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# Rule-based Fuzzy and V/f Control for Induction Motor Speed Responses Using SVPWM Switching Technique

***Abstract**. This paper describes the development of a three-phase induction motor (TIM) drive speed controller. A rule-based fuzzy logic controller (FLC) is developed for TIM speed control in non-linear systems. Speed control applications are tested by conducting simulations under different operating conditions. To achieve reliable TIM operation, the space vector pulse width modulation (SVPWM) scheme is used to generate gate signals for the three-phase, two-level inverter. The SVPWM technique demonstrates excellent performance in TIM speed control. The scalar control (V/f control), which is inexpensive, simple to implement in hardware, and applicable to medium- and high-speed rated TIM applications, is used to control the developed TIM. Results show that the implementation of rule-based fuzzy with V/f control and the SVPWM technique for TIM speed control provides superior performance, which is sufficiently robust and intelligent for real-time applications.*

***Streszczenie.** Opisano nową metodę sterowania prędkością trójfazowego silnika indukcyjnego. Wykorzystano sterownik bazujący na logice rozmytej umożliwiający sterowanie w systemach nieliniowych. Do bramkowania sygnału dwupoziomowego przekształtnika wykorzystano wektorowa modulację szerokości impulsu SVPWM. Zastosowano też skalarny przetwornik V/f. **Fuzzy logic sterownik wykorzystujący modulację SVPWM do kontroli szybkości silnika indukcyjnego***

**Keywords:** Fuzzy logic control, Induction motor, V/f controller, SVPWM, Inverter.
**Słowa kluczowe**: Logika rozmyta,. Silnik indukcyjny, sterowanie prędkością

## Introduction

Three-phase induction motor (TIM) drives are widely used in many applications, such as in utility companies, industrial plants, machine tools, and robotics. For TIM drive applications, the motor drive speed controller should be both efficient and robust [1]. Many types of TIM speed controllers have been utilized in previous works. For example, the proportional-integral-derivative (PID) controller is widely used in industrial applications because of its simple design and structure. However, the system of this controller requires a mathematical model that relies on trial and error to determine the control parameters for design [2]. Intelligent methods, such as artificial neural networks [3,4] and adaptive neuro fuzzy inference systems [5,6], have been utilized to improve TIM speed controllers. However, the aforementioned controllers encounter problems because of their huge data requirement as well as long training and learning time. Fuzzy logic controllers (FLCs) have been used in many applications for speed control because of their simple design and robustness in linear and non-linear systems [7,8]. FLCs do not require a mathematical model of the controlled system [7]. Meanwhile, V/f controls are used in closed-loop applications for lossless control of AC machines [9]. However, traditional FLCs and V/f controls can still be improved in terms of cost, size, reliablility, efficiency, and implementation [1]. Switching devices in inverters can be controlled using several techinques, such as sinusoidal pulse width modulation, SVPWM, harmonic band, random pulse width modulation, and specific harmonic elimination. Among these, SVPWM is the best method because it can reduce harmonic distortion from output signals for an inverter [10]. To solve issues related to speed control and the generation of switching signals, this study integrates rule-based fuzzy and V/f control systems to improve TIM speed control under variable speed operation using SVPWM switching techniques.

## Method and Systems

As shown in Fig. 1, the proposed TIM speed control system provides executable operations from the TIM model, fuzzy speed controller, V/f controller, and SVPWM switching techniques. The FLC speed controller is based on input and output triangular membership functions, in which slip speed $\omega_{sl}$ is added to rotor speed $\omega_r$ to obtain stator speed $\omega_s$. Stator speed is then converted to frequency *f* and fed to the V/f controller to generate peak voltage. Voltage and frequency are then converted to space vectors to generate switching signals for the inverter using the SVPWM technique. The inverted voltage is then filtered for TIM operation. The details of the individual methods and systems are presented as follows.

