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Harmonic reduction using THIPWM switching technique with type-2 fuzzy on 3-phase motor

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Abstract

The development of the increasingly advanced industrial world has increased the need and use of electric motors for various purposes. In the industrial world, many electric motors are found as a driving device to drive various equipment needed, including a three-phase induction motor. The induction motor is expected to operate normally by the desired working characteristics. But it is undeniable that in its use, there are disturbances that can cause damage to the work system of the Induction motor, one of which is harmonic interference. The influence of harmonics on the induction motor causes copper and core losses which will reduce the efficiency motor and cause harmonic torque along with fundamental torque to produce vibration and noise, which considerably affect the operation three-phase induction motor. In this study, a 3-phase inverter was used with the Third Harmonic Injection pulse width modulation (THIPWM) method, with the use THIPWM Switching Method expected to increase the output voltage three-phase inverter and reduce the harmonics caused by the three-phase induction motor. In optimizing a 3-phase induction motor's speed regulation, scalar control or voltage/frequency (v/f) regulation is used. With the use THIPWM switching on this three-phase inverter, it is evident from simulation results that the harmonic value of THDV is 55.62%. THDI is 19.04%, as well the acceleration 3-phase induction motor with a rise time value of 48.547ms with steady-state error of 0.08% at set point 1200 rpm and with rise time value of 52.938ms with steady-state error 0% at set point 1000 rpm.

1. Introduction

The development of induction motors is increasing along with the development of electric vehicles in all countries, including Indonesia. This development requires industries in the world to develop induction motors [1]. Induction motor is an alternating current electric motor that is often used in everyday life both in industry and households [2]. 3-phase induction motors are widely used in the industrial field, especially in the electric car industry because the price is relatively cheap, and it has large power. In addition, the efficiency of 3-phase induction motors is relatively high under normal circumstances with easy and inexpensive maintenance [3]. However, 3-phase induction motors have several disadvantages, namely: they cannot maintain their speed constantly when there is a change in load, the starting current of 3-phase induction motors is usually 10 - 12 times the nominal current, and the speed of the motor is difficult to control. Therefore, to obtain a constant speed and better system conditions for load changes, a control system is needed [4], [5].

In general, induction motors are used at a fixed rotation speed. The power consumption in a constant speed motor is greater than that of a variable speed motor for various loads. The variable speed can be done by setting the torque [6]. To get such variable speeds, a power converter is needed. When the induction motor gets voltage through the power converter, the voltage waveform is no longer sinusoid. Under these conditions, motor modeling no longer uses transformer models, but it uses modeling in d-q-n coordinates to perform analysis. This model is more flexible compared to the induction motor model using the transformer model. The form of the source voltage does not have to be sinusoidal and the engine parameters can be changed [7], [8]. In addition to being used for steady state condition analysis, induction motor modeling in d-q-n coordinates can also be used for transient conditions [9]. The disadvantage of induction motors is that induction motors are non-linear, and the method for regulating speed is complicated, besides that a converter is needed that will cause harmonics [10].

However, the speed setting can provide the opposite side to the properties of the induction motor so that it is difficult to maintain its speed [11]. This provides a fairly high error rate when the induction motor speed regulation is operated with an open system. Error is the difference between the reference value and the measured value [12]. One way to overcome this is to provide a control/control technique as feedback. Feedback control is quite required by the industry [13]. Controlling the speed of a 3-phase induction motor can be done through torque or motor frequency. Motor torque control can be done through voltage and frequency. For the purpose of regulating voltage and frequency, a power supply in the form of a converter is used. For that the motor must be modeled in d-q-n coordinates [14].

Some 3-phase induction motor speed settings have disadvantages. In setting the speed of a 3-phase induction motor by adjusting the frequency only, the greater the frequency value, the torque obtained on the motor will decrease [15], [16]. If the speed regulation of a 3-phase induction motor uses a setting on the source voltage only, the torque produced by the motor will be greater as well as the voltage source. However, setting the voltage source too large can result in the occurrence of a saturation phenomenon in flux [17], [18].

The speed controller of the 3-phase induction motor is carried out with scalar control or commonly called voltage/frequency (v/f) regulation. The principle of this scalar control is to force the motor to have a constant relationship between voltage and frequency [19], [20]. The advantages of using this scalar control are it has a simple, easy and fast programmable control structure, and it can be operated by the open-loop control method without a speed controller or with a speed controller, making it economically cheaper [21], [22]. The scalar control method can overcome weaknesses in the speed regulation of the induction motor, namely the starting current in the motor is not too large at low frequencies [23], [24].

