Induction motor speed control using varied duty cycle terminal voltage via PI controller

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Abstract. This paper deals with the PI speed controller for the three-phase induction motor using PWM technique. The PWM generated signal is utilized for voltage source inverter with an optimal duty cycle on a simplified induction motor model. A control algorithm for generating PWM control signal is developed. Obtained results shows that the steady state error and overshoot of the developed system is in the limit under different speed and load condition. The robustness of the control performance would be potential for induction motor performance improvement.

1. Introduction
Three phase induction motor (TIM), considering its features of ruggedness, high efficiency, simple architecture, and low inertia is the most appropriate solution for industries, which is also long lasting and economic[1]. However, speed control of TIM especially in high performance demand in industrial applications are challenged due its non-linearity and dynamic behaviour. However, to overcome the constraints for the speed control application for TIM, numerous control techniques has been designed and developed depending on its sector of applications among others scaler control is the simplest one [2]–[4]. In scalar control variables are controlled only in magnitude and not in direction. Traditionally, PI control system for the TIM speed response is the most extensively used control technique because it is less complicated in design and economic. Moreover, PI control system provides the system with higher overshoot, maintains an acceptable level of steady stare error and keeps the oscillation of speed response and torque if any changes occurs in mechanical load[5][6]. Pulse width modulation (PWM) technique is being extensively used  for induction motor speed control for a long time [7][8] and its popularity has been dramatically increased in the recent times because of the raising demands in the low cost energy conversion system. In general, main goal of PWM technique is optimized control of switching power semiconductor switches i.e. IGBT, FET etc. in the inverter circuit to provide the balanced three phase power to the terminal of TIM at a required magnitude, phase and frequency [9][10]. Numerous PWM techniques have already being developed for speed control of induction motor implemented through the Voltage Source Inverter(VSI) [11][12]. Apart from these conventional methods, Duty cycle or duty ratio based control technique is another, approach of delivering converted power in the terminal of TIM [9] and torque control as well [13][14]. Duty Cycle based control algorithm for PWM control is mostly implemented for inverters application for various operations regarding
control of power [15]–[17]. In this paper, a duty cycle based PWM technique is been proposed to introduce a scaler control for TIM by using PI control technique. The PI control system have been applied to control the speed of TIM by adjusting the duty cycle of the terminal voltage from the inverter output during the load changing conditions. To obtain a duty cycle based speed control a relationship between the duty cycle and the magnitude of each harmonics is established. Proposed system’s validity is established via simulation in MATLAB/Simulink environment. Obtained results shows the strength and weakness of robustness and performance response of the speed control system.

2. Methodology and Procedure

2.1. Model of Induction Motor

The mathematical model of TIM is considered based on traditional and simplified per phase equivalent circuit as shown in Figure 1, where voltage applied to the stator winding would directly affect the induced torque and hence slip and speed.

![Figure 1. Simplified model of TIM](image)

The relation between the torque and the voltage magnitude, slip and synchronous speed as shown in (1) and (2)

\[
\tau_{ind} = \frac{3V_{th}^2 R_2}{s} \left( \frac{R_{m}}{R_{m} + R_2 / s} + \left( X_{th} + X_2 \right)^2 \right) \quad (1)
\]

Where, \( S \) is the mechanical slip and \( S \) can be defined as-

\[
S = \frac{\omega_{sync} - \omega_{rotor}}{\omega_{sync}} \quad (2)
\]

So, the synchronous speed of the stator frequency is,

\[
N_s = \frac{120 * f}{p} \quad (3)
\]

And the rotor speed can be defined from the above as –

\[
N = N_s (1 - s) \quad (4)
\]
In (1), the variable $V_{th}$ represents the voltage applied to the stator windings. The values of $R_2$ and $R_{th}$ depend on the resistance values of the motor windings and are not frequency dependent. The variable $s$ is the slip of the motor and would depend on the rotor speed and also the speed of the rotating magnetic field of the respective harmonic. This relation can be seen in (2). The variables $X_2$ and $X_{th}$ are locked rotor reactance values related to the motor windings which depend on the inductance of the motor windings and the synchronous frequency of each harmonics.

2.2. Proposed Controller Design

The main purpose of the proposed control system is to operate the TIM at a desired speed during changeable load condition or to run the TIM at different level of reference speed. Proposed speed control system is designed based on PI control algorithm as shown in Figure 2. So, the control system takes input from a reference speed to operate it at that speed. In other words, the control system supplies necessary amount of supply voltage at the motor terminal through the voltage source inverter. The terminal voltage sets the synchronous speed of the stator’s magnetic field according to the reference speed. The rotor follows the stator’s magnetic field and runs closer to the speed of that synchronous magnetic field. During the disturbances such as changes occurring in the reference speed or change occurring in the mechanical load the rotor speed goes down from the desired frequency. So, the difference between the reference speed and actual speed increase. Here, PI controller contributes to the system by, using its proportional and integral properties to detect the error quickly and resolves the error to obtain the desired speed by using a PI control algorithm. The difference between the desired speed and the actual speed gives the error. PI controller processes the error and generates an optimal duty cycle for the PWM control signal.

