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A Comparative Study of Flux Observers in Induction Motors

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Abstract— *In this paper, a comparison of three rotor flux estimation techniques for the three-phase induction motor is presented. Three types of observers are suggested to be compared for flux estimation, open-loop flux observer, nonlinear flux observer, and sliding mode flux observer. These observers are compared according to their, simplicity of design, implementation, and convergence rate of estimated flux to the actual value. The three-phase induction motor model is derived according to the basis of nonlinear control tools. The reference frame theory is assessed and the importance of the relationship among these reference frames is clarified in accordance with the estimated flux. The three observers are designed and the stability analysis is assessed according to the Lyapunov stability analysis. Matlab has been used to simulate the three-phase induction motor in an open loop configuration with the three observers. Sliding mode flux observer was faster than the two others observers, open-loop flux observer was the simplest one with the less robust characteristics, nonlinear flux observer showed controllable convergence rate with simple observer structure. Theoretical hypothesises are confirmed through the observations simulation results comparisons in the stationary and synchronous reference frames.*

Index Terms— *Induction motor, Flux observer, Field orientation, Sliding mode observer.*

I. INTRODUCTION

The three-phase induction motor is a widely used electrical machine in various industrial applications due to its simplicity, robustness, and cost-effectiveness. It operates based on electromagnetic induction and consists of a stator (stationary part) and a rotor (rotating part). Stator windings are connected in groups of equally distributed sets of three windings sets, these windings have 120◦ phase shifts among each other, which are supplied by balanced three-phase voltage. The three-phase induction motor has a big importance in industrial applications due to its multi-use and multi-operation conditions. It occupies the role of "workhorse" in the industrial applications, with the aim of a reliability and cost-effectiveness solutions for all tasks [1]. Regarding its rigid design, simple construction, and low maintenance requirements make it a valuable solution for heavy-duty operations of manufacturing, mining, pumping, and transportation. With the development of modern control theory and the integration of variable frequency drives, three-phase induction motors have become even more multi-purpose use, enabling efficient speed control and improved energy savings [2].

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Speed control methods for machines based on AC drives and specifically the three-phase induction motors can be classified into various categories based on their role principles and difficulty. The first speed control method is the variable frequency voltage (V/F) control method, where the motor speed is managed by regulating the magnitude and frequency of the supplied voltage. (V/F) control is easy to implement but may not result precise low speed control. A higher level speed control method include vector control or field orientation control (FOC), is a highly complicated technique that provides speed precision and torque control by decoupling between the direct and quadrature stator current components. choosing the speed control method relays on the facts of the required speed range, speed accuracy, efficiency, and how far the needed application require a sophisticated control algorithm [3].

Vector control, or as it is famous as field-oriented control (FOC), is a highly complicated and widely used control technique for AC drives of electric machines. Precise control of motor flux and speed/torque achieved independently using vector control, owing to the decoupled characteristics like a separately excited DC motor. In field orientation control, the rotating reference frame of the rotor flux will considered the reference frame that stator currents are aligned with. Hence the torque components of the currents and fluxes will be decoupled, which gives outstanding performance even in dynamic conditions. By flawlessly controlling the rotor magnetic flux, field orientation assures efficient utilization of power, decreased losses, and improved motor efficiency. It also enables precise and smooth running along a broad speed range, making it perfect for industrial applications demanding variable speed control. One of the major advantages of field orientation is its capability to handle a high torque at low angular speeds, which is necessary for applications demanding a large starting torque, such as beltline drives and elevators. With the development of microprocessors and microcontrollers and drive electronics, field orientation has become a widely used control technique in AC motor drives, giving best performance, smooth operation, and energy efficiency, making it an advanced industrial automation and AC motor control systems[4, 5].

Three-phase induction motors field orientation are basically two approaches, to attain decoupled control of magnetic flux and torque, named direct and indirect field orientations. In one hand, for direct field orientation (DFOC), also famous as rotor field orientation, the reference frame is aligned with the rotor flux space vector. By manipulating the quadrature axes current components to be aligned with the rotor flux space vector reference frame, the speed and flux can be controlled independently. This method requires precise and simultaneously knowledge of the rotor flux components either by measuring the magnetic flux in the air gap or by estimate it by some sort of observer. In the other hand, indirect field orientation (IFOC), also regarded as stator field orientation, projects the components of the others variables reference frame with the stator flux space vector. The stator currents quadrature axes are controlled in the aligned stator reference frame to get isolated speed and flux control. Indirect field orientation is simpler compared to direct field orientation in implementation and have little lower performance capabilities never the less indirect field orientation not requires a flux measuring or observation. Both the DFOC and IFOC are employed in AC motor drives for industrial applications [6].

Direct field orientation control of three-phase induction motors cannot be achieved without a flux observer. However, since the rotor flux is difficult to be measured, it can be estimated by a flux observer. The widely used observer in DFOC is based on modern control theory such as the Nonlinear Observer and the Sliding Mode Observer (SMO). These observers use the motor's measurable state variable, such as stator currents and

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control variables which are the stator voltages to capture the rotor flux space vector angular position and magnitude estimation. The estimated flux information is then used to calculate the appropriate control signals required for achieving the desired torque and speed regulation. Flux observers are critical in achieving accurate and robust DFO control, even in the presence of parameter variations and disturbances. Their ability to estimate the immeasurable rotor flux helps enhance the performance and efficiency of the three-phase induction motor drive system, making them indispensable components in advanced motor control strategies [7].

Following, some relevant and recent works, devoted for the flux observer design of three phase induction motor, are briefly interviewed. In [8] suggestion to use the Artificial Neural Network (ANN) to estimate the flux vector based on open loop flux observer. Both Standard Kalman Filter (SKF) and Extended Kalman Filter (EKF) for estimating stator current, rotor flux are used in [9]. Luenberger observer with fuzzy logic adaptation mechanism flux observer has been tested in [10]. Adaptive nonlinear observer augmented with radial basis neural network assessed in [11] to get the flux modulus estimation. SOSM super-twisting flux observer based on current model and state transformation has been adopted in [12]. Slip command compensation for IFOC has been assessed in [13, 14] where flux estimation is replaced by commanded slip angle. Sliding mode flux observer with adaptive mechanism has been adopted in [15]. High order sliding mode observer is used for rotor flux estimation in [16]. Nonlinear Luenberger like flux observer has been tested in [17]. double- surface sliding mode flux observer aggregated in [18]. Open loop flux observer has been implemented using neuro-fuzzy platform in [19]. Adaptive asymptotic second order differentiator based on super twisting flux observer has employed in [20]. Adaptive fuzzy sliding mode flux observer has been tested in [21]. From all the related literature reviewed above, the focus has been applied to one or two flux observers in the same category.

The problem of this paper floats on the surface of the literature due to, the difficulty of induction motor flux measurement. So direct field orientation control of three-phase induction motors cannot be achieved without a flux observer. In this work, three different flux observers with different characteristics have been assessed and designed for a three-phase induction motor in the stationary reference frame. Both explicit state variables and state transformation have been used in the considered flux observers.

This paper are highly motivated by the recent studies in precise position and speed control of recent contributions of robust adaptive control theory presented by [22-25] with these mainly concerned with nonlinear control and observers design [4, 22, 25-30]

The main contributions of this paper are to design and compare three flux observers for the three phase induction motor according to the following objectives:

1. Design the open loop flux observer and assess the stability analysis and convergence rate.
2. Design the Nonlinear Luenberger flux observer and assess the stability analysis and convergence rate according to state variables transformation.
3. Design the sliding mode flux observer and assess the stability analysis and convergence rate according to state variables transformation.
4. Compare the three designed flux observers and assess the advantages and disadvantages by simulations.