## TIM model

The model used for the three-phase, squirrel-cage induction motor is a stationary reference frame, in which voltage models are magnetically connected between the stator and the rotor for TIM operation, as shown in models (1) to (5). The three-phase stator and rotor voltages are then converted to stator and rotor *dq* voltages using Park transformation [10].

$$v_{as} = i_{as}r_s + \frac{d\lambda_{as}}{dt} \quad , \quad v_{ar} = i_{ar}r_r + \frac{d\lambda_{ar}}{dt}$$
$$(1) \quad v_{bs} = i_{bs}r_s + \frac{d\lambda_{bs}}{dt} \quad , \quad v_{br} = i_{br}r_r + \frac{d\lambda_{br}}{dt}$$
$$v_{cs} = i_{cs}r_s + \frac{d\lambda_{cs}}{dt} \quad , \quad v_{cr} = i_{cr}r_r + \frac{d\lambda_{cr}}{dt}$$

$$(2) \quad \begin{aligned} v_{ds}^s &= p\lambda_{ds}^s + r_s i_{ds}^s \\ v_{qs}^s &= p\lambda_{qs}^s + r_s i_{qs}^s \\ v_{0r}^s &= p\lambda_{0s}^s + r_s i_{0s}^s \end{aligned}$$

$$(3) \quad \begin{aligned} v_{dr}'^s &= p\lambda_{dr}'^s + (-\omega_r)\lambda_{qs}'^s + r_r' i_{dr}'^s \\ v_{qr}'^s &= p\lambda_{qr}'^s + (\omega_r)\lambda_{ds}'^s + r_r' i_{qr}'^s \\ v_{0r}'^s &= p\lambda_{0r}'^s + r_r' i_{0r}'^s \end{aligned}$$

$$(4) \quad T_{em} = \frac{3}{2}\frac{P}{2}\left(\lambda_{dr}'^s i_{qs}^s - \lambda_{qr}'^s i_{ds}^s\right)$$

$$(5) \quad J\dot{\omega}_{rm} = T_{em} - T_L$$

where $v_{as}, v_{bs}, v_{cs}$ are the stator 3-phase voltages, $v_{ar}, v_{br}, v_{cr}$ are the rotor voltages, $i_{as}, i_{bs}, i_{cs}$ are the stator currents, $i_{ar}, i_{br}, i_{cr}$ are the rotor currents, $r_s, r_r$ are the stator and rotor resistances, $\lambda_{as}, \lambda_{bs}, \lambda_{cs}$ are the stator flux linkages, $\lambda_{ar}, \lambda_{br}, \lambda_{cr}$ are the rotor flux linkages, $v_{ds}^s, v_{qs}^s$ are the dq axis stator voltages, $v_{dr}^{\prime s}, v_{qr}^{\prime s}$ are the dq axis rotor voltages, $i_{ds}^s, i_{qs}^s$ are the dq axis stator currents, $i_{dr}^{\prime s}, i_{qr}^{\prime s}$ are the dq axis rotor currents, $\lambda_{ds}^s, \lambda_{qs}^s$ are dq axis stator flux linkages, $\lambda_{dr}^{\prime s}, \lambda_{qr}^{\prime s}$ are dq axis rotor flux linkages, $\omega_r$ is the rotor speed, *P* the number of pole pairs, $T_{em}$ the electromagnetic torque and $T_L$the load torque, respectively [10].

where $\varphi_m$ is the maximum air-gap flux, $V_p$ is the peak phase voltage and $f$ is the frequency supply in the stator of the TIM. The TIM is controlled by regulating input voltage amplitude and operating frequency [13].

**SVPWM technique**

The SVPWM technique computes for the time duration of voltage pulses using the amplitude and angular location of the reference vector. Space vector modulators are employed to generate control signals for the three-phase, two-level inverter. The modulation index *MI* is calculated based on model (9) for the SVPWM scheme as follows:

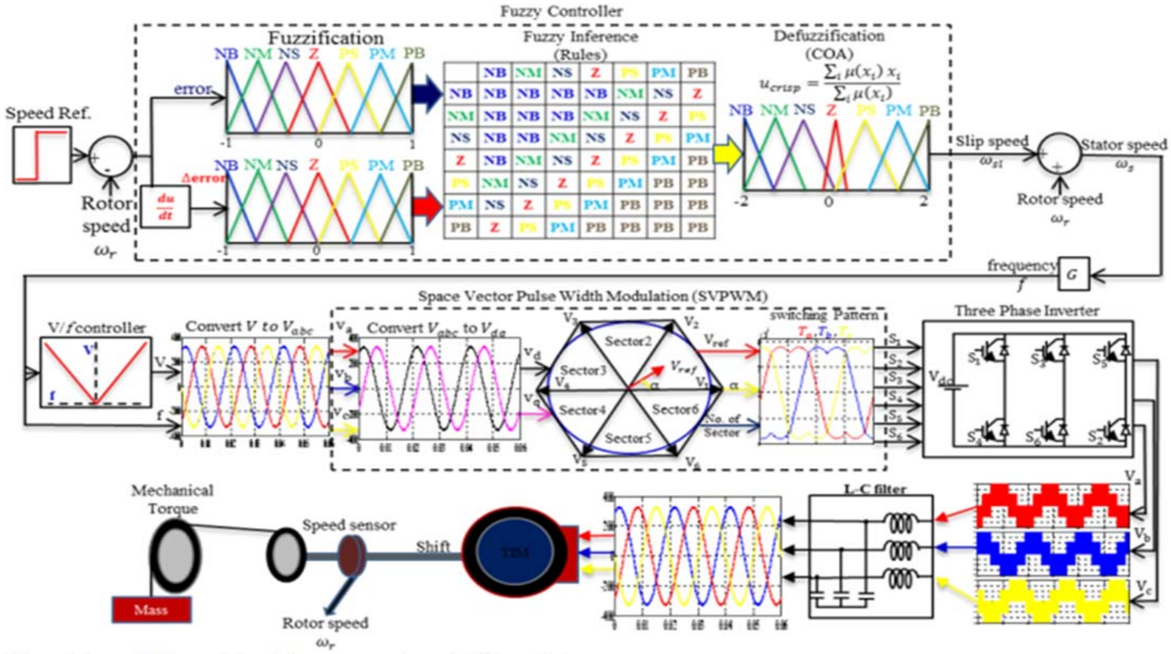



Fig. 1. Closed-loop TIM model of fuzzy speed and V/*f* control method using SVPWM switching techniques.

**Design of the fuzzy speed controller**

The Mamdani FLC is used for the proposed TIM with the *S*-function implementation program code. The design of the fuzzy speed controller is divided into input and output variables, fuzzification based on triangular membership functions, fuzzy inference based on control rules, and defuzzification using the center of average method. The calculation of error *e*, change of error *de*, and reference speed $\omega_r^*$, are defined by models (6) and (7) to determine the exact stator speed [11].

(6) $$e = \omega_r^* - \omega_r$$

(7) $$de = e(k) - e(k-1)$$

**V/f control**

V/f control (scalar control) is highly useful in medium- and high-speed TIM because of its simple implementation in hardware [12]. The operating principle of the V/f control involves keeping a constant ratio between peak phase voltage and frequency to maintain a constant magnetic flux in the air gap. Using the relationship between peak voltage and frequency, electromagnetic flux calculation can be described as follows [9]:

(8) $$\varphi_m \approx \frac{V_p}{f}$$

(9) $$MI = \frac{V_{m1}}{V_{m1six}}$$

where $V_{m1}$ is the maximum value of the fundamental voltage and $V_{m1six}$ is the maximum value of the fundamental voltage in the six step operation. $V_{m1six} = \frac{2}{\pi} V_{dc}$, where $V_{dc}$ is the DC voltage source of the inverter [14]. SVPWM switching time shares are calculated based on the location inside any sector as follows [12].

(10) $$T_1 = \frac{\sqrt{3}.T_z.|V_{ref}|}{V_{dc}}\left[\sin\left(\frac{n}{3}\pi\right)\cos(\alpha) - \cos\left(\frac{n}{3}\pi\right)\sin(\alpha)\right]$$

(11) $$\mathrm{T_2} = \frac{\sqrt{3}.\mathrm{T_z}.|\mathrm{V_{ref}}|}{\mathrm{V_{dc}}}\left[-\cos(\alpha)\sin\left(\frac{n-1}{3}\pi\right) + \sin(\alpha)\cos\left(\frac{n-1}{3}\pi\right)\right]$$

(12) $$\mathrm{T_0} = \mathrm{T_z} - (\mathrm{T_1} + \mathrm{T_2})$$

where *n*=1 to 6 within $0 \le \alpha \le \pi/3$; $T_1$, $T_2$ and $T_o$ are the time vectors of the coresponding voltage vectors, $T_z$ is the sampling period, and $\alpha$ is the angle between the reference vector and the space vector.

