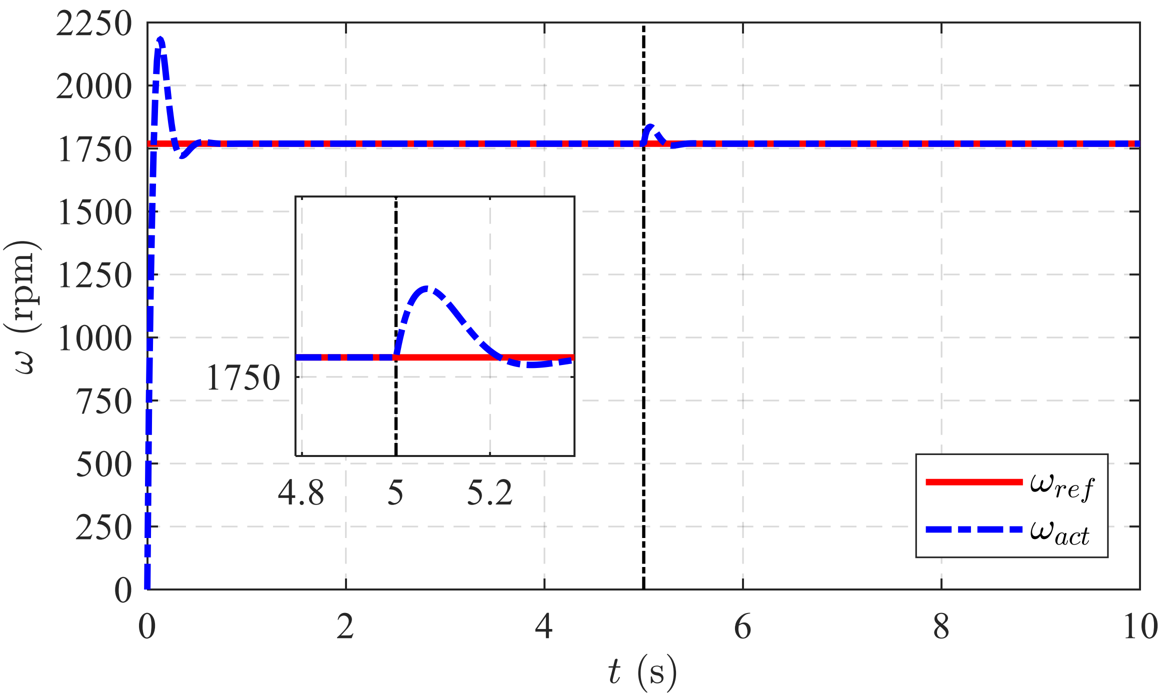

Figure 2: Speed tracking graph of PI controller

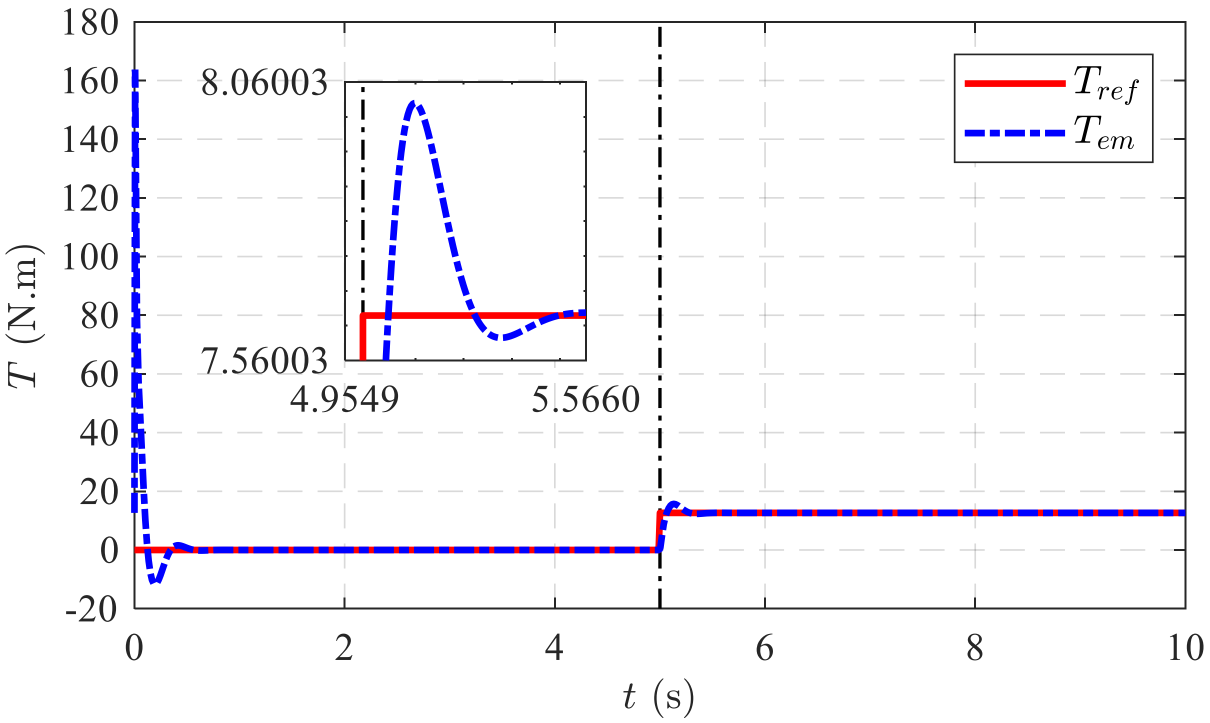

Figure 2 Torque tracking graph of PI controller

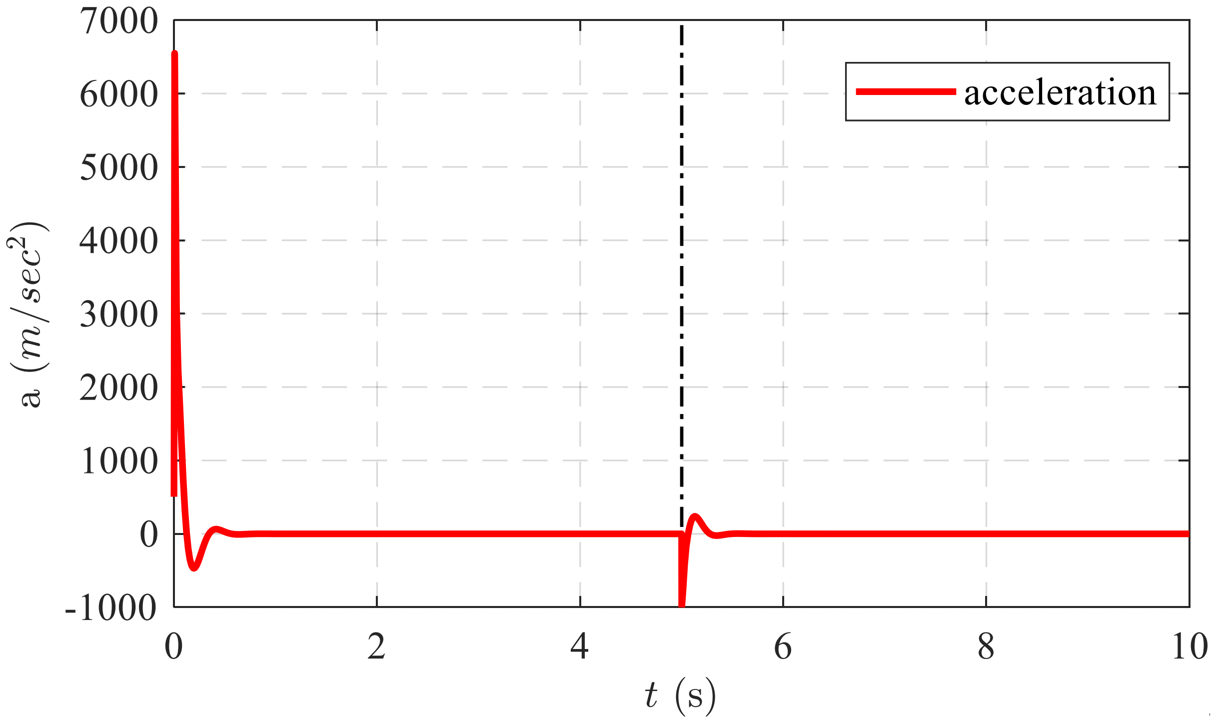

Figure 3 Acceleration of Motor

Performance Comparison with PI&SMC

Various algorithms are used to control the speed and torque of IM. Like mainly,

Direct torque control (DCT)

Field oriented control (FOC)

Proportional Control**(PI)**

These control algorithms have some drawbacks like,

Slow dynamic response

Low speed

Sensitivity to Parameter Changes

Difficulty in Tuning

Limited Response to Changing Dynamics

Sensitive to disturbance

simplicity.

