

PAPER 114 – DISTURBANCE OBSERVER FOR HARMONIC SUPPRESSION OF A Z-SOURCE INVERTER FED THREE-PHASE INDUCTION MOTOR DRIVE

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ABSTRACT

To minimize the detrimental effects of the pulse-width modulated (PWM) voltage and harmonics of a non-linear load, a second-order inductor-capacitor (LC) low-pass smoothing filter is usually added between the inverter and the drive. However, the output voltage drop via the filter inductor and resonance frequency effects are taken into consideration while designing the filters, as a result, baseband harmonics, which make up the majority of the harmonics produced by the frequency converter, are not completely removed. This paper proposes a control system for an impedance source inverter (ZSI)-driven three-phase induction motor drive to minimize AC-side voltage and current harmonics. The control system uses an observer-based output feedback servomechanism controller designed using linear quadratic techniques and linear matrix inequalities, which ensures closed-loop stability and asymptotic tracking regulation regardless of disturbances. A speed adaptation mechanism is added to the observer to enable speed-sensorless operation. The controller is evaluated using several MATLAB/Simulink simulations, which demonstrate perfect tracking, good disturbance rejection, and low voltage and current total harmonic distortions (THD).

KEYWORDS: Linear Matrix Inequality, Induction Motor, Robust Servomechanism, Observer, Harmonics, Stability

1. INTRODUCTION

Estimation techniques such as Extended Kalman Filter (EKF) and Unscented Kalman Filter (UKF) are used to replace measuring signals in a drive system equipped with an LC filter (Akin et al., 2003; Janiszewski, 2012), the observer with disturbance estimation developed for a continuous system can also be implemented in a discrete system. However, there are some significant differences between the two. In a discrete system, the observer frequency response is heavily dependent on the adopted reference system. It is noteworthy that state variables are computed in a stationary reference frame for observers with disturbance estimation, the variables that are estimated by the discrete observer in the stationary $\alpha\beta$ reference frame have larger errors than variables estimated by the observer calculated as a continuous system (Rothenhagen & Fuchs, 2007). To minimize this large error, an observer with a convex optimization is developed. The convex optimization allows the observer to consider both the state variables and the disturbance estimates. By using the convex optimization, the observer can estimate the state variables more accurately and with less error than a traditional discrete observer. Additionally, the convex optimization can be used to improve the accuracy of the disturbance estimates. In order to improve the performance of the induction motor drive, this paper proposes the use of robust servomechanism control combined with a disturbance observer based on linear matrix inequalities optimization to detect and compensate for external disturbances, which is a challenging task due to its non-linearities. Low order harmonics have been successfully eliminated for linear time invariant systems using the robust servomechanism controller (Karimi-Ghartemani & Karimi, 2021; Marwali & Keyhani, 2004), which combines the internal model principle and the optimal control theory. However, results for nonlinear load systems were not at acceptable THD levels, and their configuration necessitates mounting the induction motor on the transformer which makes the system complex and overparameterized. There was also a robust servo controller design method for AC induction motor speed control using polynomial differential operator (D. H. Kim et al., 2017), which outperformed standard PI controllers; however, obtaining those nominal values for induction motors may be impossible due to the system being linearized at an equilibrium point on which the accuracy of the linear time-invariant model developed is heavily reliant.

This paper proposes a discrete-time state-space machine model to robustly control an induction motor drive and update the time-varying rotor speed term every sampling time. It also proposes to develop a disturbance observer based on linear matrix inequalities to detect and compensate for external disturbances. The proposed design approach will be tested on a 2.2 kW three-phase induction motor, with the only measurements being the dc-link voltage and the inverter output current. The results will be compared to existing control methods for accuracy of tracking, robustness, harmonic distortion, and system stability.

2. THEORETICAL ANALYSIS

For the simplicity of modeling, the AC- and DC-sides of the circuit are considered separately, and the converter is assumed to operate in continuous conduction mode (CCM).

