Novel Direct Torque Control Based on Space Vector Modulation with Adaptive Stator Flux Observer for Induction Motors using ANFIS

Puttu Lakshmi[1], J. N. Chandra Shekar[2], A. Lakshmi Devi[3]

[1]PG Student [PS], Department of EEE, Sri Venkateswara University College of Engineering, Andhra Pradesh, India

[2]Assistant professor, Department of EEE, Sri Venkateswara University College of Engineering, Andhra Pradesh, India

[3]HOD, Department of EEE, Sri Venkateswara University College of Engineering, Andhra Pradesh, India

ABSTRACT

This paper describes a mix of direct torque control (DTC) and space vector modulation (SVM) for a customizable speed sensorless induction motor (IM) drive. The motor drive is provided by a two-level SVPWM inverter. The inverter reference voltage is gotten in view of information output criticism linearization control, utilizing the IM display in the stator – axes reference frame with stator current furthermore, transition vectors segments as state factors. Additionally, a powerful full-arrange versatile stator transition observer is intended for a speed sensorless DTC-SVM system and another speed-versatile law is given. By outlining the observer pick up matrix in view of state criticism H_∞ control hypothesis, the strength and robustness of the observer systems is guaranteed. At last, the viability and validity of the proposed control approach is verified by simulation results.

Keywords: Direct Torque Control (DTC), Speed Sensorless Induction Motor (IM) Drive, Space Vector Modulation (SVM), Adaptive Neuro Fuzzy System (ANFIS)

I. INTRODUCTION

DIRECT TORQUE CONTROL (DTC) abandons the stator current control theory, normal for field oriented control (FOC) and accomplishes bangbang torque and motion control by straightforwardly altering the stator voltage in agreement with the torque and transition errors. Along these lines, it shows a decent following for both electromagnetic torque and stator motion [1]. DTC is described by quick unique reaction, basic straightforwardness, what's more, solid power despite parameter vulnerabilities and perbutations.

One of the inconveniences of ordinary DTC is high torque ripple [2]. A few strategies have been produced to decrease the torque ripple. One of them is obligation proportion control strategy. In obligation proportion control, a chose output voltage vector is connected for a segment of one testing period, and a zero voltage vector is connected for whatever remains of the period. The pulse length of output voltage vector can be dictated by a fuzzy logic controller [3]. In [4], torque-ripple least condition amid one examining period is gotten from immediate torque variety condition. The pulse span of output voltage vector is resolved by the torque-ripple least condition. These upgrades can enormously decrease the torque ripple, however they increment the many-sided quality of DTC calculation. An option technique

to lessen the ripples depends on space vector modulation (SVM) strategy[5], [6]. Coordinate torque control in view of space vector modulation (DTC-SVM) save DTC transient benefits, besides, create better quality steady state execution in a wide speed extend. At each cycle period, SVM method is utilized to get the reference voltage space vector to precisely remunerate the motion and torque errors. The torque ripple of DTC-SVM in low speed can be fundamentally progressed. In this paper, SVM-DTC strategy in light of info output linearization control plot for acceptance machine drives is produced. Moreover, a strong full-arrange speed versatile stator transition spectator is intended for a speed sensorless DTC-SVM system what's more, a speed-versatile law is given. The spectator pick up matrix, which is gotten by fathoming straight matrix imbalance, can make strides the vigor of the versatile observer pick up in [7]. The steadiness of the speed versatile stator transition spectator is additionally ensured by the pick up matrix in low speed. The proposed control calculations are confirmed by broad extensive simulation results.

II. DTC-SVM BASED ON INPUT-OUTPUT LINEARIZATION

A. Model of Induction Motor

Under supposition of linearity of the magnetic circuit dismissing the iron misfortune, a three-stage IM show in a stationary axes reference with stator currents and motion are expected as state factors, is communicated by

$$\dot{\iota_D} = -\left(\frac{R_s}{\sigma L_s} + \frac{R_r}{\sigma L_e}\right) i_D - \omega_r i_Q + \frac{R_r \psi_D}{\sigma L_s L_r} + \frac{\omega_r \psi_Q}{\sigma L_s} + \frac{u_D}{\sigma L_s}$$
(1)

$$\dot{\iota_Q} = -\left(\frac{R_a}{\sigma L_s} + \frac{R_r}{\sigma L_e}\right) i_D + \omega_r i_Q + \frac{R_r \psi_Q}{\sigma L_s L_r} - \frac{\omega_r \psi_Q}{\sigma L_s} + \frac{u_D}{\sigma L_s}$$
(2)