PI control algorithm is widely used as a conventional technique to control the speed and torque of induction motor drive due to its simplicity. However, it has some drawbacks as well

Draw Backs of PI

The two main drawbacks are

Limited Response to Changing Dynamics

controllers may struggle to adapt to rapidly changing system dynamics, especially if the process being controlled has significant inertia or delays. In such cases, the integral action may not be sufficient to quickly eliminate errors, leading to slower response times.

Sensitivity to Parameter Changes

: PI controllers rely on tuning parameters (proportional gain and integral time) to achieve optimal performance. However, these parameters can be sensitive to changes in the system or operating conditions. Poorly tuned PI controllers may lead to oscillations, instability, or sluggish response.

Comperative result of PI and SMC Control

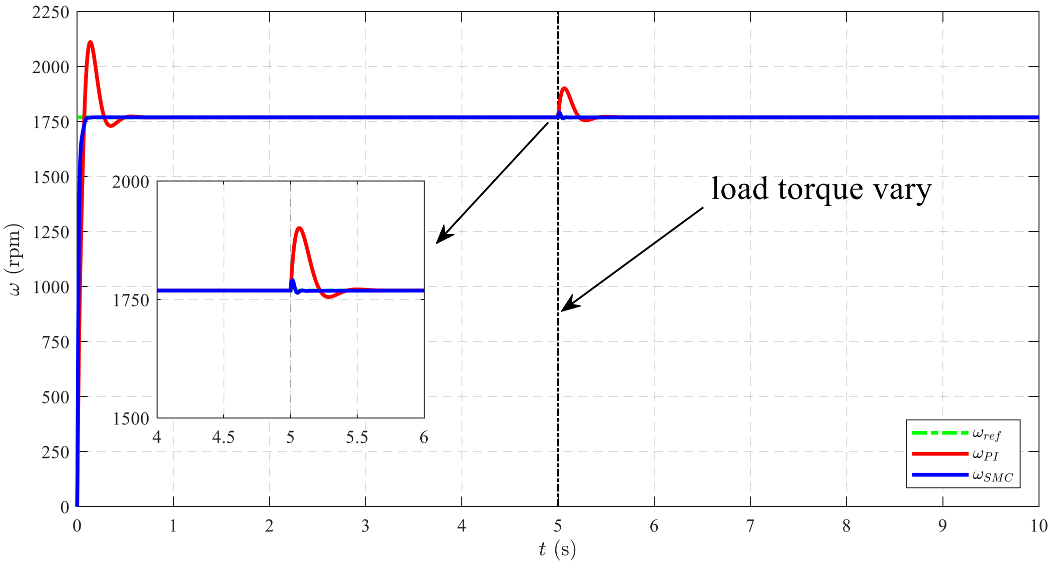

Fig 4. Comparative Speed tracking graph

In the realm of motor control systems, the choice of control strategy significantly influences the performance and efficiency of the system. This note presents a comparative analysis of speed control using Sliding Mode Control (SMC) and Proportional-Integral (PI) controllers. The focus is on evaluating the performance of these controllers in terms of speed tracking accuracy, response time, and robustness.