By testing the implementation of type-2 fuzzy in controlling the speed of the induction motor, results are obtained when there is a sudden change in load, the control system can respond quickly and stabilize the speed of the induction motor [25]. The fuzzy control system also improves the accuracy of the motor speed by minimizing the error values. The fuzzy control system has also proven to be able to inject the third harmonic very well which is shown by a significant reduction in THDi and THDv.

2. Research Method

The design and speed regulation mechanism of three-phase induction motors are discussed in this paper. The three-phase inverter uses the THIPWM method and the Inverter output were used to regulate the motor speed and the system performed is presented in Figure 1.

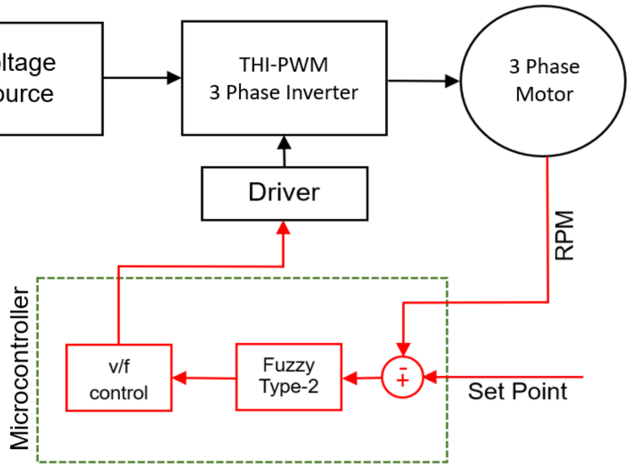

Figure 1. Block Research System Diagram

This system is illustrated in Figure 1, a 3-phase inverter using a third harmonic injection pulse width modulation (THIPWM) switching technique which will produce a modulated output voltage. The output produced from the inverter is used as a supply of 3-phase induction motors. To regulate the speed of a 3-phase induction motor, the speed value of the three-phase induction motor is used as data input as a benchmark for setting the v/f value set using type-2 fuzzy control. The output of the control will later change the value of the mf (Modulation frequency) and ma (Modulation amplitude) parameters after being processed by the scalar control in keeping the ratio of voltage and frequency ratio constant.

2.1 V/f Control

The speed of the induction motor is directly proportional to the frequency of the power source and the number of poles of the motor. Since the number of poles is determined by design, the best way to change the speed of the induction motor is to change the frequency of the power source. The torque produced by the induction motor is directly proportional to the ratio of the applied voltage and the frequency of the power source. By changing the voltage and frequency, but keeping the ratio constant between the two, the resulting torque can be kept constant throughout the speed regulation area [19], [20].

Varying the voltage and frequency by equal ratios, torque can be kept constant and independent of supply frequency across the speed range, as presented in Equation 1 below.

$$V_{eff} \propto f. \ \varphi \rightarrow \propto \varphi \propto \frac{V}{f} \quad (1)$$

Where V and φ are the stator voltage and flux respectively and f is the frequency of the input voltage. This makes v/f constan the most common speed control of induction motors, as the v/f constan graph shown in Figure 2.

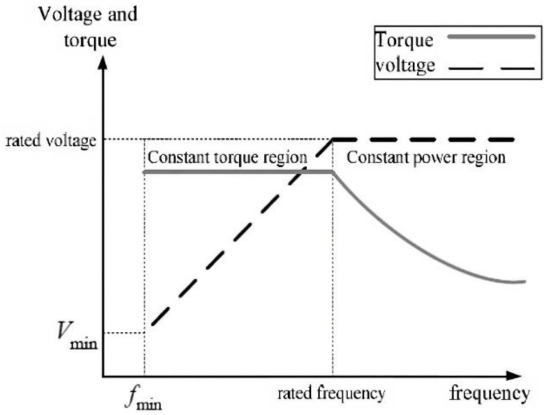

Figure 2. Constant V/f characteristic [19]

The speed regulation of the induction motor is carried out by maintaining a constant v/f ratio to avoid air gaps of flux variations. As shown in Figure 2, the goal of a constant v/f setting is to keep torque constant and frequency independent, achieving higher efficiency and lower current at *run time*.

2.2 Third Harmonic Injection Pulse Width Modulation (THIPWM)

Third Harmonic Injection PWM is one of the switching techniques used in the speed regulation of three fasa induction motor. The injection of the third harmonic in the sine signal can be formulated in Equation 2 as follows:

$$V_{(t)} = \frac{2}{\sqrt{3}}\sin(\omega t) + \frac{1}{3\sqrt{3}}\sin(3\omega t) \quad (2)$$

Referring to Equation 2.13, the modification of the form of a pure sine signal into a sine signal with the addition of a third harmonic was intended to increase the RMS (Root Mean Square) value in the inverter output PWM signal by a fundamental 2/√3 times. As long as the third harmonic at the line-to-line voltage of the three-phase system does not appear at the phase-phase voltage, it will appear in the neutral phase [26], [27].