In addition to this section, the rest of the paper comes with: Section two, the derivation of the dynamic model of the Induction motor, Section three, the flux observers design based on Lyapunov stability analysis, section four discuss the simulation results and finally Section five, comes with the conclusions.

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II. MATHEMATICAL MODEL OF INDUCTION MOTOR

Three phase Induction motor consist of mechanical system driven by an electrical system. The mathematical model of the electrical system is based on cooperation of Lenz and Faraday's laws for electromagnetic relationships with Kirchhoff's law of voltages summation of electric circuits[1].

$$\begin{aligned} \dot{\psi}_{s1} &= -R_s i_{s1} + v_{s1} \quad , \quad \dot{\psi}_{r1} = -R_r i_{r1} + v_{r1} \\ \dot{\psi}_{s2} &= -R_s i_{s2} + v_{s2} \quad , \quad \dot{\psi}_{r2} = -R_r i_{r2} + v_{r2} \\ \dot{\psi}_{s3} &= -R_s i_{s3} + v_{s3} \quad , \quad \dot{\psi}_{r3} = -R_r i_{r3} + v_{r3} \end{aligned} \tag{1}$$

Where R_s R_r represent the stator and rotor windings resistance respectively, v_s, v_r represents the stator and rotor voltages, i_s, i_r represent the stator and rotor currents, while $\dot{\psi}_s, \dot{\psi}_r$ represent the flux change of the stator and rotor windings, the subscript *1,2,3* represent the phases of the three phase system.

Seeking to simplicity of representation of the model Clarke transformation will be adopted to represent the Electrical system. Clarke transformation represents the three phase quantities by a two rotating space vectors according to the following transformation.

$$f_{ab0} = T_c f_{123} \tag{2}$$

Where T_c represent the Clarke transformation, f_{123} represent any set of induction motor variable such as currents or voltages or flux in three phase stationary reference frame and f_{ab0} represent the related transformed set of induction motor variable of f_{123} in stationary orthogonal reference frame. Hence, the electrical system can be written as a four equations instead of six. Also the model will be mentioned to be the stationary reference with stator point of view for the stator variables and with rotor point of view for the rotor ones. Zero space vectors will be omitted according to the assumption of balanced stator windings and rotor windings. The electrical system then can be written as[5]:

$$\begin{aligned} \dot{\psi}_{sa} &= -R_s i_{sa} + v_{sa} \\ \dot{\psi}_{sb} &= -R_s i_{sb} + v_{sb} \\ \dot{\psi}'_{ra} &= -R_r i'_{ra} \\ \dot{\psi}'_{ra} &= -R_r i'_{ra} \end{aligned} \tag{3}$$

The mechanical system is derived according to the Newton's second law of motion as:

$$\dot{\omega} = \frac{1}{J}(\tau_e - \tau_l) \tag{4}$$

$$\dot{\theta} = \omega \tag{5}$$

Where ω represents the rotor angular speed, τ_e represents the generated electro mechanical torque, τ_l represents the load torque, and θ represents the rotor angular position.

The point of view of the stationary reference frame due to the sinusoidal nature of all the voltages and the currents must be unified to the stator. For that purpose another transformation will be employed, named Park's transformation which is as:

$$\begin{bmatrix} f_a \\ f_b \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} f'_a \\ f'_b \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} \psi_{ra} \\ \psi_{rb} \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} \psi'_{ra} \\ \psi'_{rb} \end{bmatrix} \tag{7}$$

Also for simplifying the model of the Induction motor and describe the generated electromechanical torque the relationships of both the stator and rotor flux linkages must be used as:

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$$\begin{aligned} \psi_{sa} &= ls\, i_{sa} + lm\, i_{ra} \\ \psi_{sb} &= ls\, i_{sb} + lm\, i_{rb} \\ \psi_{ra} &= lr\, i_{ra} + lm\, i_{sa} \\ \psi_{rb} &= lr\, i_{rb} + lm\, i_{sb} \end{aligned} \tag{8}$$

Where ls represents the stator self-inductance, lr represents the rotor self inductance, and lm represents the mutual inductance due interference of the stator and rotor fluxes.

By mathematical manipulations the overall system dynamics of induction motor can be described in (a,b) stationary reference frame, with respect to considering the state variables of ($i_{sa}, i_{sb}, \psi_{ra}$, ψ_{rb}, ω) ,as

$$\begin{aligned} \dot{i_{sa}} &= -\gamma i_{sa} + \beta\alpha\, \psi_{ra} + \beta\omega\, \psi_{rb} + v_{sa}/\sigma \\ \dot{i_{sb}} &= -\gamma i_{sb} + \beta\alpha\, \psi_{rb} - \beta\omega\, \psi_{ra} + v_{sb}/\sigma \\ \dot{\psi}_{ra} &= -\alpha\, \psi_{ra} - \omega\, \psi_{rb} + \alpha l_m i_{sa} \\ \dot{\psi}_{rb} &= -\alpha\, \psi_{rb} + \omega\, \psi_{ra} + \alpha l_m i_{sb} \\ \dot{\omega} &= \mu\, (i_{sb}\, \psi_{ra} - i_{sa}\, \psi_{rb}) - \tau_l/J \end{aligned} \tag{9}$$

Where $\sigma = l_s - {l_m}^2/l_r$, $\alpha = R_r/l_r, \beta = l_m/l_r\sigma, \gamma = \frac{R_s}{\sigma} + \beta\alpha l_m$ and $\mu = 2Pl_m/3l_rJ.$

For the rest of the paper, the stator and rotor indices in state variables will be omitted for convenience and the model in the final form will be as:

$$\begin{aligned} \dot{i_a} &= -\gamma i_a + \beta\alpha\, \psi_a + \beta\omega\, \psi_b + v_{sa}/\sigma \\ \dot{i_b} &= -\gamma i_b + \beta\alpha\, \psi_b - \beta\omega\, \psi_a + v_{sb}/\sigma \\ \dot{\psi}_a &= -\alpha\, \psi_a - \omega\, \psi_b + \alpha l_m i_a \\ \dot{\psi}_b &= -\alpha\, \psi_b + \omega\, \psi_a + \alpha l_m i_b \\ \dot{\omega} &= \mu\, (i_b\, \psi_a - i_a\, \psi_b) - \tau_l/J \end{aligned} \tag{10}$$

III. OBSERVERS DESIGN

Field orientation is a tool among many tools used to assess the control of electrical machines. Three phase Induction motor speed and torque control require a decoupling method to separate the torque equation from the current space vectors interference. Direct and indirect field orientations are the main two techniques of field orientation where each technique has a various configurations. In direct field orientation the flux must be controlled hence, it must be either measured by a Hall Effect sensor or it may be observed using some kind of observer[5]. *Fig.1* illustrate the direct field orientation, this paper concerns in comparing a three types of the flux observers red shaded area of the figure.

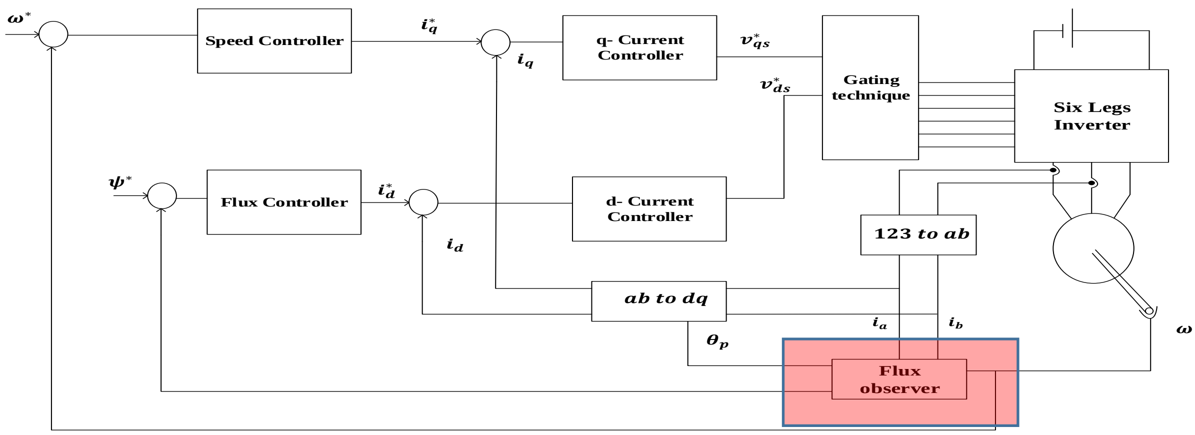

FIG. 1. DIRECT FIELD ORIENTATION BASED ON FLUX OBSERVER.