The comparative analysis highlights the superior performance of SMC over PI controllers in speed control applications. While PI controllers offer simplicity and ease of implementation, SMC provides enhanced accuracy, faster response times, and robust performance in the face of uncertainties. Therefore, SMC emerges as a preferred choice for demanding speed control applications where precision and robustness are paramount.

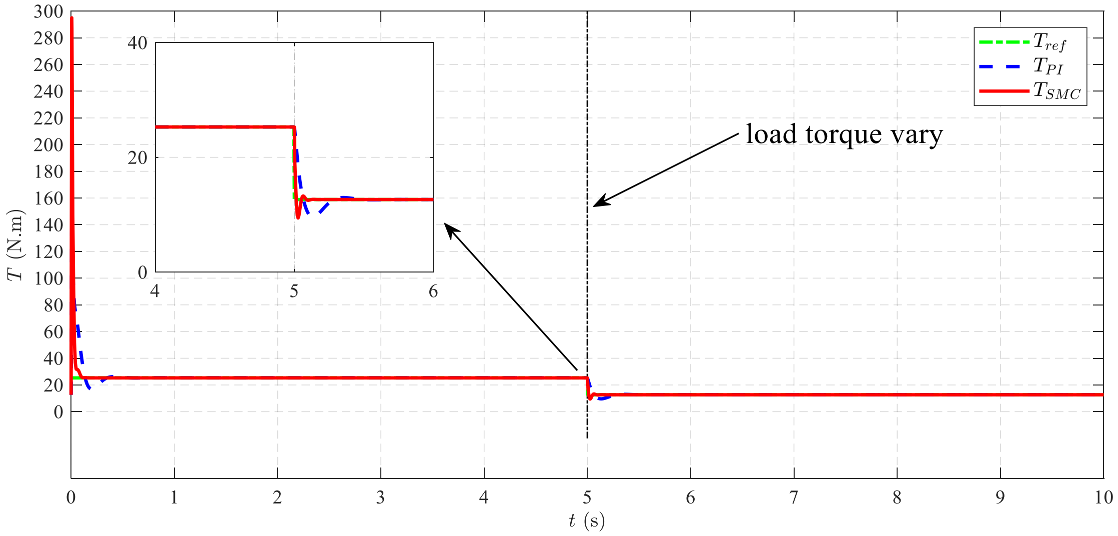

Fig 5. Comparative Torque tracking graph

Efficient torque control is crucial in various industrial applications, particularly in motor control systems where precise torque regulation is essential for optimal performance. This note presents a comparative analysis of torque control using Sliding Mode Control (SMC) and Proportional-Integral (PI) controllers, focusing on their respective performance in terms of torque accuracy, response time, and robustness.

Efficient torque control is crucial in various industrial applications, particularly in motor control systems where precise torque regulation is essential for optimal performance. This note presents a comparative analysis of torque control using Sliding Mode Control (SMC) and Proportional-Integral (PI) controllers, focusing on their respective performance in terms of torque accuracy, response time, and robustness.