The advantage of adding a third harmonic is the better utility of DC voltage than Sinusoidal PWM without any addition to the Total Harmonic Distortion (THD) value. The observation of the reference sine signal of the THIPWM method and the carrier signal is shown in Figure 3.

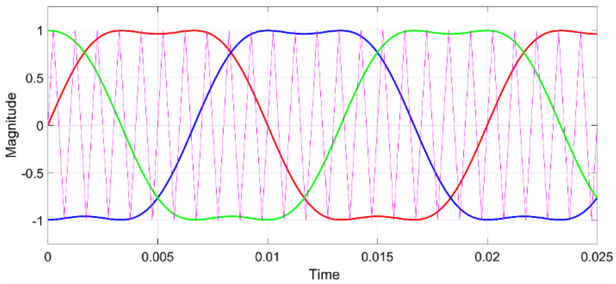

Figure 3. Three-phase Reference Sine Signal THIPWM method and Carrier Triangle Signal

The base frequency amplitude of the PWM output is controlled by ma. This is important in the case of an unregulated DC supply voltage, as the ma value can be set to compensate for variations in the DC supply voltage, resulting in a constant amplitude output. In addition, ma can be varied to change the output amplitude. If ma is greater than 1, the output amplitude increases according to ma, but it is not linear or called *an overmodulation* condition.

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2.3 Type-2 Fuzzy Logic Controller

The type-2 fuzzy controller is designed with two inputs, namely error values and error changes, and one output [28]. The type-2 fuzzy control block diagram in detail is shown in Figure 4. In general, the block diagram composition of type-2 fuzzy controller is almost the same as that of type-1 fuzzy logic controllers, which consist of fuzzification processes, inference mechanisms, and defuzzification. The difference lies in the type reduction process, where in this process the type-2 fuzzy output from the inference mechanism is reduced to type-1 so that the defuzzification process can be carried out [29]. There are several reduction algorithms that can be used, namely Karnik-Mendel (KM), Enhanced Karnik Mendel (EKM), Iterative Algorithm with Stop Condition (IACS), and Enhanced Iterative Algorithm with Stop Condition (EIACS) [30].

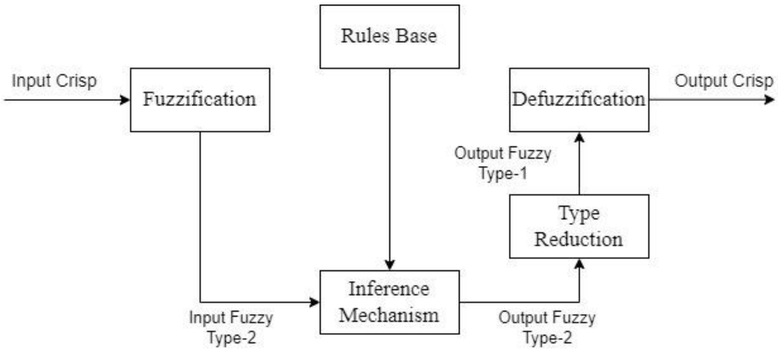


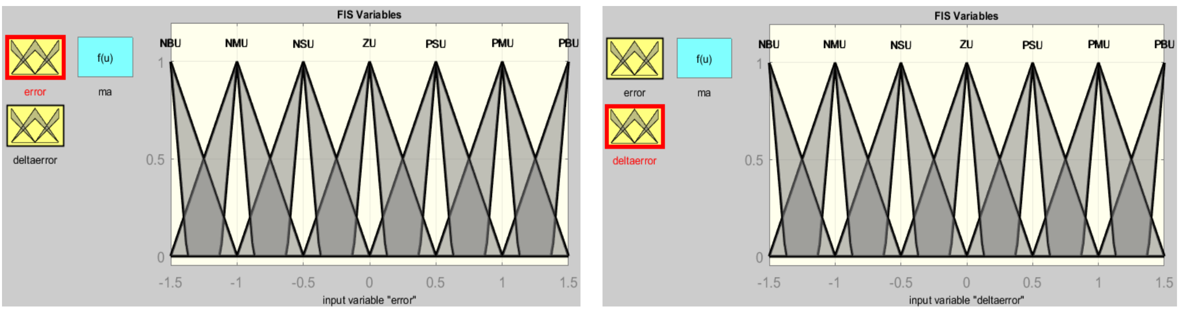
Figure 4. Fuzzy Type-2 Control Diagram

In general, the triangular type-2 fuzzy membership function equation consists of upper and lower membership functions as described in Equation 3.