2.1 System Model for the AC Side.

The inverse Γ -model (Slemon, 1989), a commonly used and somewhat accurate compromise, was chosen for use in this study. It is an accurate representation that does not involve the complex mathematics of the other models, yet still provides a reasonable representation of the machine's performance. The AC side of the system is represented in fig.1 and the state space equations of the system are given as follows:

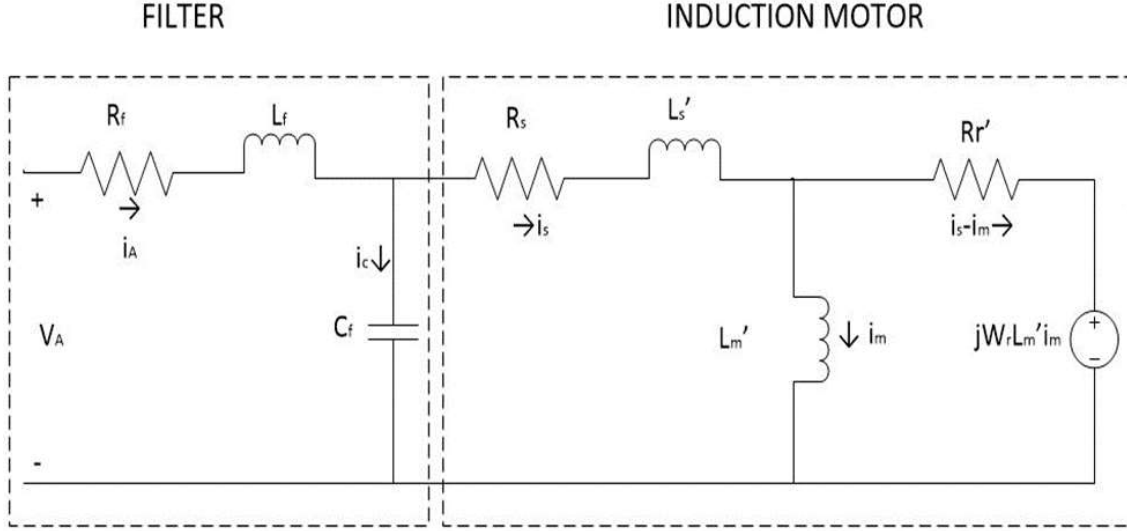


Fig.1. An equivalent circuit of the Inverse Γ model of the Induction Motor connected to an Inverter Output LC filter in a $(\alpha - \beta)$ stationary reference frame.

Where (Rasmussen, 2002);

$$L_s = L_m + L_{ls}, \quad L_r = L_m + L_{lr}, \quad \varphi_s = L_s i_s + L_m i_r, \quad \varphi_r = L_m i_s + L_r i_r, \quad \sigma = 1 - \frac{L_m^2}{L_s L_r}, \quad R_r' = (L_m / L_r)^2 R_r,$$

$$L_s' = \sigma L_s, \quad L_m' = (1 - \sigma) L_s, \quad \varphi_r = L_m i_m, \quad T_r = L_r / R_r, \quad \text{Sig}_m = \sigma L_s L_r / L_m, \quad J = [0 \ -1; 1 \ 0]$$

With States as: $(i_{A\alpha}, i_{A\beta}, V_{s\alpha}, V_{s\beta}, i_{s\alpha}, i_{s\beta}, \varphi_{r\alpha}, \varphi_{r\beta})$ and input, $U = V_A, y = i_A$