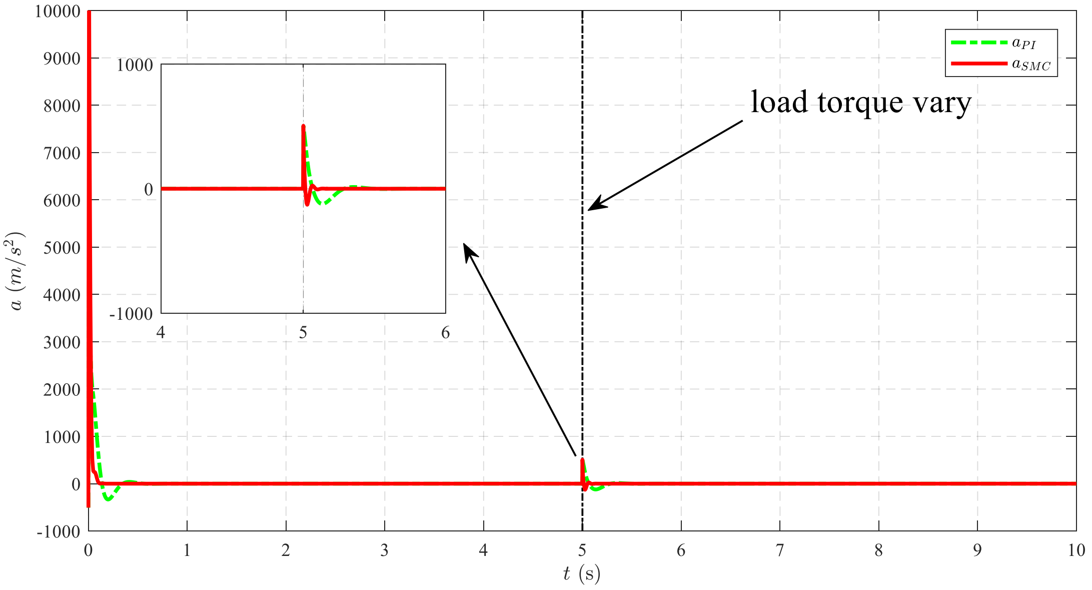

Fig 6. Comparative Acceleration of Motor

The comparative analysis of acceleration performance between Sliding Mode Control (SMC) and Proportional-Integral (PI) Controller reveals notable distinctions in their effectiveness in controlling the acceleration of a system, particularly in the context of motor drives.

SMC, known for its robustness and ability to handle nonlinearities and uncertainties, exhibits superior acceleration performance compared to traditional PI controllers. This advantage stems from SMC's inherent capability to directly influence the system dynamics through the sliding surface, ensuring rapid response to changes in the reference signal.

One key aspect where SMC outperforms PI controllers is in its ability to provide precise and prompt control action, especially in scenarios involving sudden changes in load torque or disturbances. By leveraging the sliding mode principle, SMC swiftly drives the system towards the desired acceleration trajectory, minimizing error accumulation and ensuring tight tracking of the reference signal.

Additionally, SMC offers enhanced disturbance rejection properties, making it particularly suitable for applications where disturbances are prevalent, such as in motor drives subjected to varying loads or operating conditions. Its robustness to parameter variations and external disturbances contributes to more stable and accurate acceleration control compared to PI controllers.

While PI controllers are widely used and offer simplicity in design and implementation, they may struggle to achieve the same level of acceleration performance as SMC, especially in dynamic and uncertain environments. PI controllers rely on error feedback and integral action to regulate acceleration, which can lead to slower response times and reduced accuracy, particularly in systems with nonlinearities and disturbances.

In short the comparative analysis highlights SMC's superiority in acceleration control over PI controllers, owing to its robustness, fast response, and superior disturbance rejection capabilities.

However, the choice between SMC and PI controllers ultimately depends on specific application requirements, considering factors such as system dynamics, performance objectives, and implementation constraints.

