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Direct Torque Control with Feedback Linearization for Induction Motor Drives

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Abstract*—This paper describes a controlled direct torque (DTC) asynchronous motor drive that employs linearization of feedback. The system of logic control approach has been inserted to come back up with the auxiliary control input for the feedback linearization controller. A new linear model is employed to implement a direct torque control type controller that preserves all advantages and eliminates and overcomes drawback, the flux and torque ripple. Robust, fast, and ripple-free control is achieved by using SMC with proportional control within the vicinity of the sliding surface. SMC assures robustness as in DTC, while the proportional component eliminates the torque and flux ripple. The time response of torque is analogous to traditional controlled direct torque and also the proposed solution is more flexible and highly tunable to the P component. The design of the controller is presented, and its robust stability is analyzed and shown in simulations. The sliding controller is compared with a linear controlled direct torque scheme with and without linearization of feedback. Extensive experimental results for a sensor less asynchronous motor drive validate the proposed solution. The simulation and so the experimental validation of the proposed control algorithm shows that the association of dual techniques can effectively achieve high dynamic behavior and improve the robustness against parameters variation and external disturbances. Practical implications, the theoretical, simulation and experimental studies prove that the proposed control algorithm are often used on different AC machines for variable speed drive applications like oil drilling, traction systems and wind energy conversion systems.*

Keywords*—Direct torque control (DTC), ; feedback linearization; auzillary contol;SMC.*

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I. INTRODUCTION

Controlled direct torque may be a strong and super-fast responding control method for asynchronous machine drives [1], [2]. Closed-loop hysteresis torque and flux controllers are used to pick out the voltage vector is employed by the conventional torque control method applied to the motor. Controlled direct torque will get frequent flux control and torque by not using current controllers. DTC working is related to more ripples in torque which makes a sound, noise, vibrations, and losses will increase with the voltage switching frequency of the source inverter voltage is less and changeable. Improvements in DTC operating at the constant switching frequency and by using modern control of theory have developed to scale back the ripples in torque.Controlled direct torque with modulation of space vector supported flux controllers and linear torque [4]. Many methods using the structure variable control principles are proposed. Linearization of feedback might be a control ofthe nonlinear approach [5].Linearization of feedback is employed to linearize the induction motor model concerning flux, current, and speed [6] - [11].Linearization of feedback applications to power electronics and the sliding-mode of control (SMC) could be a robust control likeminded for control systems with uncertainties or modeling errors.The feedback-linearized induction motor model is secondorder, with only the torque and stator flux magnitudeas decoupled variables of state. Thus, the new linear model is intuitive, simple, and it substantially simplifies the design of the controller. This approach supported torque–flux linearization and control are different from present existing methods which support current control [6]-[12].

II. CONTROL STRATEGIES

Controlled direct torque is an effective technique that can make a secondary way in asynchronous motor vector control [1–5]. The technique gives us good results with a simple structure and an easy control diagram. Direct torque control can be used to control directly the complete torque and also the stator flux by choosing a certain inverter voltage source state.Many methods are proposed to prevail over many of the drawbacks which are in direct torque control [4]. Some of the proposed methods are direct torque control with vector modulation [5] and the employ of a duty-ratio controller to set up a modulator connecting the active vectors which are elected from zero vectors [6–8]. By using the techniques of artificial intelligence for example Neuro-Fuzzy controllers with space vector modulation [9] these techniques gain better improvements like ripple reduction in torque and operation of switching fixed frequency.

The difficulty of the control will be increased considerably.Two-level inverter employs converter topologies by using a new advanced method to improve controlled direct torque features and different standards. Few researchers have given their variousimplementations for the neutral point clamped three-level voltage source inverter [10–16].

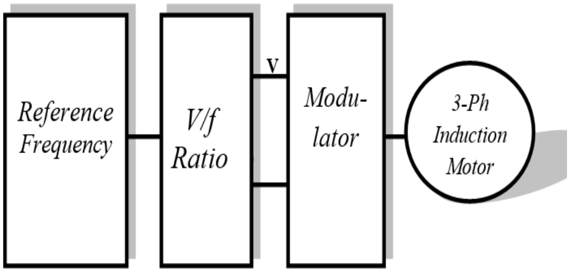

Figure 1: Frequency control by using PWM

The frequency control technique of AC drive uses controlling variables as voltage and the frequency bysome parameters generated outside of the motor. Both frequency reference and voltage are fed onto a modulating device that can simulate an AC sine wave and is used to feed windings on the stator of the motor.