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Regarding the Park's transformation of equation(6) which is used in transforming the three phase induction motor from one reference frame to another, the transformation to the synchronous d-q reference frame is done according to:

$$\begin{bmatrix} f_d \\ f_q \end{bmatrix} = \begin{bmatrix} \cos(\theta_f) & \sin(\theta_f) \\ -\sin(\theta_f) & \cos(\theta_f) \end{bmatrix} \begin{bmatrix} f_a \\ f_b \end{bmatrix} \quad (11)$$

Where $f_{a,b}$ represent any variable in the stationary reference frame like the voltages, currents, and fluxes; while, $f_{a,b}$ represent the same variables transformed in the synchronous reference frame; finally θ_f represents the angular position of the Flux modules, where considering the two rotor flux components the flux can be represented by the magnitude of the two flux components and the angle of the resultant flux vector as:

$$\psi_t = \sqrt[2]{\psi_a^2 + \psi_b^2} \quad (12)$$

$$\theta_f = \tan^{-1}\frac{\psi_b}{\psi_a} \quad (13)$$

Now, the benefit of designing the flux observer is to calculating the flux angle as:

$$\hat{\theta}_f = \tan^{-1}\frac{\hat{\psi}_b}{\hat{\psi}_a} \quad (14)$$

And then transforming the required variables to the synchronous frame as in equation by replacing the angle θ_f by its estimate $\hat{\theta}_f$.

A. Open loop Flux Observer

First observer will be considered is an open loop observer where it is just a simulation of rotor flux dynamics, hence estimation convergence cannot be adjusted and it depends on the rotor constant α [5]. The observer will take the form of

$$\dot{\hat{\psi}}_a = -\alpha\,\hat{\psi}_a - \omega\,\hat{\psi}_b + \alpha l_m i_a \quad (15)$$

$$\dot{\hat{\psi}}_b = -\alpha\,\hat{\psi}_b + \omega\,\hat{\psi}_a + \alpha l_m i_b \quad (16)$$

Where $\hat{\psi}_a$ and $\hat{\psi}_b$ represent a and b components of rotor flux estimation in fixed reference frame. Also, stator currents and rotor angular speed are considered as measured variables. Let estimation error defined for both flux variables as

$$\bar{\psi}_a = \psi_a - \hat{\psi}_a$$

$$\bar{\psi}_b = \psi_b - \hat{\psi}_b$$

Hence the estimation error dynamics will be:

$$\dot{\bar{\psi}}_a = \dot{\psi}_a - \dot{\hat{\psi}}_a$$

$$\Rightarrow \dot{\bar{\psi}}_a = -\alpha\,\psi_a - \omega\,\psi_b + \alpha l_m i_a + \alpha\,\hat{\psi}_a + \omega\,\hat{\psi}_b - \alpha l_m i_a$$

$$\Rightarrow \dot{\bar{\psi}}_a = -\alpha\,\bar{\psi}_a - \omega\,\bar{\psi}_b \quad (17)$$

Similarly

$$\dot{\bar{\psi}}_b = \dot{\psi}_b - \dot{\hat{\psi}}_b$$

$$\Rightarrow \dot{\bar{\psi}}_b = -\alpha\,\bar{\psi}_b + \omega\,\bar{\psi}_a \quad (18)$$

Now to test the convergence stability by choosing the following Lyapunov candidate

$$V(\bar{\psi}_a, \bar{\psi}_b) = \frac{1}{2}\|\bar{\psi}\|^2 \quad (19)$$

Where $\|\bar{\psi}\| = \sqrt{\bar{\psi}_a^2 + \bar{\psi}_b^2}$ then the derivative of Lyapunov candidate will be

$$\dot{V} = \bar{\psi}_a\dot{\bar{\psi}}_a + \bar{\psi}_b\,\dot{\bar{\psi}}_b$$

$$\Rightarrow \dot{V} = \bar{\psi}_a(-\alpha\,\bar{\psi}_a - \omega\,\bar{\psi}_b) + \bar{\psi}_b\,(-\alpha\,\bar{\psi}_b + \omega\,\bar{\psi}_a)$$

$$\Rightarrow \dot{V} = -\alpha\,(\bar{\psi}_a^2 + \bar{\psi}_b^2)$$

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$$\Rightarrow \dot{V} = -\alpha V$$
$$\Rightarrow V = V_0 e^{-\alpha t} \quad (20)$$

And that means $\|\bar{\psi}\| \to 0$ exponentially with convergence rate of α. It is nessary to mention that the convergance rate of the estimation error are fixed, and for adjustable convergence rate anew observer synthesis will be adopted.

B. Adjustable convergence rate Nonlinear observer

High speed control requirements demand a fast estimation convergence to perform speed control. In order to achieve fast estimation, or specifically an adjustable convergence of estimation error, for rotor flux components the following flux observer synthesis is suggested [31]

$$\dot{\hat{\psi}}_a = -\alpha\, \hat{\psi}_a - \omega\, \hat{\psi}_b + \alpha l_m i_a - L_a \quad (21)$$
$$\dot{\hat{\psi}}_b = -\alpha\, \hat{\psi}_b + \omega\, \hat{\psi}_a + \alpha l_m i_b - L_b \quad (22)$$

Where L_a, L_b are flux functions defined later. Let flux estimation error defied as

$$\bar{\psi}_a = \psi_a - \hat{\psi}_a$$
$$\bar{\psi}_b = \psi_b - \hat{\psi}_b$$
$$\Rightarrow \dot{\bar{\psi}}_a = -\alpha\, \bar{\psi}_a - \omega\, \bar{\psi}_b + L_a \quad (23)$$

And similarly

$$\dot{\bar{\psi}}_b = -\alpha\, \bar{\psi}_b + \omega\, \bar{\psi}_a + L_b \quad (24)$$

Now if $L_a = c_1\beta\dot{\bar{\psi}}_a$ and $L_b = c_1\beta\dot{\bar{\psi}}_b$ where $c_1 > 0 \in R$ is design parameter, then,

$$\dot{\bar{\psi}}_a = -\alpha\, \bar{\psi}_a - \omega\, \bar{\psi}_b + c_1\beta\dot{\bar{\psi}}_a$$
$$\Rightarrow \dot{\bar{\psi}}_a = \frac{-\alpha}{1-c_1\beta}\, \bar{\psi}_a - \frac{\omega}{1-c_1\beta}\, \bar{\psi}_b \quad (25)$$

And similarly

$$\dot{\bar{\psi}}_b = \frac{-\alpha}{1-c_1\beta}\, \bar{\psi}_b + \frac{\omega}{1-c_1\beta}\, \bar{\psi}_a \quad (26)$$

Now the same Lyapunov candidate of equation 19 are considered as

$$V(\bar{\psi}_a, \bar{\psi}_b) = \frac{1}{2}\|\bar{\psi}\|^2 \quad (27)$$

Thus, Lyapunov derivative will be

$$\dot{V} = \bar{\psi}_a\left(\frac{-\alpha}{1-c_1\beta}\, \bar{\psi}_a - \frac{\omega}{1-c_1\beta}\, \bar{\psi}_b\right) + \bar{\psi}_b\left(\frac{-\alpha}{1-c_1\beta}\, \bar{\psi}_b + \frac{\omega}{1-c_1\beta}\, \bar{\psi}_a\right)$$
$$\Rightarrow \dot{V} = \frac{-\alpha}{1-c_1\beta}\,(\bar{\psi}_a^2 + \bar{\psi}_b^2)$$
$$\Rightarrow \dot{V} = \frac{-\alpha}{1-c_1\beta}\, V$$
$$\Rightarrow V = V_0 e^{\frac{-\alpha}{1-c_1\beta}t} \quad (28)$$

And that means $\|\bar{\psi}\| \to 0$ exponentially with convergence rate of $\frac{-\alpha}{1-c_1\beta}$ which is can be adjusted (increased) by changing the parameter $c_1$where $1 - c_1\beta$ must not equel zero.