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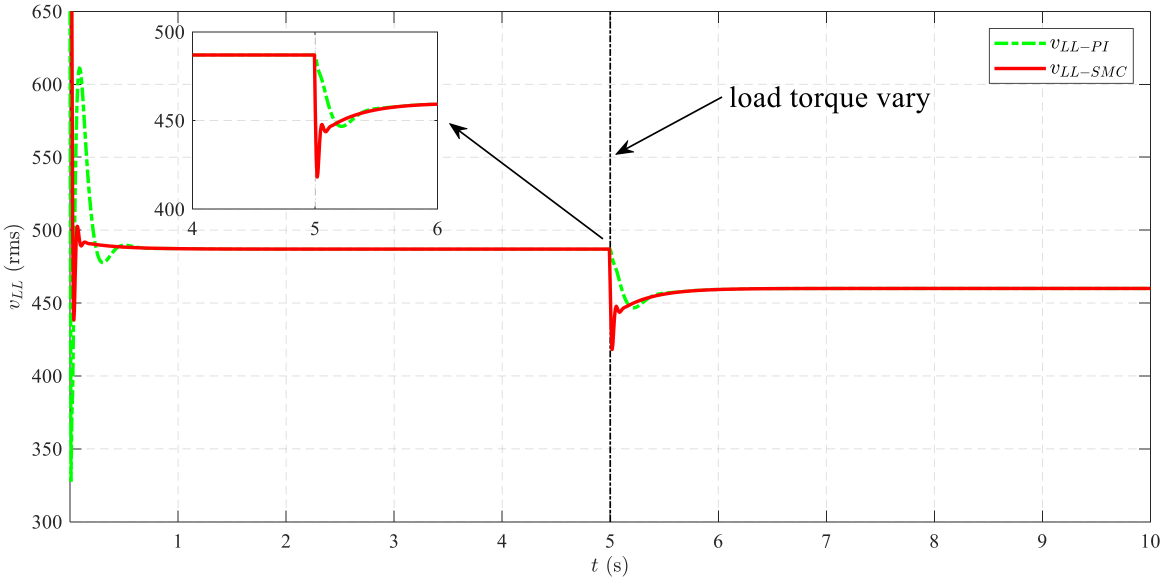

Fig 7. Operating Voltage of Induction Motor

When comparing the performance of line-to-line voltage control between Sliding Mode Control (SMC) and Proportional-Integral (PI) controller in an induction motor drive system, it's essential to consider several factors.

Dynamic Response: SMC is known for its robustness against parameter variations and disturbances. It can provide a faster dynamic response compared to a traditional PI controller, especially in the presence of uncertainties and nonlinearities in the system. This faster response can lead to improved transient and steady-state performance of the line-to-line voltage control.

Accuracy and Precision: While both controllers aim to regulate the line-to-line voltage of the induction motor, SMC often exhibits higher accuracy and precision, particularly under varying operating conditions. Its ability to directly address uncertainties and nonlinearities in the system allows for more precise voltage regulation, leading to enhanced motor performance and efficiency.

Stability and Robustness: SMC offers inherent stability due to its sliding mode dynamics, which ensures convergence to the desired voltage reference even in the presence of disturbances and parameter variations. This robustness contributes to the overall stability and reliability of the motor drive system, making it suitable for demanding industrial applications where stability is critical.

Controller Complexity: SMC may require a more complex implementation compared to a standard PI controller due to its nonlinear control law and sliding mode dynamics. However, advancements in control algorithms and computational hardware have made the implementation of SMC more feasible in practical applications, balancing the complexity with the benefits it offers in terms of performance and robustness.

In short, when comparing line-to-line voltage control performance between SMC and PI controllers, SMC often demonstrates superior performance in terms of dynamic response, accuracy, stability, and robustness. However, the choice between the two controllers depends on various factors such as application requirements, computational resources, and implementation constraints.