The open-loop drive technique called scalar control and the field-oriented is not used in the motor. Voltage and frequency are important to control variables that are to be applied to the windings on the stator. The position signal is fedbackto the status of the rotor is ignored. Torque cannot be controlled with an accurate value. A modulator signal is needed for the motor to respond when the signal is changing.

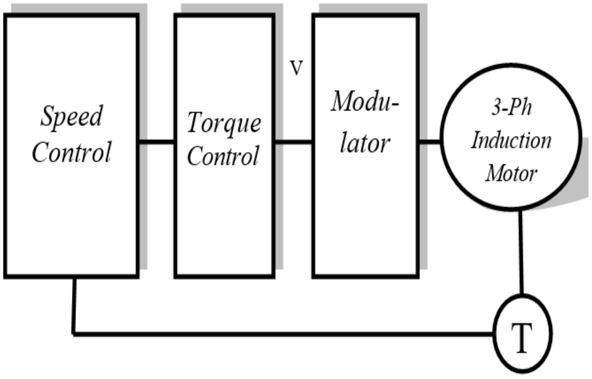

Figure 2: Flux Vector Control using PWM

The transition vector control drive should know the precise spatial situation of the rotor motion inside the AC enlistment engine. The attractive working states of a DC engine to play out the area direction measure. Transition vector for modulation of pulse width drives, the direction of the field is accomplished by electrical methods rather than the mechanical observer sweep gathering of the DC engine. First and foremost, data about the status of the rotor is gotten into taking care of rotor speed at the back and spatial connection comparative with the stator’s field by methods for a heartbeat encoder. Additionally, the engine's electrical character is numerically demonstrated with microchips that want to handle the statistics. To fit an undeniable degree of torque response and speed precision, a feedback gadget is required, and it very well may be expensive and adds intricacy to the standard straightforward AC enlistment engine. Additionally, a modulator is utilized, which hinders correspondence between the approaching voltage and recurrence signals and the requirement for the engine to answer to the current evolving signal. Albeit the engine is precisely basic, the drive is electrically unpredictable.

III. FEEDBACK LINEARIZATION OF INDUCTION MOTOR DRIVE

Customary linearization is the plan which depends on the main request guess of the framework elements at some specific operating point by dismissing elevated-request elements. This fulfilled linearization is in numerous applications wherever ordinary framework activity stays inside the assortment region or slowly fluctuating harmony. FB of an induction motor is reachable by a natural change of state factors and an info redefinition. The asynchronous motor state space model inside the stator association is addressed as

$$\frac{d\varphi_s}{dt} = -\frac{1}{T_S\sigma}\varphi_s + \frac{L_m}{L_rT_S\sigma}\varphi_r + u_s \qquad (1)$$

$$\frac{d\varphi_r}{dt} = \frac{L_m}{L_rT_S\sigma}\varphi_s - \left(\frac{1}{T_S\sigma} - j\omega_r\right)\varphi_r \qquad (2)$$

Where $\varphi_s\varphi_r$ are the rotor and stator motion space vector individually Rs, Rris the rotor and stator protections, Lr, Ls, and $L_m$are the rotor, stator, and charging inductances.
Ts=Ls /Rs, Tr= Lr/Rr, σ = (L Lr - Lm 2)/LsLr, ωr is that the rotor speed and us = Usd+ Jus Q is the voltage vector inthe stator, which goes about as information.

$$M = \psi_{sq}\psi_{rd} - \psi_{sd}\psi_{rq} \qquad (3)$$

$$R = \psi_{sd}\psi_{rd} + \psi_{sq}\psi_{rq} \qquad (4)$$

$$F_s = \psi_{sd}^2 + \psi_{sq}^2 \qquad (5)$$

$$F_r = \psi_{rd}^2 + \psi_{rq}^2 \qquad (6)$$

Where M is that the torque scaled and Fr, Fs is the square sizes of the rotor and stator motion, individually. The Rrelies upon the rotor and stator motion. For straightforwardness, we allude to M because the torque and Fs on the grounds that the motion size. We are fundamentally intrigued torque M is controlled and the stator motion extent Fs. Notwithstanding, we should likewise safeguard that the leftover state factors R and Fr are limited. The induction motor state conditions with the state factors (3) are