To that point the achieved result are satisfying, as a controlled exponential convergence, but it is worthy to mention that L_a and L_b are depending on $\dot{\bar{\psi}}_a$ and $\dot{\bar{\psi}}_b$ and by the means of the rotor flux are not available for measurement so the following variation for the observer dynamics will be proposed to get the same results.

Let $\hat{\psi}_a = ci_a + z_a$ and $\hat{\psi}_b = ci_b + z_b$ where z_a and z_b are auxilary variable that will represent the auxilary observer dynamics and $c > 0 \in R$ are design parameter. Then the estimation error can be redefined as

$$\bar{\psi}_a = \psi_a - ci_a - z_a \quad (29)$$

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$$\bar{\psi}_b = \psi_b - ci_b - z_b \tag{30}$$

Hence the estimation error dynamics will be

$$\dot{\bar{\psi}}_a = \dot{\psi}_a - c\dot{i}_a - \dot{z}_a$$

$$\dot{\bar{\psi}}_a = -\alpha\,\psi_a - \omega\,\psi_b + \alpha l_m i_a - c(-\gamma i_a + \beta\alpha\,\psi_a + \beta\omega\,\psi_b + \frac{v_{sa}}{\sigma}) - \dot{z}_a$$

$$\Rightarrow \dot{\bar{\psi}}_a = -\alpha\,\psi_a - \omega\,\psi_b + \alpha l_m i_a - c(-\gamma i_a + \beta\alpha\,\psi_a + \beta\omega\,\psi_b + \frac{v_{sa}}{\sigma}) - \dot{z}_a$$

$$\Rightarrow \dot{\bar{\psi}}_a = -\alpha(1 + c\beta)\,\psi_a - \omega(1 + c\beta)\,\psi_b + (\alpha l_m + c\gamma)i_a - \frac{c}{\sigma}v_{sa} - \dot{z}_a \tag{31}$$

If $\dot{z}_a$ is chosen as

$$\dot{z}_a = -\alpha(1 + c\beta)\,\hat{\psi}_a - \omega(1 + c\beta)\,\hat{\psi}_b + (\alpha l_m + c\gamma)i_a - \frac{c}{\sigma}v_{sa} \tag{32}$$

Then the estimation error dynamics will be

$$\dot{\bar{\psi}}_a = -\alpha(1 + c\beta)\,\bar{\psi}_a - \omega(1 + c\beta)\,\bar{\psi}_b \tag{33}$$

Similarly

$$\dot{z}_b = -\alpha(1 + c\beta)\hat{\psi}_b + \omega(1 + c\beta)\,\hat{\psi}_a + (\alpha l_m + c\gamma)i_b - \frac{c}{\sigma}v_{sb} \tag{34}$$

And then

$$\dot{\bar{\psi}}_b = -\alpha(1 + c\beta)\bar{\psi}_b + \omega(1 + c\beta)\,\bar{\psi}_a \tag{35}$$

Lyapunov candidate of equation (27) and it's derivative will indicate the following

$$\dot{V} = \bar{\psi}_a(-\alpha(1 + c\beta)\,\bar{\psi}_a - \omega(1 + c\beta)\,\bar{\psi}_b) + \bar{\psi}_b\,(-\alpha(1 + c\beta)\,\bar{\psi}_b + \omega(1 + c\beta)\,\bar{\psi}_a)$$

$$\Rightarrow \dot{V} = -\alpha(1 + c\beta)\,(\bar{\psi}_a^2 + \bar{\psi}_b^2)$$

$$\Rightarrow \dot{V} = -\alpha(1 + c\beta)\,V$$

$$\Rightarrow V = V_0 e^{-\alpha(1+c\beta)t} \tag{36}$$

Again that means $\|\bar{\psi}\| \to 0$ exponentially with convergence rate of $-\alpha(1 + c\beta)$. For summery, the rotor flux components estimations are gotten from

$$\dot{z}_a = -\alpha(1 + c\beta)\,\hat{\psi}_a - \omega(1 + c\beta)\,\hat{\psi}_b + (\alpha l_m + c\gamma)i_a - \frac{c}{\sigma}v_{sa} \tag{37}$$

$$\dot{z}_b = -\alpha(1 + c\beta)\hat{\psi}_b + \omega(1 + c\beta)\,\hat{\psi}_a + (\alpha l_m + c\gamma)i_b - \frac{c}{\sigma}v_{sb} \tag{38}$$

where $\hat{\psi}_a = ci_a + z_a$ and $\hat{\psi}_b = ci_b + z_b$. Extra requirements are needed in this observer compared to the open loop observer where stator voltages are must feed to the observer dynamics.

C. Sliding mode flux observer

Considering the induction motor model as a nonlinear model yields to the Walcott-Zak sliding mode observer. The common feature of sliding mode observer is to create a finite time sub dynamics to take the benefit of equivalent control principle of sliding mode to make the desired state estimation error converge to the zero exponentially with pre-specified convergence rate[32]. The proposed observer will take the form of [33]

$$\dot{\hat{\psi}}_a = -\alpha\,\hat{\psi}_a - \omega\,\hat{\psi}_b + \alpha l_m i_a + kE_a \tag{39}$$

$$\dot{\hat{\psi}}_b = -\alpha\,\hat{\psi}_b + \omega\,\hat{\psi}_a + \alpha l_m i_b + kE_a \tag{40}$$

$$\dot{\hat{i}}_a = -\gamma\hat{i}_a + \beta\alpha\,\hat{\psi}_a + \beta\omega\,\hat{\psi}_b + \frac{v_{sa}}{\sigma} + E_a \tag{41}$$

$$\dot{\hat{i}}_b = -\gamma\hat{i}_b + \beta\alpha\,\hat{\psi}_b - \beta\omega\,\hat{\psi}_a + \frac{v_{sb}}{\sigma} + E_b \tag{42}$$

Where $k > 0 \in R$ is design parameter, $E_a = E_0\,sgn(\bar{i}_a) = E_0\,sgn(\hat{i}_a - i_a)$ and $E_b = E_0\,sgn(\bar{i}_b) = E_0\,sgn(\hat{i}_b - i_b)$ where $E_0 > o \in R$ is also a design parameter, and stator current estimation error for a and b components are $\bar{i}_a, \bar{i}_b$ and their dynamic behaviour will be as

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$$\dot{\bar{i_a}} = \dot{\hat{i_a}} - \dot{i_a} = -\gamma\hat{i_a} + \beta\alpha\,\hat{\psi}_a + \beta\omega\,\hat{\psi}_b + \frac{v_{sa}}{\sigma} + E_a - (-\gamma i_a + \beta\alpha\,\psi_a + \beta\omega\,\psi_b + \frac{v_{sa}}{\sigma})$$

$$\Rightarrow \dot{\bar{i_a}} = -\gamma\bar{i_a} + \beta\alpha\,\bar{\psi}_a + \beta\omega\,\bar{\psi}_b + E_a \quad (43)$$