$$\mu_{1,2}(x) = \begin{cases} 0 & x < a_{1,2} \ atau \ x > c_{1,2} \\ (x - a_{1,2}) / (b_{1,2} - a_{1,2}) & a_{1,2} \le x \le b_{1,2} \\ (b_{1,2} - x) / (c_{1,2} - b_{1,2}) & b_{1,2} \le x \le c_{1,2} \end{cases} \quad (3)$$

Subscript notation 1 and 2 are upper and lower functions at a, b, and c respectively μ. The meet operation aims to form a vertically intersecting membership degree interval function, while the join operation combines horizontally intersecting membership degree interval functions. After that, the next stage is type reduction before entering the defuzzification stage [31].

In this study, type-2 fuzzy controller was designed with error input and error changes made in the form of type-2 fuzzy membership functions. The limit of the designed input value is from -1.5 to 1.5 with linguistic variables Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), and Positive Big (PB). The membership error value is shown in Figure 5(a), and the membership delta error value is shown in Figure 5(b).



(a) (b)

Figure 5. (a) Error Value Membership Design, (b) Error Delta Value Membership Design

The output membership function is based on the sugeno method which uses firm values with a range of values -1 to 1. The defined linguistic variables are the same as the input membership function with values NB = -1, NM = -0.667, NS = -0.334, Z = 0, PS = 0.334, PM = 0.667, and PB = 1. The output membership is presented in Figure 6.

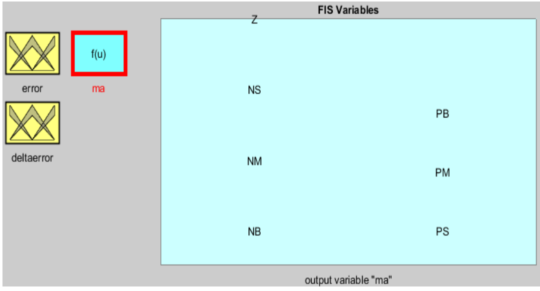


Figure 6. Output Value Membership Design

After designing the membership functions of each input and output, the next step is to establish the basis of the rule. The membership functions of both inputs have five linguistic variables, so the number of defined rule bases is 49 as shown in Table 1.

Table 1. Rule Base Fuzzy Type-2

Delta Error/Error	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NM	NS	NS	Z
NM	NB	NB	NM	NM	NS	Z	PS
NS	NB	NM	NS	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PS	PM	PB
PM	NS	Z	PS	PM	PM	PB	PB
PB	Z	PS	PS	PM	PB	PB	PB

This study used Karnik Mendel (KM) reducers at the type reduction stage. After going through the type reduction stage, a defuzzification process is carried out using the Sugeno method based on the following Equation 4.

$$z = \frac{\Sigma x_i . \mu(x_i)}{\Sigma \mu(x_i)} \quad (4)$$

where z is the assertive output value, x_i is the i-th input assertive value, and μ(xi) the membership degree for each i-th input assertive value.

3. Results and Discussion

The results were shown from testing the entire system behind closed doors with Type-2 Fuzzy controllers. The system consists of a 3-phase inverter as well as a 3-phase induction motor. For the switching ignition method on a 3-phase inverter, the THIPWM (Third Harmonic Injection Pulse Width Modullation) method is used. Figure 7 is a circuit diagram of a 3-phase induction motor controller using a type-2 fuzzy logic controller using matlab.