$$\dot{\psi_D} = u_D - R_s i_D$$
(3)

$$\dot{\psi_Q} = u_Q - R_s i_Q$$
(4)

where $\psi_D, \psi_Q, u_D, u_Q, i_D, i_Q$ are respectively the **D** –**Q** axes of the stator flux, stator voltage and stator current vector components, is the rotor electrical angular speed, L_s, L_r, L_m are the stator, rotor, and magnetizing inductances, respectively, $\sigma = 1 - \left(\frac{L_m^2}{L_s L_r}\right)$ and R_s, R_r are the stator and rotor resistances, respectively.

The electromagnetic torque in the induction motor can be expressed as

$$T_e = p_n \psi_s \times i_s = p_n (\psi_D i_Q - \psi_Q i_D)$$
(5)

where p_n is the number of pole pairs.

B. DTC-SVM Based on Input-Output Linearization

The DTC-SVM scheme is developed based on the IM torque and the square of stator flux modulus as the system outputs;
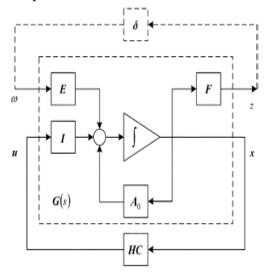

Figure 1. Standard H_∞ design.

stator voltage components defined as system control inputs and stator currents as measurable state variables.

Let the system output be

$$y_1 = T_e = p_n \psi_s \times i_s = p_n (\psi_D i_Q - \psi_Q i_D)$$
(6)

$$y_2 = |\psi_s|^2 = \psi_{ds}^2 + \psi_{qs}^2$$
(7)

Define the controller objectives and as

$$e_1 = T_e - T_{eref}$$
(8)

$$e_2 = \psi_s|^2 - |\psi_{sref}|^2$$
(9)

where , are reference value of electromagnetic torque and stator flux, respectively.

According to (1)–(5), the time derivative of is as (10)

$$\begin{bmatrix} \dot{e_1} \\ \dot{e_2} \end{bmatrix} = \begin{bmatrix} g_1 \\ g_2 \end{bmatrix} + D \begin{bmatrix} u_D^* \\ u_Q^* \end{bmatrix}$$
(10)

where

$$g_1 = p_n[c(\psi_D i_Q - \psi_Q i_D) + \omega_{\text{m}}(\ p_n(\psi_D i_D - \psi_Q i_Q) - \frac{\omega_r}{\sigma L_s} \psi_s|^2]$$

$$g_2 = -2R_s(\psi_D i_Q - \psi_Q i_D)$$

$$D = \begin{bmatrix} (i_Q - \frac{\psi_Q}{\sigma L_s}) & -(i_D - \frac{\psi_D}{\sigma L_s}) \\ 2\psi_D & 2\psi_Q \end{bmatrix}$$

$$C = -(\frac{R_r \psi_D}{\sigma L_s} + \frac{R_r}{\sigma L_r})$$

According to , the characteristic determinant of is as follows:

$$\det(D) = -\frac{4L_m}{\sigma L_r} p_n |\psi_r| . \psi_s \cos(\psi_r, \psi_s) \qquad (11)$$

From (11), is D a nonsingular matrix since the inner product of stator flux vector and rotor flux vector can not be physically zero.

Based on input-output feedback linearization [8], the following control inputs are introduced:

$$\begin{bmatrix} u_D^* \\ u_Q^* \end{bmatrix} = \text{inv}(D) \begin{bmatrix} -g_1 + u_x \\ -g_2 + u_y \end{bmatrix} \qquad (12)$$

where , are the auxiliary control inputs and are defined based on the pole placement concept of the linear control systems so that

$$u_x = -c_1 e_1, \quad u_y = -c_2 e_2 \qquad (13)$$

where c_1 and c_2 are positive constants.