Taking Kirchhoff's Current Law (KCL) and Kirchhoff's Voltage Law (KVL) around the loops of fig.1, the open loop state space model can be formed:

$$A_p = \begin{bmatrix} \frac{-R_f}{L_f} I_{2 \times 2} & \frac{1}{L_f} I_{2 \times 2} & 0_{2 \times 2} & 0_{2 \times 2} \\ \frac{1}{C_f} I_{2 \times 2} & 0_{2 \times 2} & \frac{-1}{C_f} I_{2 \times 2} & 0_{2 \times 2} \\ 0_{2 \times 2} & a_4 I_{2 \times 2} & a_1 I_{2 \times 2} & a_2 I_{2 \times 2} - a_3 W_r J \\ 0_{2 \times 2} & 0_{2 \times 2} & a_6 I_{2 \times 2} & -a_5 I_{2 \times 2} + W_r J \end{bmatrix}$$

$$\text{Where } a_1 = \frac{-(R_s + \frac{L_m^2 R_r}{L_r^2})}{\sigma L_s}, \quad a_2 = \frac{1}{\text{Sig}_m} \left(\frac{1}{T_r} \right), \quad a_3 = \frac{1}{\text{Sig}_m}, \quad a_4 = \frac{1}{\sigma L_s}, \quad a_5 = \frac{1}{T_r}, \quad a_6 = \frac{L_m}{T_r}$$

$$B_p = \left[\frac{1}{L_f} I_{2 \times 2} \ 0_{2 \times 2} \ 0_{2 \times 2} \ 0_{2 \times 2} \right]^T,$$

$$C_p = [I_{2 \times 2} \ 0_{2 \times 2} \ 0_{2 \times 2} \ 0_{2 \times 2}],$$

$$D_p = [0_{2 \times 2}], \text{ where } I_n \text{ denotes an } n \text{ dimensional identity matrix.}$$

Taking away the varying part of the state matrix, which is updated at each sampling time, A_p is further divided into

linear time-invariant A , and linear time varying matrices A_w .

$$A = \begin{bmatrix} \frac{-R_f}{L_f} I_{2 \times 2} & \frac{1}{L_f} I_{2 \times 2} & 0_{2 \times 2} & 0_{2 \times 2} \\ \frac{1}{C_f} I_{2 \times 2} & 0_{2 \times 2} & \frac{-1}{C_f} I_{2 \times 2} & 0_{2 \times 2} \\ 0_{2 \times 2} & a_4 I_{2 \times 2} & a_1 I_{2 \times 2} & a_2 I_{2 \times 2} \\ 0_{2 \times 2} & 0_{2 \times 2} & a_6 I_{2 \times 2} & -a_5 I_{2 \times 2} \end{bmatrix}, \quad A_w = \begin{bmatrix} 0_{2 \times 2} & 0_{2 \times 2} & 0_{2 \times 2} & 0_{2 \times 2} \\ 0_{2 \times 2} & 0_{2 \times 2} & 0_{2 \times 2} & 0_{2 \times 2} \\ 0_{2 \times 2} & 0_{2 \times 2} & 0_{2 \times 2} & -a_3 W_r J \\ 0_{2 \times 2} & 0_{2 \times 2} & 0_{2 \times 2} & W_r J \end{bmatrix}$$

Which yields

$$\begin{aligned} x &= (A + w_r A_w)x_p + B_p u & (1) \\ y(k) &= C_p x_p + D_p & (2) \end{aligned}$$

2.2 Plant Discretization

The system equations generated from (1) to (2) is not stabilizable and detectable under continuous mode except it is scaled, hence the need to operate in discrete mode. Explicit (forward) Euler method of discretization which helps the fast discretization of the varying part of A matrix at every sampling interval is used (Kullick & Hackl, 2018; Unbehauen, 2009).

2.3 Robust Servomechanism Controller

The controller has two parts: a servo-compensator which ensures the asymptotic tracking of the reference signals in the presence of disturbances, and a stabilizing compensator which must, as its name suggests, stabilize the augmented model with the dynamics of the servo-compensator. The stabilizing compensator selected is a linear quadratic (LQ) optimal state feedback to which an observer is added in order to dispense with additional sensors and estimate the immeasurable states.