$$\frac{dM}{dt} = -\left(\frac{1}{T_r\sigma} + \frac{1}{T_S\sigma}\right)M - \omega_r R - \psi_{rq}U_{sd} + \psi_{rd}U_{sq} \qquad (7)$$

$$\frac{dF_S}{dt} = -\frac{2}{T_S\sigma}F_s + \frac{L_m}{L_rT_S\sigma}R + 2\psi_{sd}U_{sd} + \psi_{sq}U_{sq} \qquad (8)$$

$$\frac{dF_r}{dt} = -\frac{2}{T_r\sigma}F_r + \frac{2L_m}{L_ST_r\sigma}R \qquad (9)$$

$$\frac{dR}{dt} = -\left(\frac{1}{T_r\sigma} + \frac{1}{T_S\sigma}\right)R + \omega_r M + \frac{L_m}{L_rT_S\sigma}F_S + \frac{L_m}{L_rT_S\sigma}F_r \qquad (10)$$

$$+\psi_{rd}U_{sd} + \Psi rqU_{sq} \qquad (11)$$

Linearization of feedback decouples the state factors of interest, to be specific, the torque M and hence the stator transition extent Fs and along these lines essentially rearranges the controller plan for the IM drive framework. Furthermore, since the subsequent framework is direct, the traditional straight control procedures are regularly utilized. Since the M, Fs, and Fr have elements with left plane posts, the info yield dependability of the excess state factors is regularly effectively ensured given that the R is limited.A section from the start-up, this circumstance never happens throughout the ordinary activity. Inside the actual drive, the transition has been introduced to drive the controller guarantees. Reenactment consequences are the way that the control of torque has begun with a 40msec delay after the controlled transition when motions are at ostensible levels. It is along these lines expected that the changeable R joins.

A. Direct torque control with sliding mode:

SMC strategy is mainly acclimated to accomplish a speedy and vigorous activity of induction motor drive. This drive utilizes straightforward torque, speed and motion onlookers, and a P- speed controller. The drive information and a fast depiction of the spectators are given inside the Appendix.These are then subbed to get the actual data sources U_{sd} and U_{sq}, individually. In any case, blunders inside the computation of the actual data sources are inescapable and should be represented and remedied to deliver powerful execution. The blunders inside the actual control information sources might be addressed as

$$\frac{dM}{dt} = g_M + w_q \qquad (12)$$

Here the g_m gives the uncertainty elements of the FBL torque condition. The term g_m is not known from (13), a gauge of the elements is given by

$$g_M = -\left(\frac{1}{T_r\sigma}+\frac{1}{T_s\sigma}\right) M. \qquad (13)$$

We expect that the assessment blunder for$g_M$is limited and given as

$$g_M - g_M <= G_M. \qquad (14)$$

$$S_M = M - M_d. \qquad (15)$$

For the decision of sliding surfaces, we utilize the sliding mode control

$$W_q = - g_M - k_M \operatorname{sgn}(S_M), \qquad k_M > 0. \quad (22)(16)$$

The term $-kM$sgn (SM) is called remedial control. We pick the Lyapunov quadratic work competitor $V= S2M/2$. The framework combines to the sliding surface if the subordinate of a Lyapunov work is seen as negative along with all the directions of the framework. The subsidiary of V is

$$\frac{1}{2}\frac{d}{dt}S_m^2 = (g_M - \hat{g}_M - k_M sgn\,(s_M))\, S_M \quad (17)$$

$$= (g_M - \hat{g}_M)\, S_m - k_m|S_m|. \qquad (18)$$

For the hearty assembly of the sliding surface, the subordinate should stay negative within the sight of vulnerabilities. So, we pick the restorative control to acquire kMas in (19)

$$k_m = G_m + \eta_M \qquad (19)$$

This gives the sliding condition

$$\frac{1}{2}\frac{d}{dt}S_m^2 \leq -\eta_M|S_m| \qquad (20)$$

Here $\eta_M$is an optimistic consistent. The gain Km of (19) incorporates the term GM to guarantee the hearty steadiness and the term ηM. Enormous ηMmakes the framework direction to hit the surface sliding in a more limited time, however, can bring about higher chatting. Comparable outcomes can be gotten and seen by utilizing a fundamental sliding surface

$$S_M = \left(\frac{d}{dx}+\lambda_M\right)\int_0^t (M - M_d)\, d_T \qquad (21)$$