**Results and Discussion**

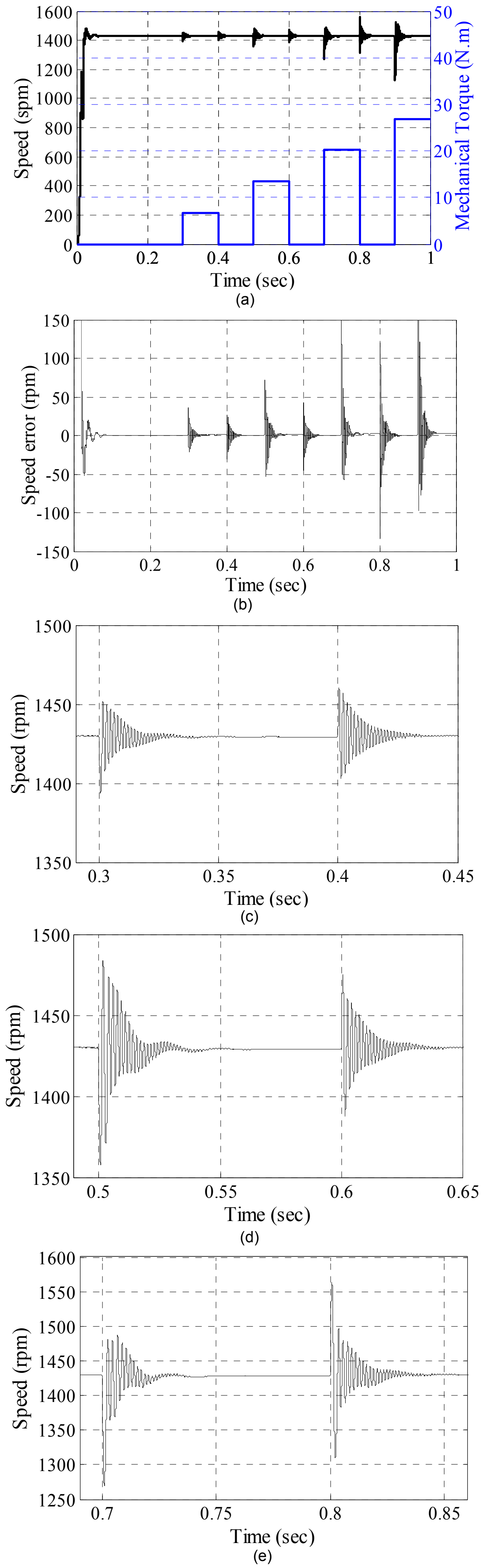
A TIM (50 Hz, 4 KW, 400 V, 1430 rpm) is designed and tested with the fuzzy speed controller. The implementation of the closed-loop TIM model, fuzzy speed controller, and

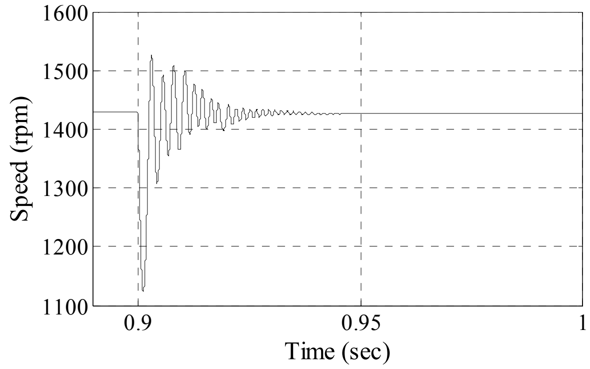
V/f controller are developed using the *S*-function in MATLAB. The objective in using the fuzzy controller is to provide actual rotor speed to track the commanded or reference speed. The speed controller provides the required slip for measuring rotor speed to produce the desired inverter frequency. A V/f relationship is developed to fix the TIM at its rated flux linkage. The proposed SVPWM scheme generates the exact gating signal, which is then fed to the inverter rather than to the TIM. The performance of the TIM is evaluated in terms of speed responses. To demonstrate the effectiveness of the developed controller, two tests are conducted in non-linear systems, namely, speed response under varying torque and speed. Speed response with varying load is shown in Fig. 2. Speed error is calculated between the reference speed and the rotor speed. Average error is measured at 0.17332% with a standard deviation (STD) of 1.34384% for each 1 sec, as shown in Fig. 2b. The calculations also show that at 0.3 sec and 0.4 sec with 25% rated load, torque distortions were 2.09% and 1.74% from rated speed; at 0.5 sec and 0.6 sec with 50% rated load, torque distortions were 3.49% and 2.79% from rated speed; at 0.7 sec and 0.8 sec with 75% rated load, torque distortions were 4.19% and 5.59% from rated speed; and at 0.9 sec with full rated load, torque distortion was 6.64% from rated speed. The increase in the distortion of speed response is attributed to a sudden change in mechanical torque when the TIM is operated from no load to half torque, three-quarters torque, or full torque. Moreover, distortion time is slightly related to the duration of one cycle (0.02 sec). The second step is to check the robustness of the proposed control structures against variations in induction machine speed reference. As shown in Fig. 3, the change in reference speed starts with the full speed of 1430 rpm at 0.3 sec to 70% rated speed of 1000 rpm at 0.6 sec, and then continues to 1 sec with the overall rated speed. Speed error is calculated between the reference speed and the rotor speed. Average error is measured at 0.16278%, and STD is 1.35021% for each 1 sec, as shown in Fig. 3b.