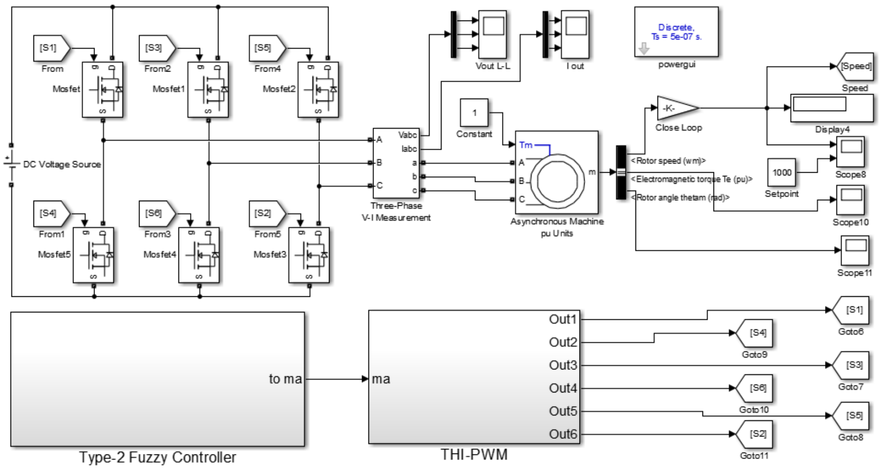


Figure 7. System Circuit Diagram with Simulink Matlab

The 3-phase inverter generation signal using third harmonic injection *pulse width modulation* (THIPWM) is generated by comparing the reference signal, namely the sinusoidal + 3' harmonic injection signal, with the carrier signal, the triangular signal. The reference signal has an angle difference of 120 to represent a 3-phase source that has a phase angle difference of 120. The output of the signal comparator is used as a 3-phase inverter signal generation in the mosfet switching component where the generation signal consists of a high signal and a low signal. The signal will drive from 6 mosfets on a 3-phase inverter. Block circuit diagram of sinusoidal pulse width modulation (SPWM) using Matlab simulink as shown in Figure 8.

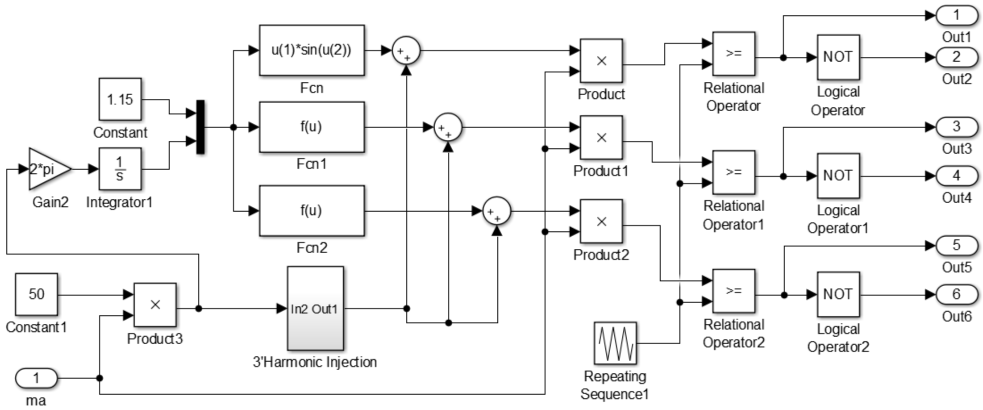


Figure 8. Third Harmionic Injection Pulse Width Modulation (THI-PWM) Circuit Diagram

3-phase inverter block in Figure 9 consists of 6 mosfets (switching components) where the generation signal at the gate foot is obtained in the THIPWM signal generation process. The amount of DC input voltage is 311 Volt in order to produce an inverter output voltage of 220 Vrms so that it can be used as a source of a 3-phase induction motor.

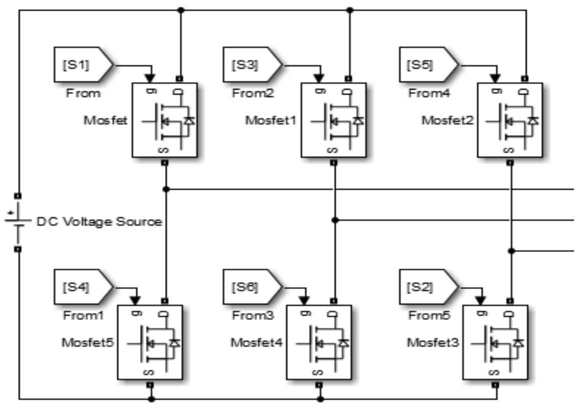


Figure 9. Three Phase Inverter Circuit Diagram

In this study, the induction motor used has a capacity of 1.5 HP or equivalent to 1.2 KW with a nominal motor voltage of 220 Vrms. Table 2 shows the specification of the three-phase induction motor used in this study.

Table 2. Specification of Three Phase Induction Motor

No	Parameters	Value	Unit
1	R_{stator}	5.27	Ω
2	R_{rotor}	3.40	Ω
3	L_{stator}	4.33	Mh
4	L_{rotor}	4.46	Mh
5	$L_{magnetization}$	270	Mh
6	Power	1.5	HP
7	$V_{L\text{-}L\ (rms)}$	220	Volt
8	Frequency	50	Hz
9	Pole	4	Unit
10	Motor Speed	1435	Rpm

The 3-phase induction motor block has three inputs, namely A, B, C. These three inputs are the outputs of the 3-phase inverter block. The parameter taken from the block is the rotor speed, where the rotor speed is used as feedback or input from a controller. In Figure 10 It is the entire block of controllers consisting of v/f Scalar Control and Type-2 Fuzzy Logic Controller. In block scalar control, the parameters observed are frequency (f) and modulation amplitude (ma).