And similarly

$$\dot{\bar{i_b}} = -\gamma\bar{i_b} + \beta\alpha\,\bar{\psi}_b + \beta\omega\,\bar{\psi}_a + E_b \quad (44)$$

Let

$$V_1(\bar{i_a}, \bar{i_b}) = \frac{1}{2}\left(\bar{i_a}^2 + \bar{i_b}^2\right) \quad (45)$$

$$\dot{V_1} = \bar{i_a}\dot{\bar{i_a}} + \bar{i_b}\dot{\bar{i_b}} = \bar{i_a}(-\gamma\bar{i_a} + \beta\alpha\,\bar{\psi}_a + \beta\omega\,\bar{\psi}_b + E_a) + \bar{i_b}(-\gamma\bar{i_b} + \beta\alpha\,\bar{\psi}_b + \beta\omega\,\bar{\psi}_a + E_b)$$

$$\Rightarrow \dot{V_1} = -\gamma\left(\bar{i_a}^2 + \bar{i_b}^2\right) - E_0\,sgn(\bar{i_a})\bar{i_a} - E_0\,sgn(\bar{i_b})\bar{i_b} + \bar{i_a}(\beta\alpha\,\bar{\psi}_a + \beta\omega\,\bar{\psi}_b) + \bar{i_b}(\beta\alpha\,\bar{\psi}_b + \beta\omega\,\bar{\psi}_a)$$

$\because\ sgn(\bar{i_a})\bar{i_a} = |\bar{i_a}|\,, sgn(\bar{i_b})\bar{i_b} = |\bar{i_b}|$ and let $f_1 = \bar{i_a}(\beta\alpha\,\bar{\psi}_a + \beta\omega\,\bar{\psi}_b)$ also $f_2 = \bar{i_b}(\beta\alpha\,\bar{\psi}_b + \beta\omega\,\bar{\psi}_a)$

$$\Rightarrow \dot{V_1} = -\gamma\left(\bar{i_a}^2 + \bar{i_b}^2\right) - |\bar{i_a}|\,(E_0 - |f_1|) - -|\bar{i_b}|\,(E_0 - |f_2|)$$

$$\Rightarrow \dot{V} < 0\ \ \forall\, E_0 > \max[|f_1|, |f_2|] \quad (46)$$

And sliding motion will occur on $\bar{i_a} = 0\,, \bar{i_b} = 0$ (finite time convergence). During sliding motion the equivalent control principle will be activated, and that's mean

$E_a = E_{a\,eq.}, E_b = E_{b\,eq.}$ And $\bar{i_a} = \dot{\bar{i_a}} = 0\,, \bar{i_b} = \dot{\bar{i_b}} = 0$ where that lead to,

$$0 = \beta\alpha\,\bar{\psi}_a + \beta\omega\,\bar{\psi}_b + E_{a\,eq} \Rightarrow E_{a\,eq} = -\beta\alpha\,\bar{\psi}_a - \beta\omega\,\bar{\psi}_b \quad (47)$$

$$0 = \beta\alpha\,\bar{\psi}_b - \beta\omega\,\bar{\psi}_a + E_{b\,eq} \Rightarrow E_{b\,eq} = -\beta\alpha\,\bar{\psi}_b + \beta\omega\,\bar{\psi}_a \quad (48)$$

By substituting that result in equations 39, 40 of flux estimation

$$\dot{\hat{\psi}}_a = -\alpha\,\hat{\psi}_a - \omega\,\hat{\psi}_b + \alpha l_m i_a + kE_{a\,eq} = -\alpha\,\hat{\psi}_a - \omega\,\hat{\psi}_b + \alpha l_m i_a - k\beta\alpha\,\bar{\psi}_a - k\beta\omega\,\bar{\psi}_b$$

$$\dot{\hat{\psi}}_b = -\alpha\,\hat{\psi}_b + \omega\,\hat{\psi}_a + \alpha l_m i_b + kE_{b\,eq} = -\alpha\,\hat{\psi}_b + \omega\,\hat{\psi}_a + \alpha l_m i_b - k\beta\alpha\,\bar{\psi}_b + k\beta\omega\,\bar{\psi}_a$$

and flux estimation error dynamics will be :

$$\Rightarrow \dot{\bar{\psi}}_a = -\alpha(1 + k\beta)\,\bar{\psi}_a - \omega\,(1 + k\beta)\bar{\psi}_b \quad (49)$$

$$\Rightarrow \dot{\bar{\psi}}_b = -\alpha(1 + k\beta)\bar{\psi}_b + \omega\,(1 + k\beta)\bar{\psi}_a \quad (50)$$

Now for the assessment of flux estimation error convergence *Lyapunov* candidate of equations 19 and 27 also will be used as $V_2(\bar{\psi}_a, \bar{\psi}_b) = \frac{1}{2}\|\bar{\psi}\|^2$

$$\dot{V_2} = \bar{\psi}_a(-\alpha(1 + k\beta)\,\bar{\psi}_a - \omega(1 + k\beta)\,\bar{\psi}_b) + \bar{\psi}_b\,(-\alpha(1 + k\beta)\,\bar{\psi}_b + \omega(1 + k\beta)\,\bar{\psi}_a)$$

$$\Rightarrow \dot{V} = -\alpha(1 + k\beta)\,(\bar{\psi}_a^2 + \bar{\psi}_b^2)$$

$$\Rightarrow \dot{V} = -2\alpha(1 + k\beta)\,V$$

$$\Rightarrow V = V_0 e^{-2\alpha(1+k\beta)t} \quad (51)$$

And that means $\bar{\psi}_a \longrightarrow 0\,,\ \bar{\psi}_b \longrightarrow 0$ exponantially.

IV. SIMULATION RESULTS

The Induction motor model and the observers are simulated using MATLAB/SIMULINK environment. The running parameters of Induction motor are listed in Table (1), also the design parameters of each observers which adopted to give the same convergence are listed in Table. I The considered Induction model parameters represents an academic platform used in [34].

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TABLE I. INDUCTION MOTOR PARAMETERS AND OBSERVERS DESIGN PARAMETERS

Parameter	Value and unit	Parameter	Value and unit	Design Parameter	Value
R_s	5.3 Ω	R_r	3.3 Ω	c	25
l_s	0.365 H	l_r	0.375 H	k	12.5
l_m	0.34 H	J	0.0075 Kgm^2	E_0	10^4

Applied three phase voltage was of amplitude 12 Volts with 25 Hz frequency to mimic steady reference speed of 82 Rad/sec. *Fig 2* shows the applied three phase voltage where 120 degree of phase shift among each phase and the others phases. A clear view to the three phase voltage is as in *Fig. 3* where it is zoomed.