2.3.1 Servo-compensator

Keyhani & Marwali, (2012), clearly outlined principles of this approach as follows. If the tracking/disturbance poles to be considered are $\pm j\omega_1$, $\pm j\omega_5$, and $\pm j\omega_7$, etc., where $f = 50\text{hz}$, $\omega_1 = 2\pi \times 50 \text{ rad/s}$, $\omega_5 = 5\omega_1$, and $\omega_7 = 7\omega_1$, etc., the servo-compensator is represented as,

$$\dot{\eta} = A_c \eta + B_c e \quad (3)$$

Where $e = V_{ref,\alpha\beta} - V_{s,\alpha\beta}$ is the estimated load voltage tracking error;

$$\eta = [\eta_1 \ \eta_2 \ \dots \ \eta_i]^T, \quad i = 1, 2, \dots, n$$

$$A_c = \text{block diag}[A_{c1}, A_{c2}, \dots, A_{cn}]$$

$$B_c = [B_{c1}, B_{c2}, \dots, B_{cn}]^T$$

$$\text{With } A_{ci} = \begin{pmatrix} \vec{0}_{2 \times 2} & \vec{I}_{2 \times 2} \\ -w_i^2 \vec{I}_{2 \times 2} & \vec{0}_{2 \times 2} \end{pmatrix}$$

$$B_{ci} = (\vec{0}_{2 \times 2} \ \vec{I}_{2 \times 2})^T$$

Which depicts the continuous transfer function, $1/(s^2 + w_i^2)$ representation in a state space.

2.3.2 Observer - Stabilizing Compensator

The stabilizing compensator is, however, not unique (Davison & Ferguson, 1981); there are various classes of stabilizing compensators that can be used in a robust servomechanism controller. One of them, adopted is the observer-based stabilizing compensator. This type of compensator uses an observer to estimate the system states \hat{x}_p , both available and unavailable and then uses the estimated states to design a stabilizing compensator.

The stabilizing compensator may be formed in the presence of the servo compensator by augmenting the system matrices of both the plant (1&2) and the servo-compensator (3), which is expressed as,

$$\begin{aligned} \begin{bmatrix} \dot{X} \\ \dot{\eta} \end{bmatrix} &= \begin{bmatrix} (A + w_r A_w) & 0 \\ -B_c C_p & A_c \end{bmatrix} \begin{bmatrix} X \\ \eta \end{bmatrix} + \begin{bmatrix} B_p \\ -B_c D_p \end{bmatrix} u, \\ \begin{bmatrix} Y_m \\ \eta \end{bmatrix} &= \begin{bmatrix} C_m & 0 \\ 0 & I \end{bmatrix} \begin{bmatrix} X \\ \eta \end{bmatrix} + \begin{bmatrix} D_m \\ 0 \end{bmatrix} u \end{aligned} \quad (4)$$

The stabilizing compensator, with the control signal,

$$u = K_0 \hat{x}_p + K_1 \eta = [K_0 \ K_1] \check{x} = K \check{x} \quad (5)$$

ensures the stability of the augmented model, via a feedback gain K that minimizes the linear quadratic performance index (i.e., the optimization criterion) in (6).

$$J_\epsilon = \sum_{k=0}^{\infty} \left(z(k)' Q z(k) + \mu(k)' R \mu(k) \right) \quad (6)$$

Consequently, the feedback gain K is obtained from Matlab function dlqr (),
Now, consider a load torque which causes disturbance to the motor speed and in turn cause the inverter to generate more voltage or current in order to maintain the desired motor speed, (1) – (2) can be re-written in the discrete form as follows considering the input as disturbance:

$$\begin{aligned} \dot{x}_p(k+1) &= A_d x_p(k) + B_{d1} w(k) \\ y(k) &= C_{d2} x_p(k) \end{aligned} \quad (7)$$

where $x \in R^n$ and is the state vector, $A \in R^{n \times n}$ and is the state matrix, $B \in R^{n \times r}$ and is the input matrix, $w \in R^r$ and is the exogenous input, $C \in R^{m \times n}$ and is the output matrix, $y \in R^m$, and it is assumed that (A_d, C_{d2}) is detectable.