Here, PI control system is designed to take the error value by mathematical operation to obtain the difference between reference speed and the actual speed. Then a residual ratio is taken from the error value to the set point value for the input to the proportional and integral action of the controller. Main purpose of the residual ratio is to track the deviation of the actual speed from the desired speed so that, when actual speed i.e. slip is deviated from the desired then controller takes necessary actions to reduce the gap by using PI controller properties. Proportional gain and integral gain of the PI controller is estimated via iterative method. Also, a discrete time integration is performing the integral action of the
PI controller by summing up the error values of instantaneous time until the error gets to zero. Whereas proportional part of the controller ensures that control system’s response is proportional to the error signal. Proportional part of the controller doesn’t let the deviation between the reference speed and the actual speed into a large quantity. However, output of both proportional and integral part is added and kept between a limit of 0 to 0.5. Hence, PI controller is providing the right duty cycle the at which voltage source inverter is operated to provide the terminal voltage.

2.3. PWM and Voltage Source Inverter Model

PWM technology is usually implemented for controlling the average power to the load through an induction motor control circuit. The simplest way to get a PWM is to compare a DC signal with a saw tooth signal. In this proposed speed control system PWM signal is generated from comparing the PI controller output and the time period of set point frequency in the PWM signal generator block as shown in the Figure 2. Here, the necessary carrier waveform for the comparator block is being generated from the set point frequency, which is basically converted into a saw tooth signal. The required DC signal is set the PI controller, where the output of the PI controller limit is set between 0 to 0.5. With the variation from speed due to change in reference or load disturbances the output of the controller is varied which alters the pulse width of the PWM wave as shown in the Figure 3(a). In figure 3(b) actual PWM control signal output from the simulation model is shown.

Figure 3. Modulated wave generation by the controller comparator action.
The generated PWM control signal from the controller determines the switching signal for the power electronic switches and the necessary duty cycle for this speed control system. In this proposed speed control system, PWM is implemented via a single stage H bridge inverter. Since, target of the PWM is to generate an output voltage from the voltage source inverter according to the reference speed. Moreover, a balanced set of three phase voltage of equal magnitude with 120-degree phase shift from each other is needed for AC machine to operate. So, PWM control signal is divided into three parts with a time delay of 1, 2/3 and 1/3 respectively to get a balanced three phase output from the inverter with 120-degree phase shift. The power inverter topology used in this controller is a single stage H bridge for all the phases of the induction motor is shown in the figure below. In this voltage source inverter, to produce a balanced three phase PWM voltage to the motor terminal a balanced three phases set of PWM wave input is considered and output of inverter’s duty cycle is provided by the PWM generator and voltage is supplied by a DC source.

![Single Leg of H Bridge Inverter](image)

**Figure 4.** Single phase voltage output from H Bridge circuit

This would mean that the inverter can be able change the voltage polarity on the load given to it according to the individual switching time of the IGBTs. Hence, PWM voltage source inverter system is designed in Simulink as a subsystem based on an operating principle of a single stage H-bridge inverter. An optimal three phase balanced set of PWM wave is generating the optimal switching pulses for the inverter.

### 2.4. Duty Cycle and Speed Control Relationship

Duty cycle can be expressed as the ratio of duration of pulse i.e. pulse width and the time period of a rectangular waveform, which is usually expressed in percentage (%). Since, the DC voltage is the input voltage of the inverter circuit so, the input voltage has a constant value of \( V_{dc} \). Duty cycle is the measure of how long the inverter output is set for on function i.e. \( T_{on} \) and a total time period of operation \( T \) where \( T_{off} \) is the total time period when the inverter is off in as shown in (6) and can be referred to the Figure 4 above.

\[
T = T_{on} + T_{off}
\]  

And Duty Cycle \( \frac{T_{on}}{T_{on} + T_{off}} = \frac{T_{on}}{T} \)  

So, Total time period, \( T = T_{on} + T_{off} \)  

From the equation 1 above, Variable \( V_{th} \) represents the supply voltage applied to the stator windings of the TIM. Moreover, TIM slip is proportional to rotor resistance, stator voltage and frequency. Since, supply voltage would depend on the duty cycle applied to the system so, duty cycle is directly related to
the motor speed. The PWM control algorithm which is generating duty cycle percentage is provided below in Figure 5.

![Control Algorithm for PWM control signal generation](image).

**Figure 5.** Control Algorithm for PWM control signal generation

### 3. Result and Discussion:

The effect of the duty cycle based PI control on TIM has been presented based on evaluating the performance of speed response of the system by varying the reference speed in different interval and also by varying the load in different intervals. A duty cycle percentage measurement is also calculated while evaluating the speed response for both two cases respectively reference speed variation and load variation. Robustness of the control system performance is included to evaluation system by testing the system with abrupt changes in reference speed at a constant load and sudden changes mechanical load at a constant speed. The results of variation in speed with at a constant load and variation is load with a constant speed is presented below.