Here $\lambda_M$is a positive plan consistent boundary. This boundary decides how quickly the blunder comes to zero one time the state will be on a superficial level. The sliding mode of control exertion can be picked as

$$W_q = - g_M - \lambda_M(M - M_d) - k_M sgn(S_m), \quad k_M>0 \qquad (22)$$

The condition for sliding holds for $k_M=G_M+\eta_M$. To abstain from chatting, we characterize a limit layer circuitous the sliding surface $BM(t) =\{x,|S_M(x)|\leq h_M\}$, where$h_M>0$ is the limit thickness of the layer.The stator motion elements seen are practically comparable and indistinguishable. The vast majority of the examination is overlooked, for curtness. Additionally, to torque, the surface sliding is

$$SF_s = F_S - F_{sd} \qquad (23)$$

Also, the straight framework input control is

$$W_d = - \hat{g}F_s - k_{Fs} sgn\,(S_{Fs}),\ k_{Fs}>0. \qquad (24)$$

Concerning torque, we utilize a thin limit layer across the surface sliding, with corresponding control to maintain a strategic distance from complete babbling.

B. Robustness study and controller design:

The Sliding-method of the FBL controller will accomplish vigorous soundness in most significant mistakes, which influence the IM model. Engine boundary detuning and speed perception blunders.

$$U_s=\left(\frac{w_d}{2R}-\frac{L_m R_s}{L_s L_r - L_m^2}\right)\varphi_r + j\left(\frac{w_q}{R}+w_r\right)\varphi_s \quad (25)$$

Despite the fact that $w_d$and $w_q$are delivered by the sliding mode of control and has no vulnerability, it can supplant the blunder in the control signal with identical mistakes in *wd*and *wq*. The same blunder is $\Delta w=\Delta wd+j\Delta wq$ and (25) can be rewritten as

$$U_s=\left(\frac{w_d+\Delta w_d}{2R}-\frac{L^\wedge{}_m R^\wedge{}_s}{(L_m+L_{S\sigma})(L_m+L_{r\sigma})-L_M^2}\right)\varphi_r$$

$$+j\left(\frac{w_q+\Delta w_q}{R}+\omega^\wedge{}_r\right)\varphi_s \quad (26)$$

Here $\hat{L}m$is deliberate charging inductor and $\hat{R}s$ is the deliberate stator opposition and $\hat{\omega}r$is the rotor speed gauge. Utilizing (30) and (31), the same mistake is given by

$$\Delta w \quad =\Delta w_d + j\Delta w_q \quad (27)$$

$$= 2\left(\frac{\hat{L}_m \hat{R}_s}{(L^\wedge{}_m+L_{S\sigma})(\hat{L}_m+L_{r\sigma})-L_M^2}-\frac{L_m R_s}{L_s L_r - L_m^2}\right.$$

$$+j(w_r - w^\wedge{}_r)R \quad (28)$$

Feedback linearized torque and the transition of stator elements inthe presence of errors in *wd*and *wq*are

$$\frac{dM}{dt} = -\left(\frac{1}{T_r\sigma}+\frac{1}{T_s\sigma}\right) M + w_q - \Delta w_q \quad (29)$$

$$\frac{dF_s}{dt} = -\frac{2}{T_s\sigma}F_s + w_d - \Delta w_d \quad (30)$$

It very well may be accepted as the most extreme deviation of each dubious boundary and the greatest estimation or assessment mistake for the speed of the rotor is known. For this examination $\eta M=10$, $\eta Fs=10$ which gives a unique practical reaction for torque and transition. The fundamental concentration for this part is powerful security as opposed to dynamic reaction.

i. *Speed (ωR):*

Blunders in the speed assessment can basis model irritations that may impact the framework reaction. The speed blunders having no impact on stator motion elements except for a change in the torque (13) to

$$\frac{dM}{dt} = -\frac{1}{\sigma}\left(\frac{1}{T_r}+\frac{1}{T_s}\right) M + (w^\wedge{}_r - w_r)R + w_q \quad (31)$$

ii. *Stator resistance* (R$_s$):

The stator opposition changes with the temperature and it additionally impacts the stator transition elements. Acquainting a bother due with stator opposition blunder, the stator transition elements (34) is given by

$$\frac{dF_s}{dx} = -\frac{2}{T_{s\sigma}}F_s + \frac{2L_m}{L_r L_s \sigma} R\,(R_s - R^\wedge{}_s) + w_d \quad (32)$$