A Luenberger observer of the form is to be designed (Caverly & Forbes, 2019):

$$\begin{aligned} \dot{\hat{x}}_p(k+1) &= A_d \hat{x}_p(k) + L_d (y(k) - \hat{y}(k)) \\ \hat{y}(k) &= C_{d2} \hat{x}_p(k) \end{aligned} \quad (8)$$

The gain L_d is determined by minimizing standard H_2 (or H_∞) norm of the transfer function between e and w_k while also stabilizing the dynamics of the estimate error, and ensuring the sub-system $T(z)$ (11) meets the requirements for disturbance attenuation performance.

The error state is defined as:

$$e(k) = x_p(k) - \hat{x}_p(k) \quad (9)$$

The error dynamics is derived as,

$$\dot{e}(k) = (A_d - L_d C_{d2}) e(k) + B_{d1} w(k) \quad (10)$$

The observer gain, L_d is to be designed in such a way that the H_2 norm provided by the transfer function (11) of the input $w(k)$, on the output e , to minimize model deviation and the effect of the disturbance $w(k)$ to the estimated error.

$$T(z) = (ZI - (A_d - L_d C_{d2}))^{-1} B_{d1} \quad (11)$$

This amounts to solving an optimization problem whose constraints are formulated using Linear Matrix Inequalities (LMIs), if there exist a symmetric matrix X and a matrix Y satisfying the transfer function (11) which is equivalent to minimizing $J(\gamma) = \gamma^2$ subject to (Caverly & Forbes, 2019; Duan & Yu, 2013)

$$[A_d^T X + A_d X + C_{d2} Y + Y^T C_{d2} + I_8] < 0 \quad (12)$$

$$\begin{bmatrix} -Z & X B_{d1}^T \\ X B_{d1} & -X \end{bmatrix} < 0 \quad (13)$$

$$\text{trace}(Z) < \gamma^2 \quad (14)$$

Where $C_{d2}^T = C_{d2}^{-1}$ is a special case of congruence transformation., It is desired to stabilize the poles of the observer matrix $(A_d - L_d C_{d21})$ in a vertical strip region defined by $\mathbb{D} = \mathbb{H}_{\alpha, \beta} = \{z = x + iy: \alpha < x < \beta \mid z \in \mathbb{C}^{-\infty} \cap \mathbb{C}^{\beta}, \alpha < \text{Re}(z) < \beta\}$, where \mathbb{D} is the open unitary disk centered at the origin (Marx et al., 2003), where $J_{H_2}(L_d) = \|T(z)\|_2$ is minimized, the resulting constraints are:

$$X A_d + Y C_{d2} + (X A_d + Y C_{d2})^T + 2\alpha X < 0 \quad (15)$$

$$X A_d + Y C_{d2} + (X A_d + Y C_{d2})^T + 2\beta X > 0 \quad (16)$$

$$\begin{bmatrix} -X & X A_d \\ X A_d^T & -X \end{bmatrix} \quad (17)$$

$$\begin{bmatrix} -X & X A \\ A_d^T X & -X - \gamma C_{d2}^T C_{d2} \end{bmatrix} < 0 \quad (18)$$

where X and Z are symmetric matrices, and $Y = -L_d^T X$ is a "change of variable" matrix. Once the problem is solved using convex optimization algorithm, the full-order observer gain with pole location limitations is retrieved thus

$$L_d = -(X^{-1}) Y^T \quad (19)$$

3. EXPERIMENTAL PROCEDURE

The design of the control system is carried out using MATLAB R2022a software at a switching frequency of 5 kHz with the PowerGUI set to a sampling rate of 2 e-06. An MSi GE620DX computer with an Intel (R) Core i7-2670QM CPU @ 2.20GHz processor was used to perform the simulation. The Control system comprises of blocks such as the Discrete PI DC-link Controller, modified space vector modulation, coordinate transforms, etc.