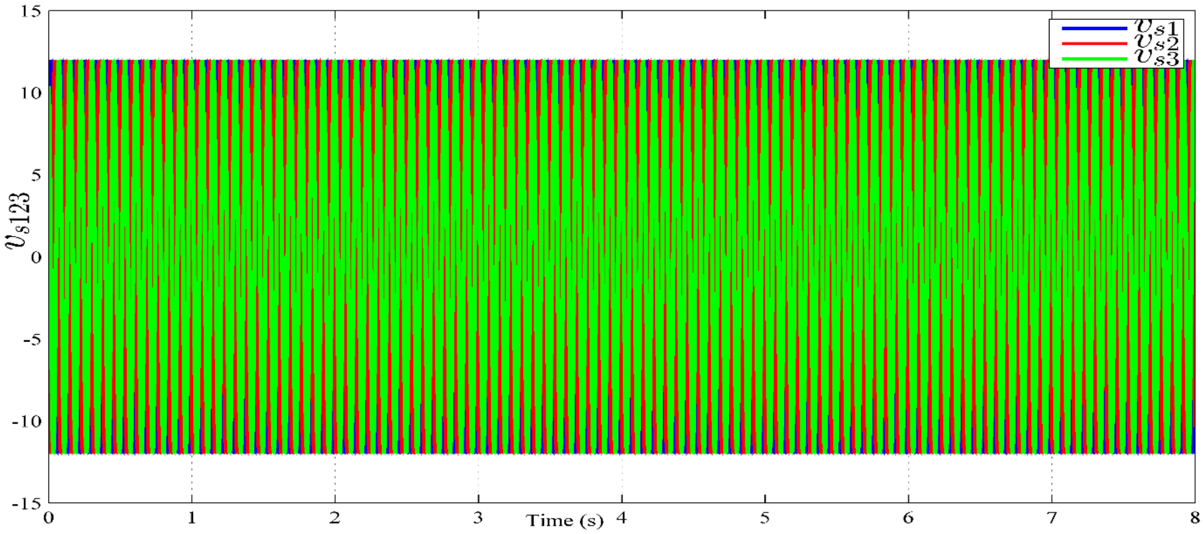

FIG. 2. APPLIED THREE PHASE VOLTAGE.

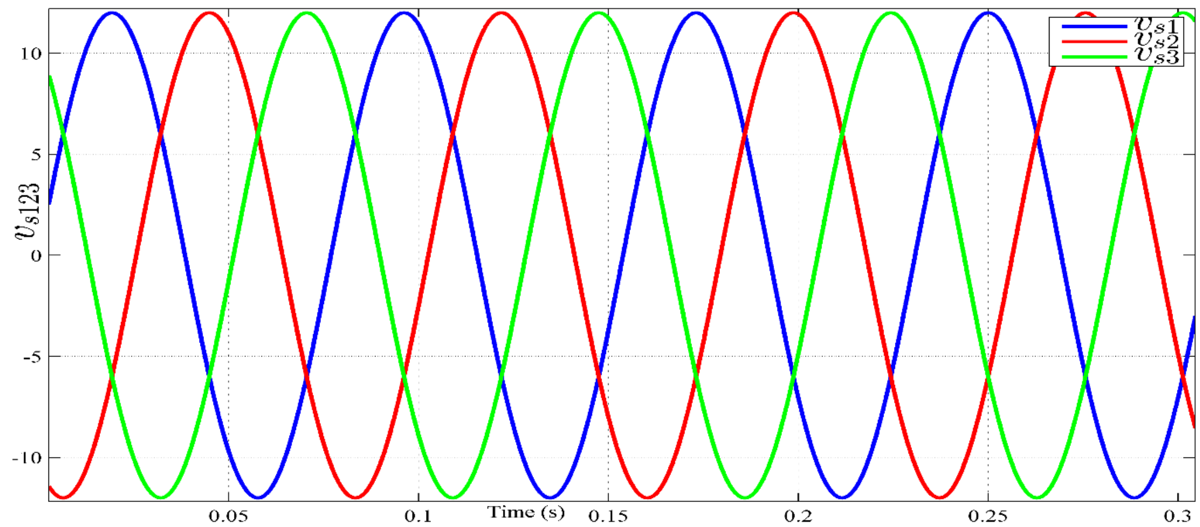

FIG. 3. APPLIED THREE PHASE VOLTAGE (ZOOMED).

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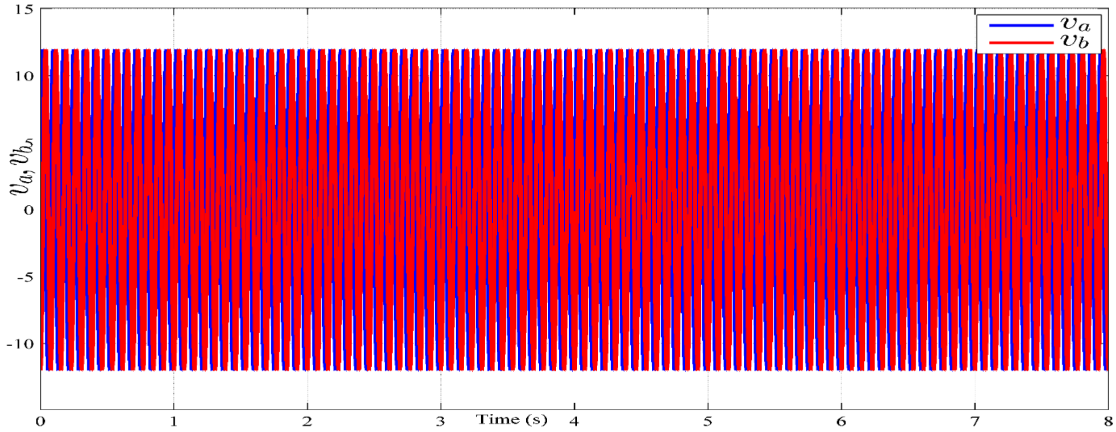

FIG. 4. STATOR VOLTAGES IN STATIONARY REFERENCE FRAME.

Clarke transformation on stator voltages are showed in *Fig. 4* where the phase shift is 90 degree between the a-component and b-component. *Fig 5* shows the stator currents in the stationary reference frame where it is clear that starting currents is high then the currents goes to the steady state. *Fig. 6* shows the rotor angular speed.

The most important figures to this work comes from *Fig. 7* where it shows the actual A-axis flux in the stationary reference frame plotted with it estimations of each of the three observers, due to the oscillatory nature of the flux in the stationary reference frame the performance statement is not clear in *fig 7*. Hence, a zoomed version of the A-axis flux (black dash-dotted line) transient is showed for assessment in *Fig. 8;* the open loop observer (green dashed line) converges due to the rotor constant of the motor and so its estimate convergence cannot be controlled and regardless of it is simplicity it has slow convergence; nonlinear flux observer (red line) is a mimic to the famous linear Luenberger observer based on change of coordinates, the convergence is arbitrary and can be controlled to any exponential convergence, so it faster than the open loop observer; Sliding mode observer (blue dashed line) has faster convergence rate than the open loop observer and the nonlinear observer. The same analysis is done to the B-axis flux (black dash-dotted line) in stationary reference frame as in *fig 9* and *10*, a zoomed version of the B-axis flux transient is showed for assessment in *Fig 10*; the open loop observer (green dashed line) converges slowly compared to the others observers; nonlinear flux observer (red line) is faster than the open loop observer; Sliding mode observer (blue dashed line) has faster convergence rate than the open loop observer and the nonlinear observer.

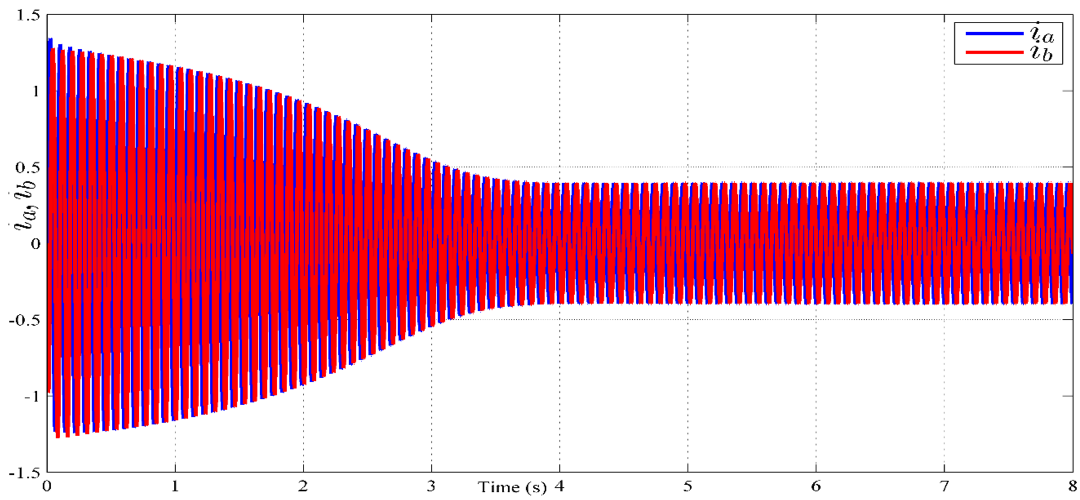

FIG. 5. STATOR CURRENTS.