III. SPEED ADAPTIVE STATOR FLUX OBSERVER

A. Speed Adaptive Stator Flux Observer

Using the IM model of (1)–(4), the speed adaptive stator flux observer is introduced:

$$\begin{aligned} \dot{x} &= Ax + BU \\ i_s &= Cx \end{aligned} \qquad (14)$$

Where

$$\mathbf{x} = (i_D\ i_Q\ \psi_D\ \psi_Q)^T, \mathbf{u} = (u_D\ u_Q)^T, \boldsymbol{i}_s = (i_D\ i_Q)^T,$$

$$\mathbf{B} = \begin{bmatrix} \frac{1}{\sigma L_s} \boldsymbol{I}\ \boldsymbol{I} \end{bmatrix}^T, \mathbf{C} = [\mathbf{I}\ 0], \mathbf{I} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \mathbf{J} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix},$$

$$\mathbf{A} = \mathbf{A}_0 + \Delta\mathbf{A}_R + \omega_r \mathbf{A}_w$$

$$= \begin{bmatrix} -(\frac{R_{s0}}{\sigma L_s} + \frac{R_{r0}}{\sigma L_r})\mathbf{I} & \frac{R_{r0}}{\sigma L_s L_r}\mathbf{I} \\ -R_{s0}\mathbf{I} & 0 \end{bmatrix} + \begin{bmatrix} -(\frac{\Delta R_s}{\sigma L_s} + \frac{\Delta R_r}{\sigma L_r})\mathbf{I} & \frac{\Delta R_r}{\sigma L_s L_r}\mathbf{I} \\ -\Delta R_s\mathbf{I} & 0 \end{bmatrix} +$$

$$\omega_r \begin{bmatrix} J & -\frac{1}{\sigma L_s}J \\ 0 & 0 \end{bmatrix}$$

the uncertain parameters in matrix $\mathbf{A}$ are part in two sections; one relating to apparent or steady operation and the second to obscure conduct. R_{s0} and R_{r0} what's more, are apparent estimation of stator protection and rotor protection, ΔR_s and ΔR_r are stator protection what's more, rotor protection vulnerabilities, separately.

The state observer, which estimate the state current and the stator motion together, is given by the accompanying condition

$$\frac{d\hat{x}}{dt} = (\boldsymbol{A}_0 + \Delta \boldsymbol{A}_R + \widehat{\omega}_R A\omega) + \mathbf{B}u + \mathbf{H}(\hat{\imath}_s - i_s) \quad (15)$$

where $\hat{\boldsymbol{x}} = (\widehat{\imath_D}\ \widehat{\imath_Q}\ \widehat{\psi_D}\ \widehat{\psi_Q})^T$ are evaluated estimations of the state variable and $\mathbf{H}$ is the spectator pick up matrix.

Assuming state mistake is $\mathbf{e}$, i.e $\mathbf{e} = \hat{\boldsymbol{x}} - \boldsymbol{x}$

$$\frac{d}{dt}(\mathrm{e}) = \frac{d}{dt}(\widehat{\boldsymbol{x}}) - \frac{d}{dt}(\boldsymbol{x})$$

$$= (\mathbf{A}_0 + \mathbf{HC} + \Delta \boldsymbol{A}_R + \omega_R A\omega)\mathbf{e} + \Delta\omega_r A\omega\widehat{\boldsymbol{x}} \qquad (16)$$

With a specific end goal to determine the versatile plan, Lyapunov hypothesis is used. Presently, let us characterize the accompanying Lyapunov work:

$$V = \mathbf{e}^T\mathbf{e} + (\widehat{\omega}_r - \omega_r)^2/\lambda \qquad (17)$$

The time subordinate of V is as per the following:

$$\frac{d\mathbf{V}}{dt} = \mathbf{e}[(\mathbf{A}_0 + \mathbf{HC} + \Delta \boldsymbol{A}_R + \omega_R A\omega)^T] + (\mathbf{A}_0 + \mathbf{HC} + \Delta \boldsymbol{A}_R + \omega_r A\omega)\mathbf{e} + \Delta\omega_r(\widehat{\boldsymbol{x}}T A_\omega^T \boldsymbol{e} + \mathbf{e}^T A\omega\widehat{\boldsymbol{x}}) + \frac{2}{\lambda}(\widehat{\omega}_r - \omega_r)\frac{d\widehat{\omega}_r}{dt}$$

$$(18)$$

Let

$$\Delta \omega_r(\widehat{\boldsymbol{x}}T A_\omega^T \boldsymbol{e} + \mathbf{e}^T A\omega\widehat{\boldsymbol{x}}) + \frac{2}{\lambda}(\widehat{\omega}_r - \omega_r)\frac{d\widehat{\omega}_r}{dt} = 0 \ (19)$$

in the event that we select observer pick up system with the goal that the validity of the disparity

$$\mathbf{e}^T[(\mathbf{A}_0 + \mathbf{HC} + \Delta \boldsymbol{A}_R + \omega_R A\omega)^T] + (\mathbf{A}_0 + \mathbf{HC} + \Delta \boldsymbol{A}_R + \omega_r A\omega)\mathbf{e}$$
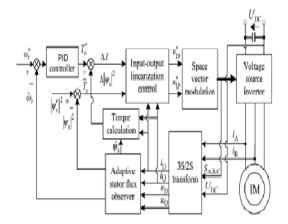$$< 0 \qquad (20)$$