The simulation follows a three-step approach: modeling, parameter identification, and control design. The mathematical model of the system was created in the Simscape Electrical domain and was simulated in Simulink. The parameters of the model were identified based on the operating data of the system.

Simulation parameters for the drive are as follows:

3hp, 415 V, 4.6 A, four-pole, 50 Hz, 1435 rpm star connected, three-phase Squirrel Cage Induction Motor (SQIM)

Induction motor parameters

$$R_s = 4.55 \Omega, R_r = 1.39 \Omega, L_s = 281.9 \mu\text{H}, L_r = 281.9 \mu\text{H}, L_m = 267.8 \mu\text{H}, J = 0.089 \text{ Kg}\cdot\text{m}^2$$

Filter parameters

$$C_f = 40 \mu\text{F}, L_f = 2.6 \text{ mH}, R_f = 1 \Omega$$

Z-source parameters

$$L1 = L2 = L = 500 \mu\text{H}, C1 = C2 = C = 500 \mu\text{F}$$

where R_f , L_f , and C_f are the per-phase ac resistance of the filter inductors, the inductance of the filter-inductors, and the capacitance of the filter-capacitors, respectively. Also, R_s , R_r , L_s , L_r , L_m , and J are respectively Per-phase stator resistance, Per-phase rotor resistance, Per-phase stator inductance, Per-phase rotor inductance, magnetizing inductance, and the moment of inertia.

After parameter identification, the control system was designed based on the mathematical model of the system. The Discrete PI DC-Link Voltage Controller was designed to keep the DC-Link voltage constant irrespective of fluctuations from intermittent sources. The modified space vector modulation technique was developed to maintain the switching frequency, modulation index, and pulse duration constant.

4. RESULTS AND DISCUSSION

4.1 System Harmonics

The (IEC 61000-3-2 and IEEE 519) standards recommend that electric drives have a total harmonic distortion (THD) of less than 5%. This sub-section evaluates the effectiveness of the robust servomechanism controller in eliminating baseband harmonics and, in general, the harmonics of the entire system to a globally acceptable standard.

The corresponding THD at 8sec. is 1.87% for 4 cycles as shown in provided in fig.2.