The relating reproduction bother for the boundary esteems is $GFs=L2rLLms\sigma R\times0.69=28.16$. We can pick the restorative control acquire $kFs=\eta Fs+GFs=$ 40>38.16.Since the torque elements are autonomous of the obstruction mistake, we should utilize a similar worth $kM=20$, for comparative unique execution.

iii. *Rotor resistance (R$_R$):*

Rotor obstruction changes with the heat. The prominent preferred position of the projected feedback linearization is that the progressions inside Rr don't change the stator elements transition and torque and don't influence the control. Notwithstanding, they change the elements of the two other state factors (R, Fr); this will significantly impact the speed gauge. Subsequently, the rotor protection blunders are represented by speed mistakes are talked about.

iv. *Magnetizing inductance (L$_m$)*

The charged inductance can go astray from its deliberate incentive because of the attractive immersion. Changes in the polarizing inductance will cause progressions in both rotor and stator inductance. This will have no impact on the torque elements it changes the stator

$$\frac{dF_s}{dt}=-\frac{2}{T_s\sigma}F_s+2R_rR_s\frac{L_m}{L_sL_r-L_m^2}\left(\frac{L_m}{(L_m+L_s\sigma)((L_m+L_r\sigma)-L_m^2}\right)+w_d \qquad (33)$$

$$\Delta_L=\frac{L_m}{L_sL_r-L_m^2}\frac{L_m}{(L_m+L_s\sigma)((L_m+L_r\sigma)-L_m^2} \qquad (34)$$

The proposed sliding mode of control configuration depends on the predefined dynamic reaction (ηM, ηFs) and the most extreme vulnerability (GM, GFs). The dynamic reaction is application subordinate and is picked by the planner. Condition (34) gives the most extreme vulnerability brought about by the linearization of the feedback controller. For the η and G for transition and torque the architect picks an additional sliding bigger than GM + ηMfor the torque controller and greater than GFs + ηFs for the motion controllers.

This decision of the remedial control acquires winds up in a durable and better stable framework that works at the predetermined speed while smothering jabbering. Looking at all recreation results, we presume that bigger increases lead to a quicker and strong.

C. Fuzzy logic based induction motor drives:

In feedback linearization, the primary idea assumes a focusing part in the majority of applications if standard or, just, fluffy principle. Despite the fact, the standard frameworks based have an extended utilization history in processing (AI). The absence of such frameworks could be a component for adapting to consequents and fluffy forerunners. Unadulterated math of fluffy standardsis a reason for it could be called the Dependency Fuzzy and inquiry language (FDCL). Even though FDCL is not exploited inside the device stash it was among all foremost components. In the greater part of the emblematic rationale use, a representative rationale is an interpretation of arrangement is the individual's answer in FDCL.