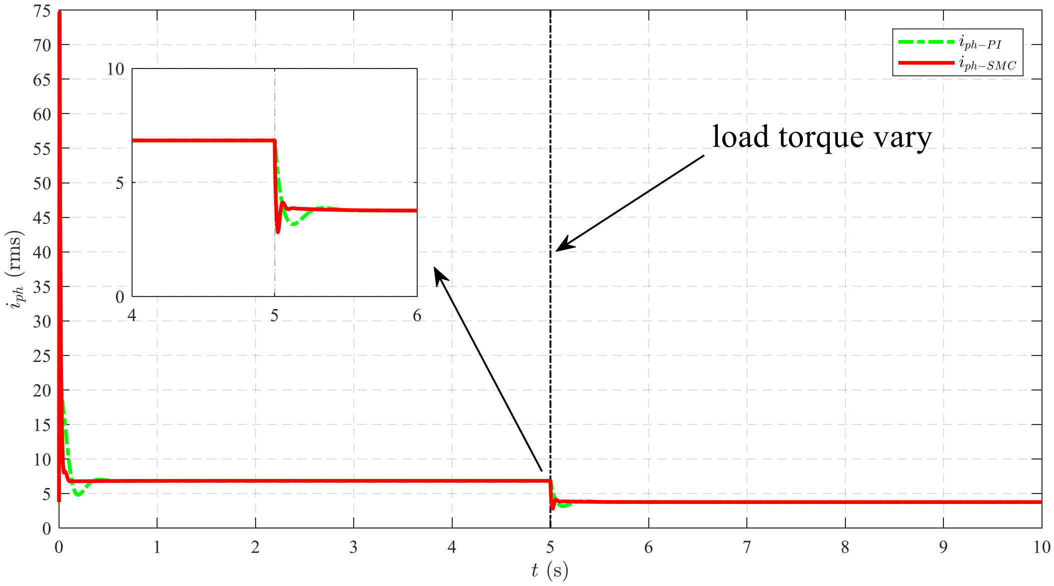

Fig 8. Phase current of IM

PI Control: PI controllers can achieve satisfactory steady-state accuracy with proper tuning. However, they may exhibit steady-state error in certain situations, particularly in the presence of disturbances or parameter variations.

Performance under Nonlinearities:

SMC: Sliding mode control is well-suited for systems with nonlinearities due to its robustness properties. It can handle nonlinearities effectively and maintain stability under varying operating conditions.

PI Control: PI controllers may struggle to maintain stability in systems with significant nonlinearities, requiring careful tuning and adaptation to ensure satisfactory performance.

In summary, while both SMC and PI controllers can regulate phase currents in motor control applications, SMC generally offers superior performance in terms of robustness, dynamic response, and stability, especially in the presence of nonlinearities and uncertainties.