In this work, the performance of the FLC is compared based on speed control with the TIM under varying parameters, such as change in torque and speed reference. The findings demonstrate that the improved FLC obtained better results in TIM speed control than the other controllers. In Table 1, the results of a comparative study with previous works are presented based on specified measurements of errors and STD. As shown in the table, the results of the proposed controller are better than those of the controller presented in [2]. Moreover, the comparison between steady state error (SSE%) and settling time shows that the obtained results is superior to those in [15], [16] and [17]. The potential contribution of this work is the minimization of disturbances that occur in speed response when mechanical torque or speed reference change or when maximum overshoot (3.5%), settling time (0.05 sec), and steady state error (0%) are reduced.

Table 1. Comparison study

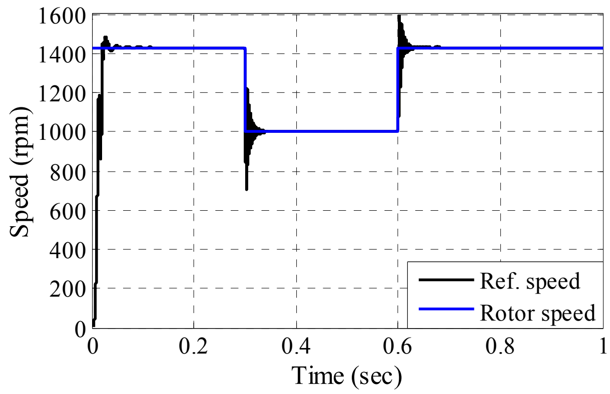
| | Control method | Error (%) | STD (%) | SSE (%) | ST (sec) |
|---|---|---|---|---|---|
| Proposed | V/f control | 1.038 | 8.04 | 0 | 0.05 |
| [2] | V/f control | 4.07 | 13.2 | 1.31 | 0.15 - 0.2 |
| [15] | Vector control | N/A | N/A | 1.25 | 0.5 – 0.6 |
| [16] | Vector control | N/A | N/A | 0.1 | 2.14 |
| [17] | Vector control | N/A | N/A | 1 | 0.15 |



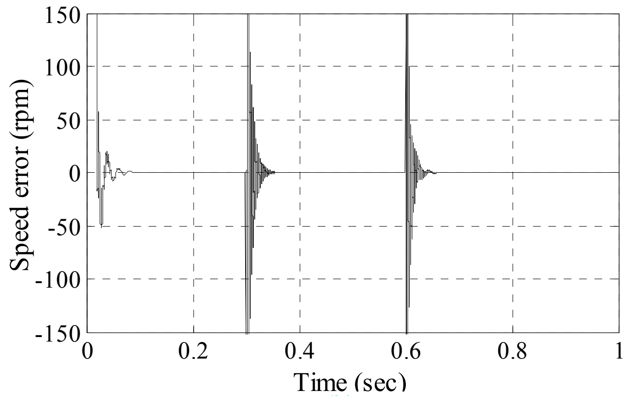



(f)

Fig. 2. (a) Speed response during change in mechanical torque, (b) speed error (c) zoom 25% rated torque, (d) zoom 50% rated torque, (e) zoom 75% rated torque and (f) zoom full rated torque.




(a)




(b)

Fig. 3. (a) Speed response during change in speed, and (b) speed error.

## Conclusions

In this study, the performance of an FLC was compared in terms of TIM speed control while considering changes in mechanical torque and reference speed. The improved FLC obtained better results than other controllers. In addition, it minimized the disturbance that occurs with speed response because of changes in torque or speed reference. Thus, reduced maximum overshoot, decreased settling time, and zero SSE% would improve the speed control performance of the TIM under variable speed operation conditions in real-time applications.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