Figure 2. The block diagram of the existing DTC-SVM system.
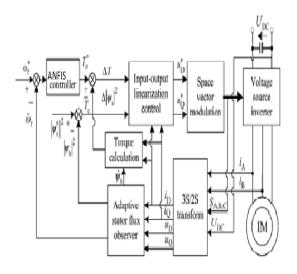
Figure 3. The block diagram of the Proposed DTC-SVM system.

can be ensured, the state observer is steady.

The versatile plan for speed estimation is given by

$$\widehat{\omega r} = \left(K_p + \frac{K_i}{P}\right)(\psi_s^T)\boldsymbol{J}(\widehat{\iota_S} - i_S) \qquad (21)$$

B. Observer Gain Matrix Computation

Let's introduce a theorem about quadratic solidness of vulnerability system before plan the observer pick up matrix.

Lemma: Uncertainty system

$$\dot{x}(t) = \big(\boldsymbol{A}_0 + \Delta\boldsymbol{A}(T)\big)x(t), \quad x(0) = x_0 \qquad (22)$$

is quadratic stable, if and just if is steady and

$$\|f(s\boldsymbol{I} - \boldsymbol{A}_0)^{-1}\boldsymbol{E}\|_\infty < 1 \qquad (23)$$

where is apparent network, which should be well known, is represents to the vulnerabilities on due to unmodeled conduct or parameter float, and are the vulnerability structure networks of the system, is vulnerability coefficient.

On the off chance that is additionally composed as , so system (16) is quadratic stable, if and just if is steady and

$$\|f(s\boldsymbol{I} - \boldsymbol{A}_0 - \omega r\boldsymbol{A\omega} - \mathrm{HC})^{-1}\boldsymbol{E}\|_\infty < 1 \qquad (24)$$

Assuming , K=HC quadratic steadiness issue of system (16) can be changed to static state criticism control H_∞ issue for the system as Figure 1.

A state-space acknowledgment of Figure 1 is as (25)

$$G(s) = \begin{bmatrix} (\boldsymbol{A}_0 + \omega r\boldsymbol{A\omega} & \boldsymbol{E} & \boldsymbol{I} \\ \boldsymbol{F} & 0 & 0 \\ \boldsymbol{I} & 0 & 0 \end{bmatrix} \qquad (25)$$

As system (25), there will be a state criticism controller , if and just if there are certain clear network and to

make straight matrix imbalance (26) is fulfilled

$$\begin{bmatrix} (\boldsymbol{AX} + \boldsymbol{W} + (\boldsymbol{AX} + \boldsymbol{W})^T & \boldsymbol{E} & (\boldsymbol{FX})^T \\ \boldsymbol{E}^T & -\boldsymbol{I} & 0 \\ \boldsymbol{FX} & 0 & -\boldsymbol{I} \end{bmatrix} < 0 \qquad (26)$$

In the $\boldsymbol{X^*}$ **and** $\boldsymbol{W^*}$ event that and is a doable answer for direct system disparity (26), at that point **u**= $\boldsymbol{W^*}$ $(\boldsymbol{X^*})^{-1}$ **x** is a state criticism controller H∞ of system (25). In this way, $\boldsymbol{K} = \boldsymbol{W^*}\,(\boldsymbol{X^*})^{-1}$. The spectator pick up matrix can be acquired from **H=KC⁻¹**.