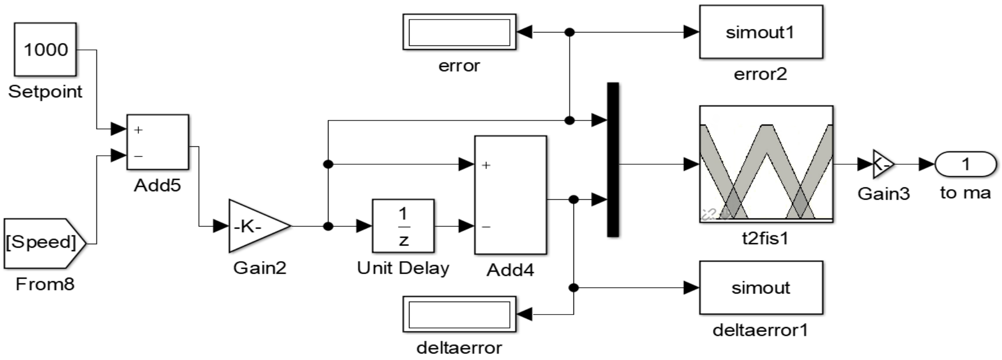


Figure 10. Type-2 Fuzzy Controller Circuit Diagram

Figure 11 is an image of the VL-L output voltage wave from a 3-phase inverter connected to a 3-phase induction motor.

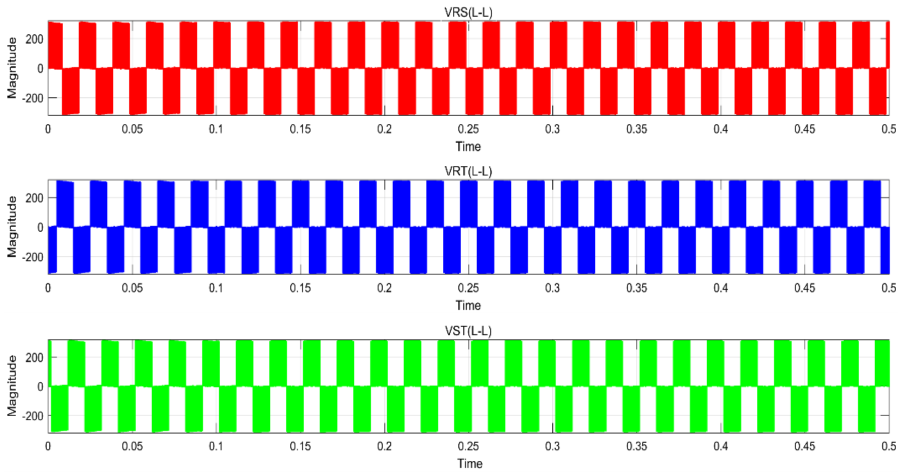


Figure 11. Output Voltage Line to Line Three Phase Inverter

Figure 12 shows the inverter output current wave at each phase. The load used in the study was a three-phase motor, resulting in a fairly large starting current that reached 10 to 12 times its nominal current.