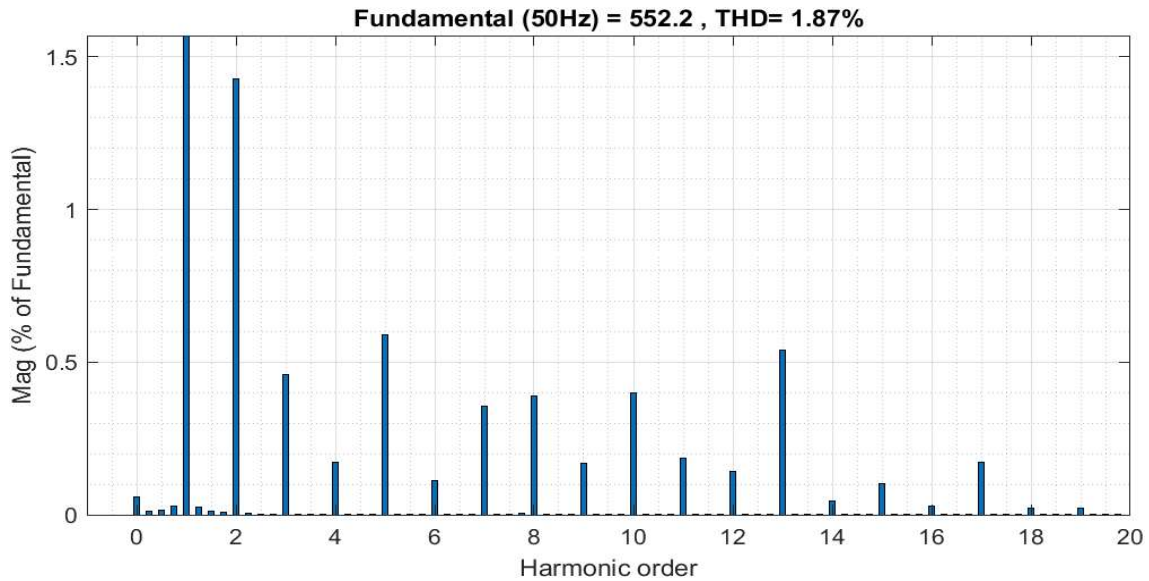


Fig.2: Harmonic spectrum for the stator voltage

Figure .3 is the harmonic spectrum for the stator current which shows a THD of 4.5% at 8.5sec. and 4 cycles

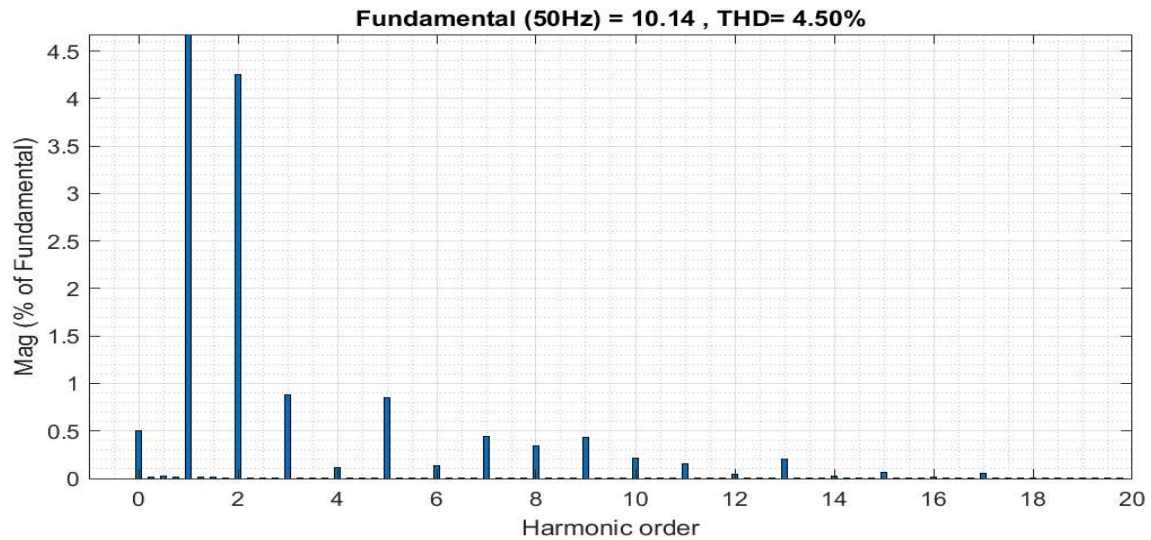


Fig.3: Stator current harmonic profile

4.2.1 Comparison of Harmonic Result

Sivakumar et al., (2023), used a fuzzy logic controller-based shunt active filter (SAF) to reduce the THD of the source current to 2.66%, but did not reveal the voltage of the power grid with a 3-phase induction motor drive (IMD). Nishizawa et al., (2019), introduced a space vector pulse width modulation technique for reducing inverter input current harmonics, but with an exponential increase in THD in over-modulation mode. Voltage harmonics were not examined in depth.

5. CONCLUSION

The outcome for the simulated system met the IEC 61000-3-2 and IEEE 519 standards, demonstrated an excellent harmonic profile for the induction motor drive, and had good stability margins and robustness, which will be revealed in later publications. Overall, the simulation showed good performance that met the desired requirements for the induction motor drive system. To ensure that the induction motor drive system meets the desired requirements, further tests need to be conducted under real-time conditions. This will allow for the evaluation of the system's robustness and operating performance. To maintain steady-state operation during these tests, it is recommended that the changes in stator resistance caused by temperature and load variations be modeled in the system. Additionally, a control modification or advanced ZSI design can be implemented in order to further improve the system's performance and energy efficiency.

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