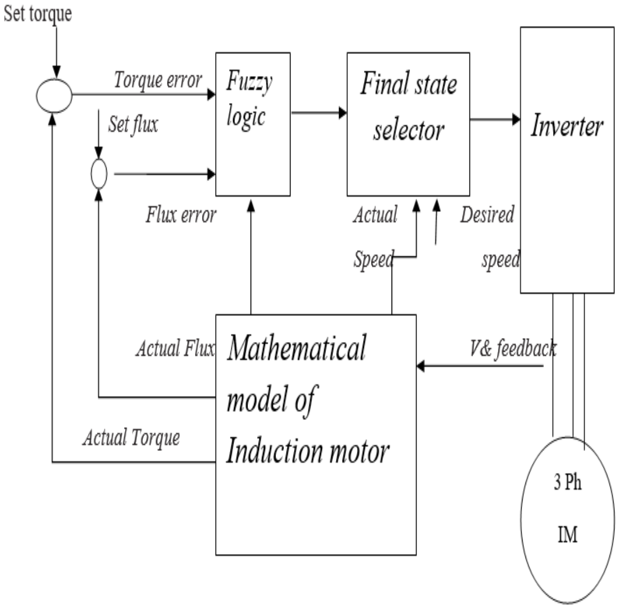

Figure 3:Induction Motor's block diagram of DTC using a fuzzy logic controller

IV. RESULTS AND OBSERVATIONS

A. Circuit diagram and results:

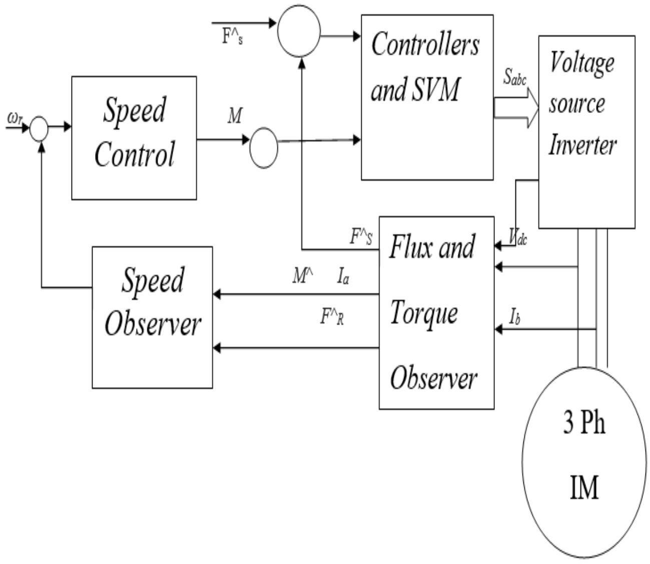

Figure 4: Sensors less DTCIM drives block diagram with feedback linearization.

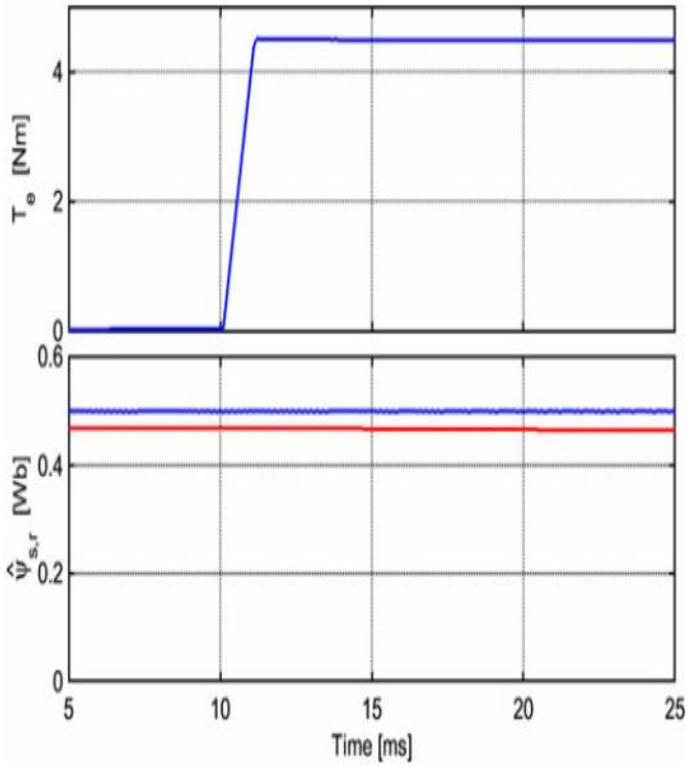

Figure 5: TransientTorqueforstartup fromstandstillwithfeedbacklinearizationandSMC(a)torqueand(b)statorandrotorfluxmagnitudes.

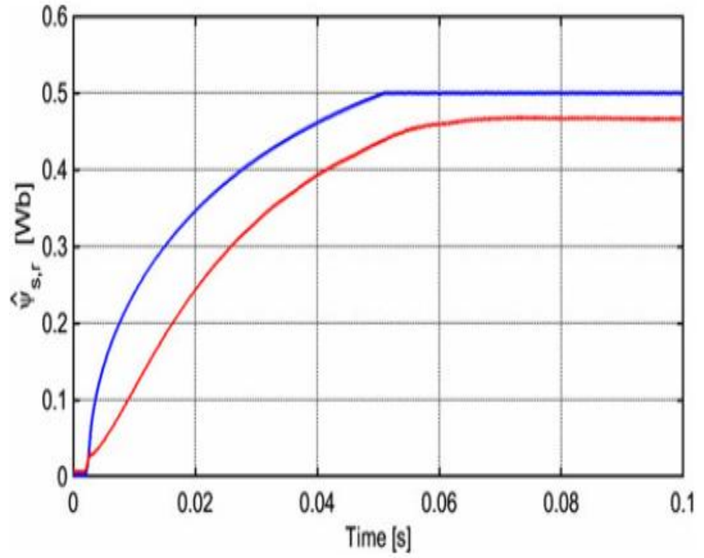

Figure 6:Stator(blue)androtor(red fluxmagnituderesponseto0.5 WbstepcommandwithfeedbacklinearizationandSMC