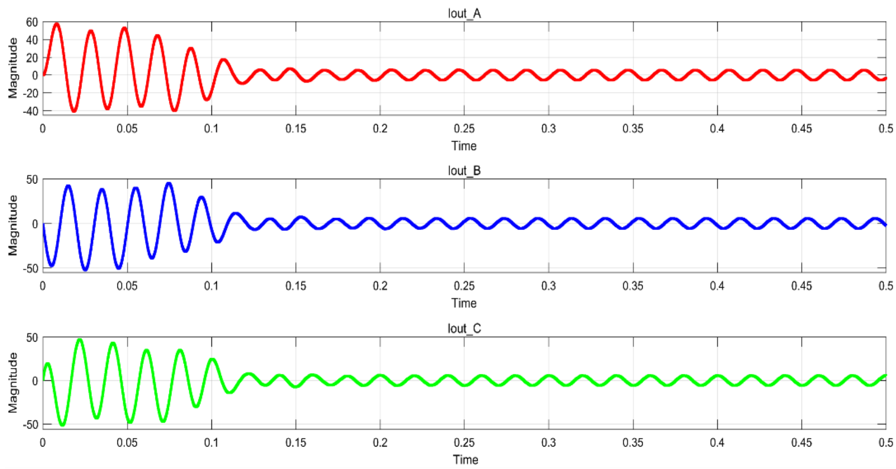
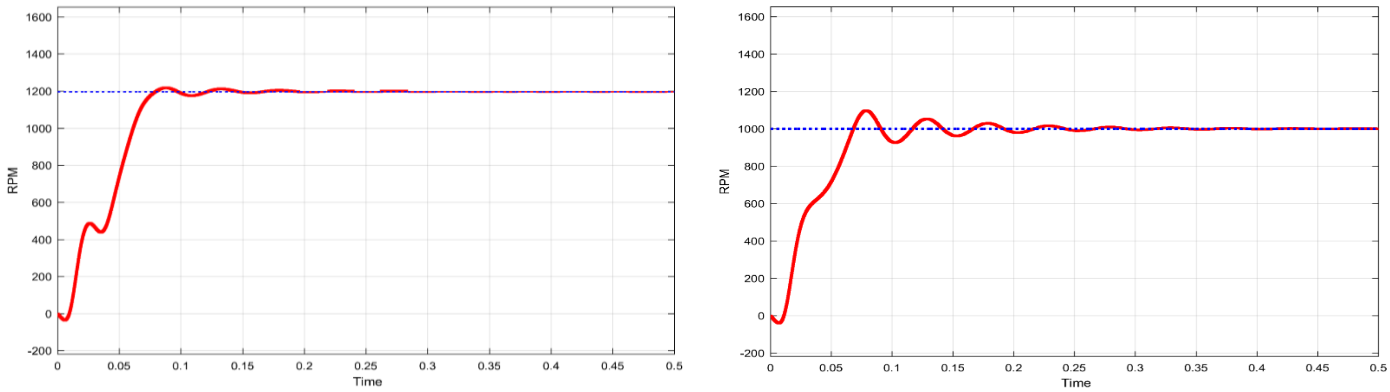


Figure 12. Output Current Three Phase Inverter

The test results respond the speed of 3-phase induction motor by providing a variation of the speed set point during close loop conditions with type-2 fuzzy controller. In testing, the set point values used are 1000 rpm and 1200 rpm, the results of the test can be seen in Figure 13 (a), (b).

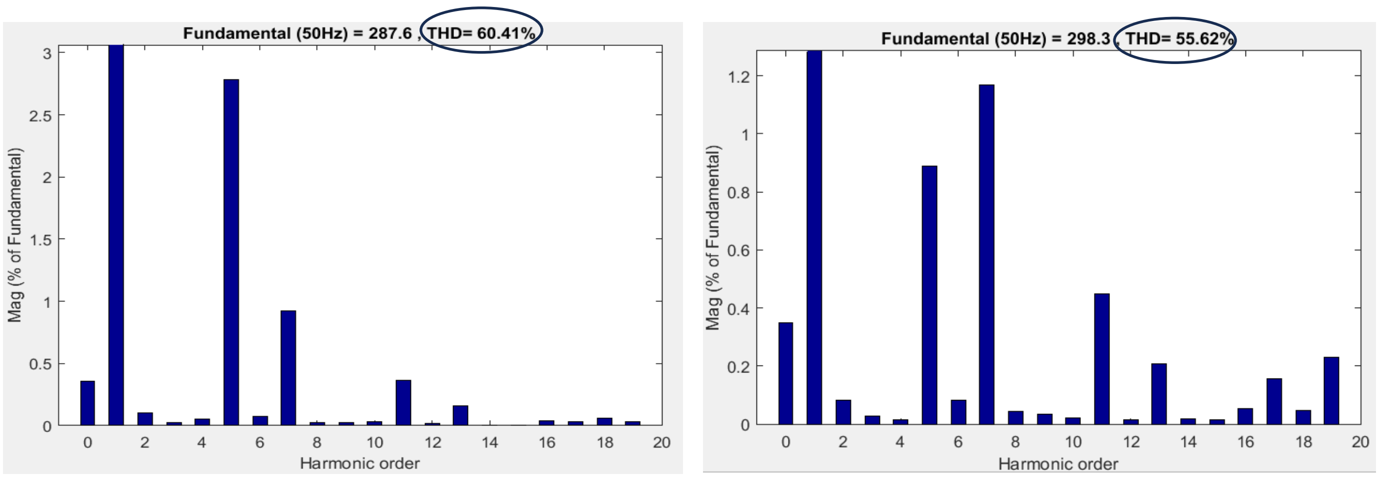


(a) (b)

Figure 13. (a) Close Loop Response RPM 1200, (b) Close Loop Response RPM 1000

From the results of the study on motor speed regulation, it can be known that a setpoint of 1200 rpm produced a motor output speed of 1199 rpm with a reference voltage ratio value with a carrier (ma) of 0.85 and a frequency of 42.5 Hz. The error value (the difference between the setpoint value and the measured) obtained was 0.08%. Likewise, with a setpoint of 1000 rpm, the output speed of the motor is 1000 rpm with a reference voltage ratio value with a carrier (ma) of 0.714 and a frequency of 35.7 Hz. From these results, the error value (the difference between the setpoint value and measured) obtained was 0%.