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Using the flux estimates to calculate the rotor synchronously rotating magnetic field according to the equation (14) and by employing the Parks transformation the a,b stationary coordinates will transformed to the d,q coordinates where the field orientation achieved for control the torque or the angular speed and flux. The transformed flux based on the assumption of all the flux of the stationary reference frame will aligned with the d-axis of the synchronous reference frame and the q-axis flux will be zero. *Fig.11* shows the d-axis flux (black dash-dotted line) and its estimates according to the three observers, the zoomed window shows the oscillation of the sliding mode observer estimate with slightly small bound around the actual flux due to using the discontinuous injection and chattering phenomena effects on the observations. *Fig. 12* is a zoom in to the transient of the d-axis flux and its estimates, the convergence of the estimates to the actual value will be from the slower to the faster as; the open loop observer was the slower on the comes the nonlinear observer and the faster one was the sliding mode observer. According to the visual inspection, the performance and convergence metrics of the three observers is listed in the table II.

TABLE II. FLUX OBSERVERS METRICS

Parameter	**Settling time**			**Steady state oscillation**
	ψ_a	ψ_b	ψ_d	
Open loop observer	0.355 sec	0.3 sec	0.5 sec	-
Nonlinear observer	0.1 sec	0.08 sec	0.1 sec	-
Sliding mode observer	0.05 sec	0.03 sec	0.05 sec	∓ 0.0002

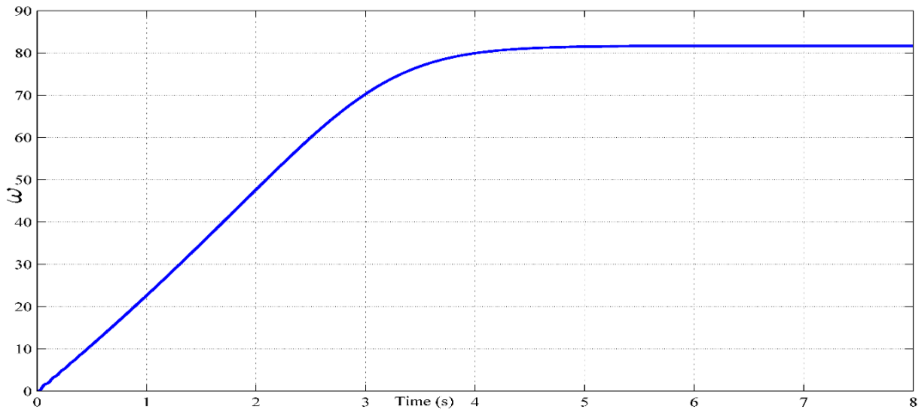

FIG. 6. ROTOR ANGULAR SPEED.

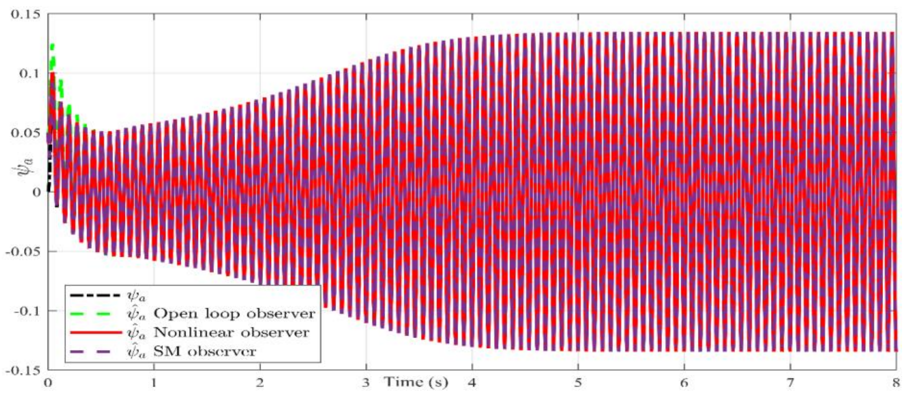

FIG.7. ROTOR FLUX OF A-AXIS IN STATIONARY REFERENCE FRAME.

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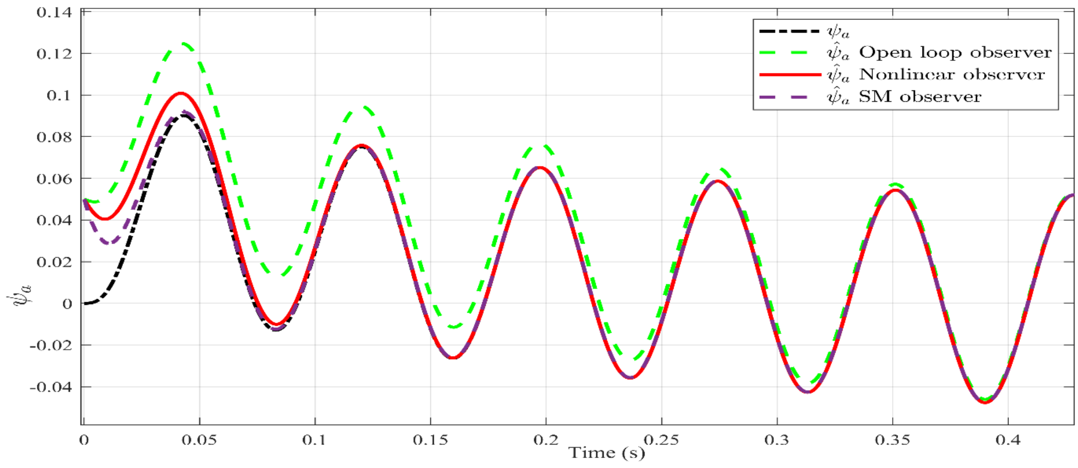

FIG. 8. ROTOR FLUX OF A-AXIS IN STATIONARY REFERENCE FRAME (ZOOMED).

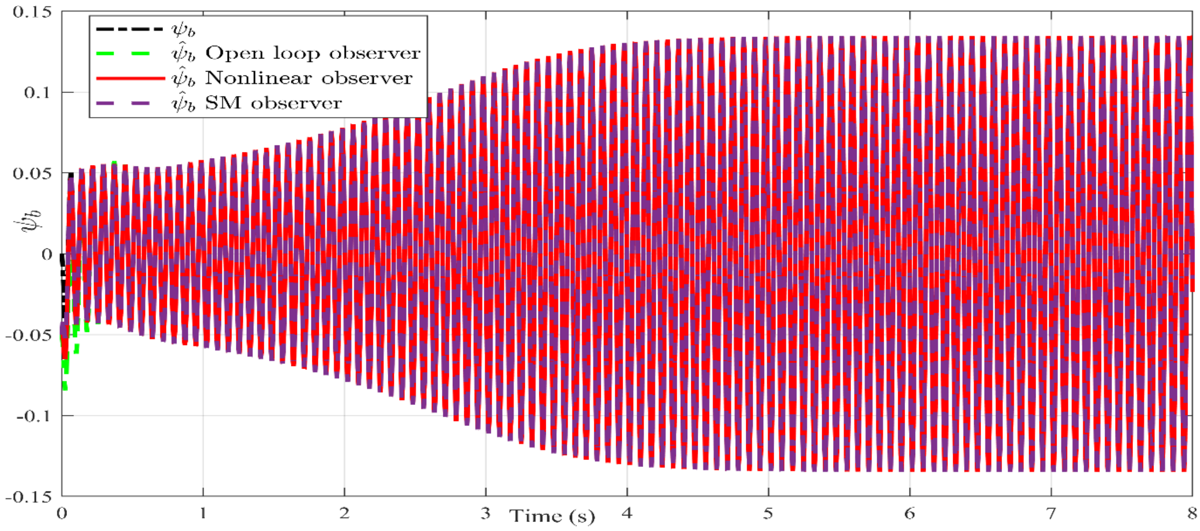

FIG. 9. ROTOR FLUX OF B AXIS IN STATIONARY REFERENCE FRAME.