#### 3.1. Speed variation with constant load:

The speed response is evaluated in a range of set point speed from a lower value to a higher value with a different disturbance level in a time interval. To evaluate the performance of the duty cycle based speed controller, changes in different level of speed is introduced at a no-load condition. At the start of the operation, TIM is operated at its rated speed, 1430rpm for 5 seconds when with sudden deviation the speed goes down to 75% of the rated speed until 5 seconds, 1073rpm, then again speed changed to 50% of rated speed, 715rpm for next 5 seconds and finally it goes down to 25% of the rated value for another 5 seconds. Then in similar way speed is gradually increased back to the rated speed value at 5
second interval as shown in Figure 6. The good results of speed response performance are summarized in the Table 1.

![Figure 6. Speed Response with Reference Speed Variation](image-url)

**Figure 6.** Speed Response with Reference Speed Variation
**Table 1.** Speed response performance with variation in reference speed and constant load.

| Time Interval (sec) | Reference Speed Variation (rpm) | Steady State Error (%) | Overshoot (%) | Duty cycle variation Percentage |
|--------------------|---------------------------------|------------------------|---------------|--------------------------------|
| From 0, To 5       | From 0, To 1430                 | 1.2                    | 0.016         | 37.60                         |
| 5, 10              | 1430, 1073                      | 1.68                   | 0.026         | 20.69                         |
| 10, 15             | 1073, 715                       | 1.60                   | 0.021         | 17.45                         |
| 15, 20             | 715, 357.5                      | 2.51                   | 0.464         | 9.83                          |
| 20, 25             | 357.5, 715                      | 2.35                   | 0.036         | 17.783                        |
| 25, 30             | 715, 1072                       | 1.96                   | 0.003         | 21.59                         |
| 30, 35             | 1072, 1430                      | 1.68                   | 0.0003        | 24.11                         |

The variation in duty cycle of PWM at these variable speed is also found as such - each time the changes in reference speed occurs the duty cycle varies with the changes. When the speed gradually goes down with the decrease in reference speed duty cycle goes down to zero i.e. no PWM control signal is generated from the PI controller. Where, when the speed is being increased gradually then of duty cycle increases. The variation of duty cycle with the speed variation is shown in Figure 7 below.

![Figure 7. Duty cycle vs Time during Speed Variation with a Constant Load](image)

3.2. Load variation with a constant speed:
Now, the TIM is operated based on a constant speed with a variable mechanical load condition. Here, as constant speed 75% of rated speed is taken as a reference where per unit mechanical load is being gradually increased and decreased at 5 second interval as shown in Figure 8(a). In Figure 8(b) the speed response in being plotted against the reference speed where the variation of actual speed from the reference speed is visible with the attachment of the higher per unit torque value. Since the controller vary the duty cycle of the PWM control signal to reach the desired speed the variation in duty cycle (%) of the modulated pulses are also being observed during the load variation.
At the starting condition, motor is operated at no load speed for a 5 second interval at 75% of its rated speed value. Then the mechanical load is being increased 0.2pu in every 5 second interval to a maximum value of 0.8pu. With the engagement of higher value of load the deviation in actual speed from the desired speed increases and the height value of deviation is found to be around 6% from at 0.8pu mechanical load. The mechanical load is then gradually decreased back to no load again while the speed of the motor gradually increases and eventually catches up to the reference value at no load condition. The speed response of the controller with the disturbance in load and the changes in the duty cycle (%) is summarized in Table 2, where the good results are stated.

**Table 2.** Speed response performance with variation of mechanical load with a constant speed.

| Time Interval (sec) | Mechanical Load Variation (pu) | Steady State Error (%) | Overshoot (%) | Duty cycle (%) |
|---------------------|-------------------------------|------------------------|---------------|----------------|
| From    | To     | 0 | 0.005 | 0.84 | 33.25 |
| 5      | 10     | 0.2 | 0.37 | 0.84 | 49.9 |
| 10     | 15     | 0.4 | 1.72 | 1.32 | 50 |
| 15     | 20     | 0.6 | 3.31 | 1.73 | 50 |
| 20     | 25     | 0.8 | 5.87 | 2.77 | 50 |
| 25     | 30     | 0.7 | 4.42 | 0.68 | 50 |
| 30     | 35     | 0.5 | 2.47 | 0.38 | 50 |
| 35     | 40     | 0.3 | 1.08 | 0.09 | 50 |
| 40     | 45     | 0 | 0.05 | 0.93 | 27.4 |

**Figure 8.** Speed response Performance with load variation
4. Conclusion
In this paper, a PWM based speed controller is utilized for TIM drive, where the duty cycle of PWM is determined by PI control algorithm to control the terminal voltage of the motor. The proposed controller is executed under different reference speed and load conditions. The obtained results show that the developed controller perform well on the TIM speed tracking under the conditions above. The simulation results also demonstrate that the speed response is also achieved with a reduced overshoot and state error as explained in Table1 and Table2. Thus, the robustness of the proposed controller would be very potential to improve the performance of TIM.

5. References
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