Table 1. Parameters Of Im

Rated power P(kW)	3
Rated voltage Us(V)	380
Rated current Is(A)	6.8
Rated frequency f(Hz)	50
Magnetic pole pairs pn	2
Rated speed n(r/min)	1420
Stator inductance Ls	0.086
Rotor inductance Lr	0.086
Mutual inductance Lm	0.243
Stator resistance Rs	1.635
Rotor resistance Rr()	1.9
Stator flux linkageψ_s(Wb)	0.8

Extension:

ANFIS Controller: An adaptive neuro-fuzzy inference system or adaptive network-based fuzzy inference system (ANFIS) is a kind of artificial neural network that is based on Takagi–Sugeno fuzzy inference system. The technique was developed in the early 1990s. Since it integrates both neural networks and fuzzy logic principles, it has potential to capture the benefits of both in a single framework. Its inference system corresponds to a set of fuzzy IF–THEN rules that have learning capability to approximate nonlinear functions. Hence, ANFIS is

considered to be a universal estimator. For using the ANFIS in a more efficient and optimal way, one can use the best parameters obtained by genetic algorithm.
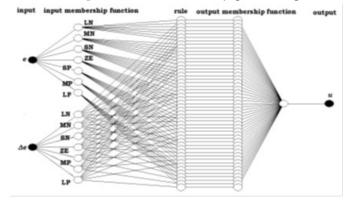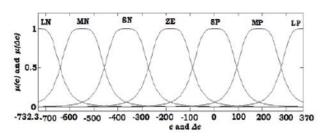

Figure 4. The network of ANFIS controller

Figure 5. Membership functions for error and change in error.
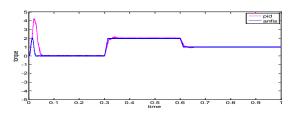
IV. SIMULATION RESULTS

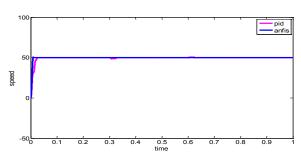**Figure 6.** Torque response curve of Proposed and Extension.

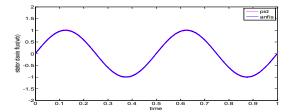**Figure 7.** Speed response curve of Proposed and Extension.

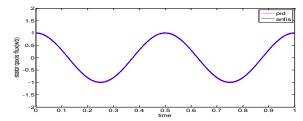**Figure 8.** D-axes stator flux curve.
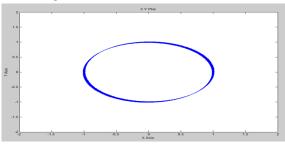

Figure 9. Q-axes stator flux curve.

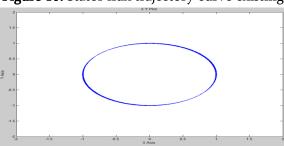**Figure 10.** Stator flux trajectory curve existing
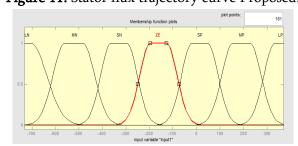

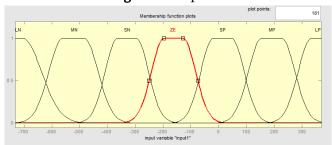**Figure 11.** Stator flux trajectory curve Proposed.
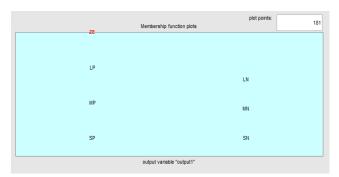

Figure 12. Input 1

Figure 13. Input 2

Figure 14. Output

Table 2. Rules Of Anfis

c/ce	LN	MN	SN	ZE	SP	MP	LP
LN	LN	LN	MN	MN	SN	SN	ZE
MN	LN	MN	MN	MN	SN	ZE	SP
SN	LN	MN	SN	SN	ZE	SP	MP
ZE	LN	MN	SN	ZE	SP	MP	LP
PS	MN	SN	ZE	SP	SP	MP	LP
MP	SN	ZE	SP	ZE	SP	MP	MP
LP	LP	ZE	SP	MP	LP	LP	LP

Table 3. Comparison For Controllers

PARAMETER	PID(%)	ANFIS PI(%)
FLUX	3.502	0.8
TORQUE	3.1523	2.5

V. CONCLUSION

A novel DTC-SVM plot has been produced for the IM drive system, which is on the premise of info output linearization   control. In this control strategy, a SVPWM inverter is utilized to bolster the engine, the stator voltage vector is gotten to completely adjust the stator motion and torque errors. Besides, a robust full-arrange versatile motion spectator is intended for a speed sensorless DTC-SVM system. The stator motion and speed are evaluated synchronously. By planning the consistent observer pick up network in light of state criticism control hypothesis, the heartiness and soundness of the observer systems is guaranteed. Accordingly, the proposed sensorless drive system is able to do consistently working in low speed, has significantly littler torque ripple and shows great dynamic and enduring state execution.

In future replacing ANFIS controller with FUZZY-PI will exhibits better performance of the system.

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