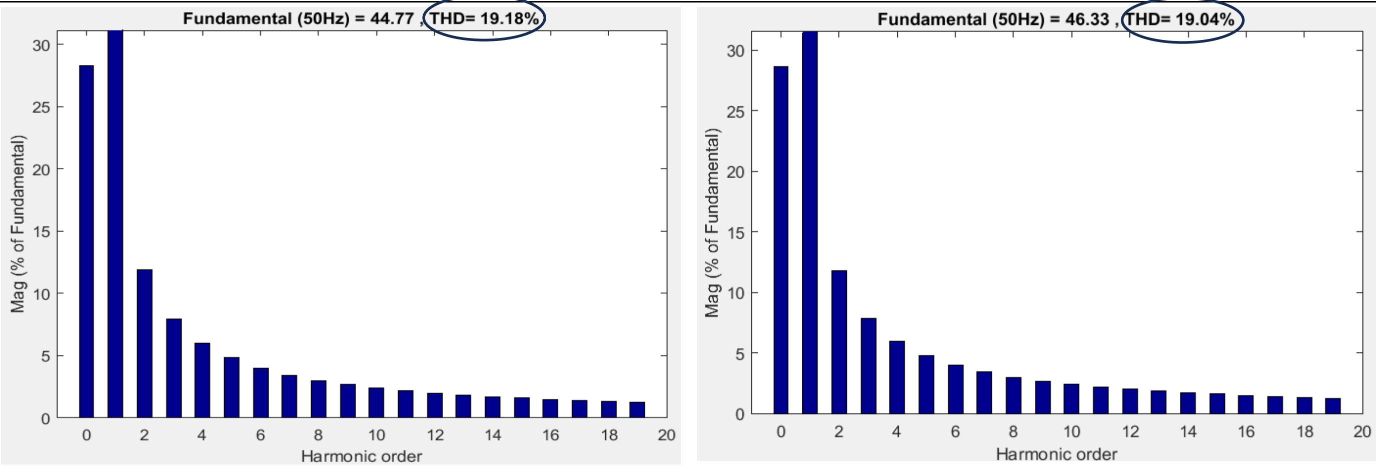
The results of the simulation, the total harmonic distortion value of THDv that without the THIPWM switching method is shown in Figure 14 (a), and the total harmonic distortion value of THDv with the THIPWM switching method is shown in Figure 14 (b). The total harmonic distortion value of THDi that without the THIPWM switching method is shown in Figure 15 (a), while the total value of the THDi harmonic distortion with the THIPWM switching method is shown in Figure 15 (b).



(a) (b)

Figure 14. (a) THDv Value without THIPWM, (b) THDv Value Using THIPWM

The total value of THDv harmonic distortion from the simulation results proves that THIPWM switching method can reduce the value of THDv harmonics by 4.79%. This can happen because the THIPWM switching method can reduce harmonics in *the* 3rd Order and 5th Order. The result of this decrease in harmonic value can increase the power produced.



(a) (b)

Figure 15. (a) THDi Value without THIPWM, (b) THDi Value Using THIPWM

The THDi harmonic value obtained from the simulation results by without THIPWM switching technique has a higher harmonic content. By using the THIPWM switching technique, the results of the study can reduce the value of THDi harmonics by 0.16%. The result of decreasing the value of THDi harmonics can reduce noise in the motor and can reduce the effect of heat on the motor.

4. Conclusion

Based on simulations conducted using THIPWM switching, the total harmonic distortion value of THDV has a harmonic content of 55.62% and THDI has a harmonic content of 19.04%, so that the THIPWM switching technique is proven to reduce harmonic content. The speed response of the induction motor using type-2 fuzzy at set points of 1200 and 1000 rpm obtained a response that was in accordance with the set point. From the response obtained, the system has a low steady state error value, as well as a fast *rise time* and *settling time* value so that the motor is fast in a *steady state*.

Notation

V_{eff} : Effective voltage.
z : Fuzzy Type-2 Firm Output Value.
μ : the average value of data.
f : Frequency.

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