Thefigureshowsestimatedspeed,measuredspeed,torque andstatorandrotorfluxmagnitudes.Noticehowrigidlythefluxandtorquearekeptto setpointsduringspeedtransients.Forcomparison thesametestwasrunwithFBLandPIcontrollers. Whilethespeedresponseissimilar,thetorqueandstatorfluxmagnitudesshowoscillationsduringspeedtransients,which indicatealackofrobustnessandimperfectdecouplingforthePIcontroller.Despitethesimplefluxandspeedobserverand othererrors,thespeedcontrolisfastandaccurateinallcases.LowspeedoperationwithSMCandFBLisillustrated whichshowsfastreversalsat ±3 Hzelectricalspeed.Thetorquecontrolisfast,whilethestatorfluxiskeptconstant,whichreplicatesthesamerobustbe havior

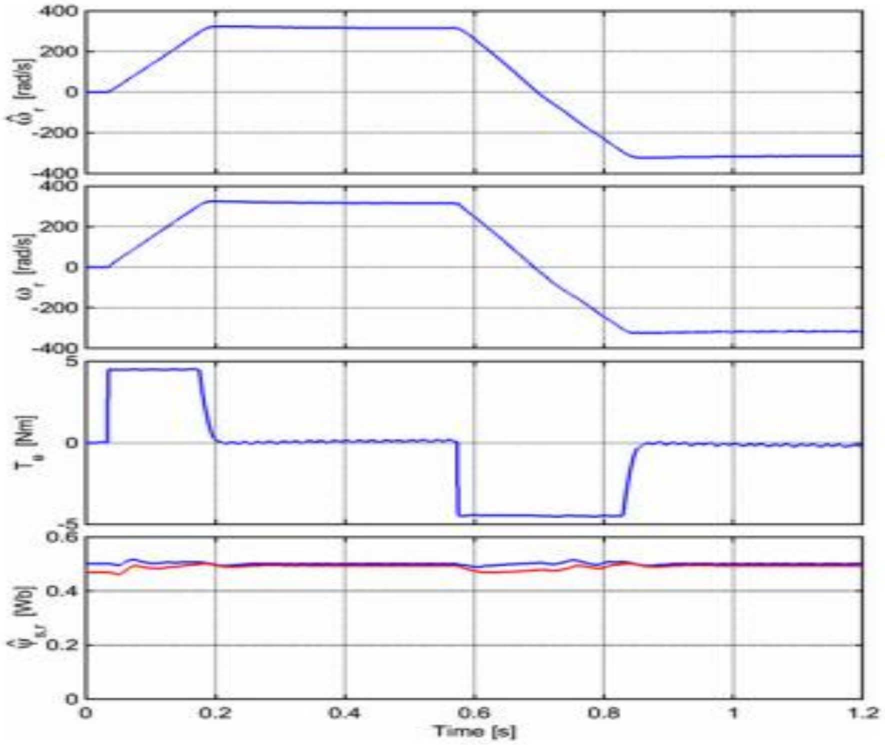

Figure 7: IMstartupwithFBLandPIcontrol(a)estimatedspeed,(b)measured speed, (c)torque,and(d)stator(blue)androtor(red)fluxmagnitudes.

The motion on the stator is introduced before and it is extent addresses that the linearization of feedback adequately decoupled the motion. The torque arrives at 4.4 Nm in less than 2 mill seconds and hence the overshoot is immaterial with extremely low consistent state swell. The stator and rotor transition size reactions to a 0.5 Weber step order of the stator motion size. The increasing speed from 0 hertz to 50 hertz follows an inversion from +50 Hertz to -50Hertz. Regardless of the direct transition and speed spectator and different blunders, the speed control is quick and precise inside and outside.

V. CONCLUSION:

This drive is having a quick and hearty reaction, as a customary direct torque control drive, and disposes of the torque and transition well. Overall, the appropriate response consolidates the advantages of the regular and direct DTC. These favorable circumstances are a direct result of the sliding mode controller and hence the linearization which will decouple the torque and the stator transition extent.

Broad test results distributed exhibit that torque-motion feedback linearization could be a helpful way to deal with an induction motor drive control. It permits the autonomous plan of the controllers, onlookers and encourages relatively straightforward coordination of traditional direct and nonlinear controllers. The utilization of existing direct onlookers is moreover straightforward.

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