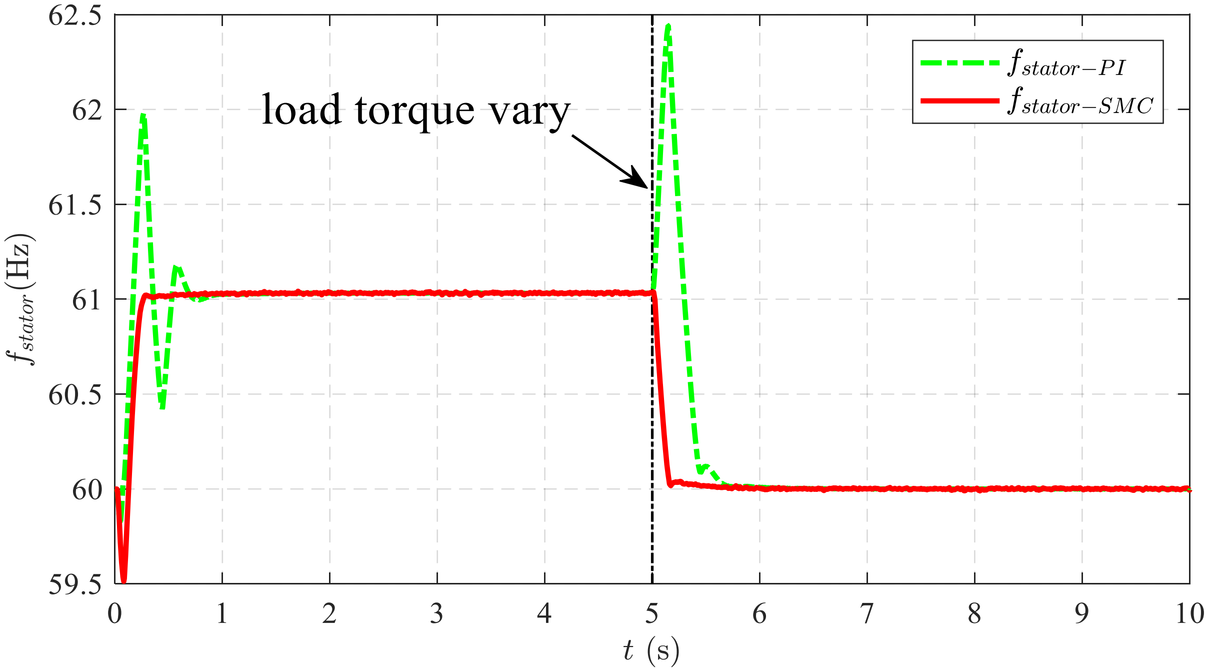

Fig 9. Stator frequency of IM

Stator frequency refers to the frequency of the alternating current (AC) supplied to the stator windings of an electric motor. In an induction motor, for example, the stator frequency determines the speed of the rotating magnetic field, which in turn influences the motor's speed of operation.

In a typical three-phase induction motor, the stator windings are connected to an AC power supply. The frequency of this AC power supply determines the speed at which the magnetic field rotates within the motor. The synchronous speed of the motor, which is the speed at which the magnetic field rotates, can be calculated using the formula:

Where:

By adjusting the frequency of the AC power supply, the speed of the rotating magnetic field (and consequently, the motor's speed) can be controlled. This method is commonly used in variable frequency drives (VFDs) or adjustable speed drives (ASDs) to vary the speed of induction motors for different applications, such as in industrial machinery, HVAC systems, and conveyor belts.

Conclusions and Future Research Recommendations

Performance Evaluation: The non-linear sliding mode control (SMC) approach demonstrated superior performance in regulating the speed and torque of the induction motor drive compared to traditional control methods like PI control. This was evidenced by improved dynamic response, robustness against parameter variations, and enhanced disturbance rejection capabilities.

Robustness: SMC exhibited robustness against uncertainties and disturbances inherent in practical motor control applications. The sliding mode control law ensured that the system remained stable and maintained desired performance even in the presence of non-linearities and external perturbations.

Steady-State Accuracy: The proposed SMC algorithm achieved satisfactory steady-state accuracy, minimizing errors and ensuring precise speed and torque control under various operating conditions. This is crucial for applications requiring precise motor performance, such as robotics, automation, and electric vehicles.

Adaptive Capabilities: The sliding mode control framework offered adaptability to varying operating conditions and system parameters. This adaptability is essential for real-world applications where conditions may change over time, allowing the motor drive system to maintain optimal performance

.

Based on the prior scenario our future work includes:

Implementation Considerations: Further research could focus on practical implementation aspects of non-linear sliding mode control for induction motor drives, including hardware-in-the-loop (HIL) simulations, experimental validations, and industrial implementations. This would provide valuable insights into the real-world applicability and scalability of the proposed control strategy.

Advanced Control Strategies: Investigating advanced control strategies, such as adaptive sliding mode control, predictive control, or neural network-based control, could further enhance the performance and robustness of induction motor drives. These approaches may offer improved disturbance rejection, faster transient response, and better energy efficiency.

Fault Diagnosis and Tolerance: Research into fault diagnosis and fault-tolerant control techniques for induction motor drives could improve system reliability and safety. Developing methods to detect and mitigate faults in real-time can prevent catastrophic failures and downtime, enhancing overall system availability.

Integration with Renewable Energy Systems: With the increasing integration of renewable energy sources like wind and solar power into electrical grids, exploring the integration of non-linear sliding mode control with renewable energy systems and grid-connected applications could be beneficial. This would enable efficient and stable operation of induction motor drives in renewable energy-based applications.

Practical implementation of the proposed controller on a real system.

To work on the general paper nonlinear sliding mode control.

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