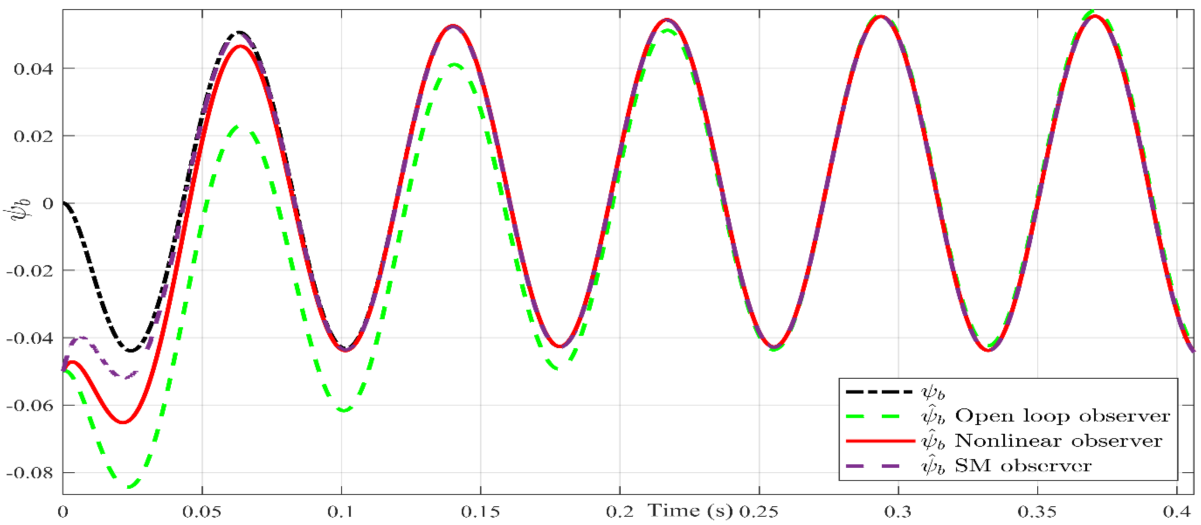

FIG. 10. ROTOR FLUX OF B AXIS IN STATIONARY REFERENCE FRAME (ZOOMED).

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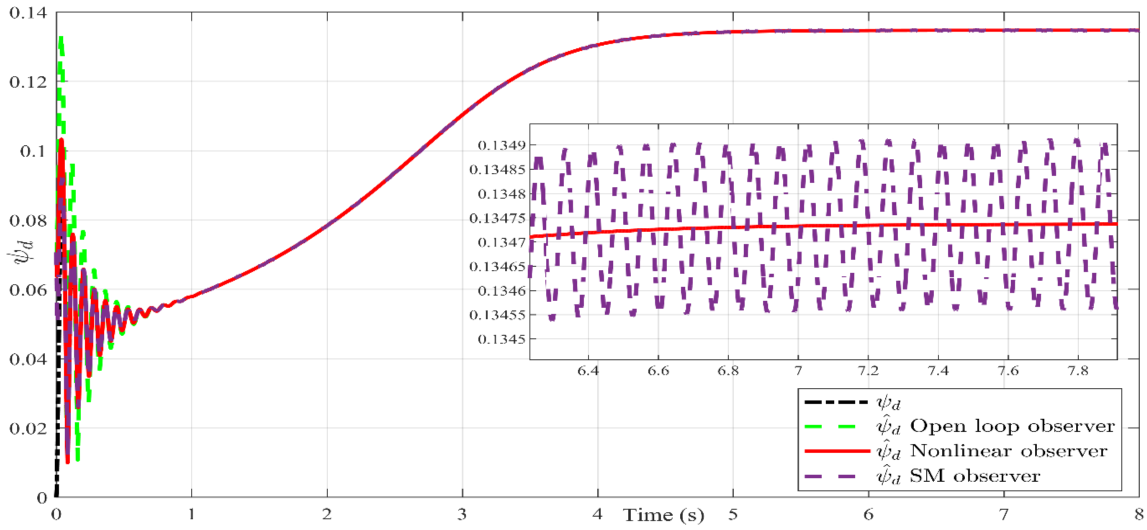

FIG. 11. ROTOR FLUX OF D AXIS IN SYNCHRONOUS REFERENCE FRAME.

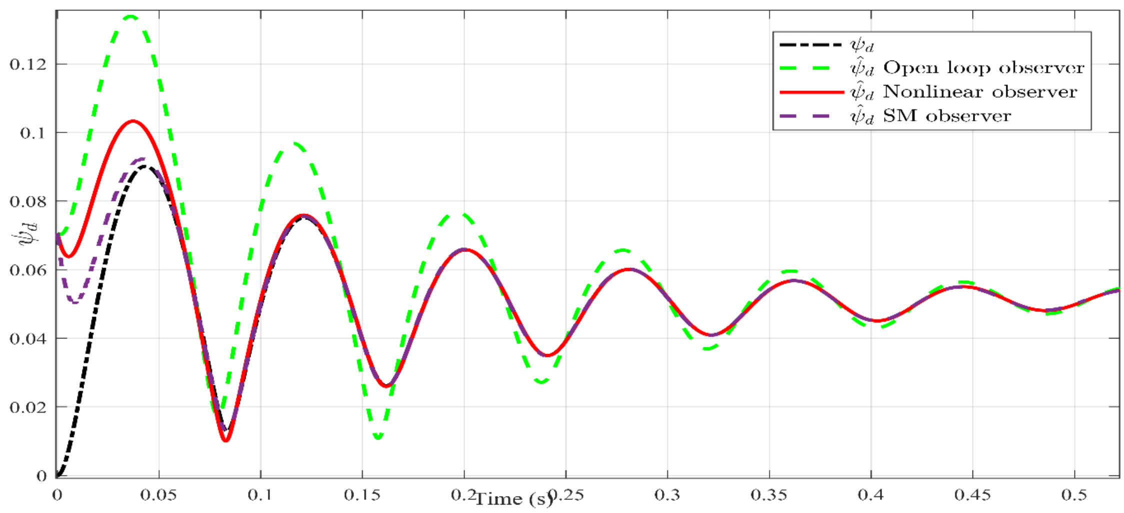

FIG. 12. ROTOR FLUX OF D AXIS IN SYNCHRONOUS REFERENCE FRAME (ZOOMED).

V. CONCLUSIONS

This paper has achieved a comparison of rotor flux estimation of a three-phase induction motor based on three types of observers. The three observers to be compared for flux estimation are named, open loop flux observer, nonlinear flux observer, and sliding mode flux observer. These observers have been compared according to their simplicity of design, implementation, and convergence rate of estimated flux to the actual value. Matlab has been used to simulate the three-phase induction motor in an open loop (steady speed reference) configuration with the three observers. Open loop flux observer was the simplest observer but lacks the estimation convergence speed, also its convergence speed cannot be controlled. Nonlinear flux observer based on state transformation is faster than the open loop. Sliding mode flux observer give the fastest convergence rate of the three observers, for the steady state it has been noticed an

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oscillation in the synchronous rotating reference frame d-flux is due to the chattering phenomena and equivalent control effect.

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