Design and Implementation of Microcontroller Based Three Phase Induction Motor Experimental Set

1st Abdullah Berkay Bayındır (Student Member, IEEE)
Faculty of Engıneering,
Dep. of Electrical and Computer Engineering
Texas A&M University at Qatar
Doha, Qatar
abdullah.bayindir@qatar.tamu.edu

2nd Ali Shraida
Faculty of Engıneering,
Dep. of Electrical and Computer Engineering
Texas A&M University at Qatar
Doha, Qatar
ali.shraida@qatar.tamu.edu

3rd Sertac Bayhan (Senior Member,IEEE)
Qatar Enviroment and Energy Research Institute,
Hamad Bin Khalifa University
Doha, Qatar
sbayhan@hbku.edu.qa

4th Haitham Abu-Rub (IEEE Fellow)
Faculty of Engıneering,
Dep. of Electrical and Computer Engineering
Texas A&M University at Qatar
Doha, Qatar
haitham.abu-rub@qatar.tamu.edu

Abstract—**Electrical engineering students face multiple challenges during studying electrical machines drives and control. One of the most common difficulties is to find an experimental kit that has the flexibility to implement any desired approach related to control algorithms, and switching functions. This paper proposes an educational, open-source, and fast experimental setup to provide the students with the ability to perform open and closed-loop speed control of three-phase AC machines. The proposed setup consists of a STM32H735G microcontroller, three-phase inverter, measurement board, speed sensor, and induction motor (IM). Although various speed control applications can be conducted by this set, this paper focuses on the v/f method as a case study. The experimental setup provides the ability to perform open and closed-loop control, real-time monitoring, graphical user interface (GUI), variable frequency, variable modulation index, variable proportional gain, and variable integral gain. Moreover, this solution can be used in a wide range of experimental setups including AC drives, DC drives, inverters, and rectifiers.**

Keywords— v/f control, microcontroller, induction motor drive, SPWM, electrical machines training set

I. INTRODUCTION

Engineering courses consist of theoretical and experimental parts. The theoretical part aims to enhance the learner's ability to analyze and solve complex problems using mathematical relations and logic. While, the experimental part intends to apply mathematical operations and logic in practice. Hardware experiments have a great effect on the understanding of theoretical science [1]. Such experiments boost the ability of students to understand the physics beyond the theory. Moreover, learning through trial and error, leads to noticeably improved performance in total learning, which can be applied through experimental learning [2]. Therefore, it is essential to design an experimental set that includes experiments with microcontrollers and software tools since computer-aided teaching tools have been an integral aspect of the experimental learning [3].

Electrical engineers are required to understand well the basics of electrical motors effectively at the undergraduate level. This is because electric drive systems are continually developing and being used in almost all industrial applications. Furthermore, the theoretical education alone is insufficient to ensure that learners grasp the required knowledge. To reinforce this issue, it is important to provide useful tools to assist experimental tests in the labs. Therefore, various experimental sets have been designed to assist laboratory studies for electrical engineering students. It's common to categorize these training sets in two groups. The first group represents interactive settled training sets. Some examples for this group are: the usage of the Arduino Uno platform for the measurement of static and dynamic characteristics of dynamic systems [4], position and speed control of servo motors using a microcontroller [5], and microcontroller programming sets [6, 7]. In the second group, experiments are web-based kits. These systems are designed to allow users to access the systems remotely. In engineering education, web-based training systems are also commonly employed [8-12]. These sets were implemented based on different kinds of simple microcontrollers like ARDUINO and PIC. However, these controllers have a limited operating frequency and are not suitable for three-

phase applications. This is in particular when a high resolution incremental encoder is attached to a high speed motor. Furthermore, these microcontrollers support only RS232 to communicate with a computer. This makes it completely useless for fast data monitoring. Therefore, there is a need for generalized and flexible solutions that can be given to the students for enhancing their practical knowledge in various drives aspects.

It is realized that the literature suffers from the lack of such experimental solutions that can provide full flexibility to adopt any control strategy. Hence, this paper responds effectively to this need.

In this paper, a three phase IM experimental set is designed and implemented using a STM32H735G microcontroller. The proposed setup supports both open and closed loop control with a sampling frequency of more than 1 MHz. The developed training setup can be configured to control any type of three phase AC motor. Moreover, the speed measurement and reference signal can be monitored using the embedded screen and PC screen.

The rest of the paper is organized as follows, the theory of control algorithm is introduced in section II. The developed experimental setup is described in section III. Experimental results and suggested experiments are presented in section IV. Finally, the paper is concluded in section V.

II. V/F CONSTANT SPEED CONTROL

This control algorithm focuses on the relation between voltage and frequency. The frequency is also proportional with synchronous speed. Conversely, the number of poles is disproportional with synchronous speed as it can be seen from the Eq. (1) [13].

$$N_s = \frac{120f}{P} \tag{1}$$

where, P is the number of poles, f is the frequency that the IM is driven by, and N_s is the synchronous speed. Based on Eq. (1), any increment in f is going to increase the actual speed. The relation between the voltage, flux, and frequency is given by [13],

$$V = C_1 \varphi f T \tag{2}$$

where V stands for induced emf of the induction motor, C_1 is a constant, φ is the maximum flux, and T is the number of turns.

Equation (2) can be written in terms of the voltage as,

$$\varphi = \frac{V}{C_1 f T} \tag{3}$$

On the other hand, the maximum torque (T_{max}) can be computed as follows [13],

$$T_{max} = \frac{3}{\omega_{ms}} \left[\frac{V^2}{R_s \mp \sqrt{R_s^2 + (X_s + X_r)^2}} \right] \tag{4}$$

or,

$$T_{max} = \frac{3}{2\pi f} \left[\frac{V^2}{R_s \mp \sqrt{R_s^2 + (2\pi L_s f + 2\pi L_r f)^2}} \right] \tag{5}$$

where, ω_{ms} is the maximum angular frequency of the stator, R_s is the stator resistance, X_s and X_r are stator and rotor reactance respectively

To simplify Eq. (5), it can be written as follows,

$$T_{max} = \frac{3}{2\pi} \left[\frac{\left(V/f\right)^2}{\frac{R_s}{f} \mp \sqrt{\left(\frac{R_s}{f}\right)^2 + 4\pi^2 (L_s + L_r)^2}} \right] \tag{6}$$

Since R_s is relatively small, the terms that include R_s are neglected. As a result, Eq. (6) can be simplified as follows,

$$T_{max} = K \left[\frac{\left(V/f\right)^2}{\mp \sqrt{4\pi^2 (L_s + L_r)^2}} \right], K = \frac{3}{2\pi} \tag{7}$$

where K represents the constant terms. After some mathematical calculations, Eq. (7) can be written as,

$$T_{max} = \mp K \left[\frac{\left(V/f\right)^2}{2\pi (L_s + L_r)} \right] \tag{8}$$

If the frequency is used alone to control the speed, the torque of the motor will be affected negatively as shown in Fig.1. Therefore, it is important to keep a constant ratio between the voltage and frequency. This will lead to increased stability of the speed controller without affecting the torque.
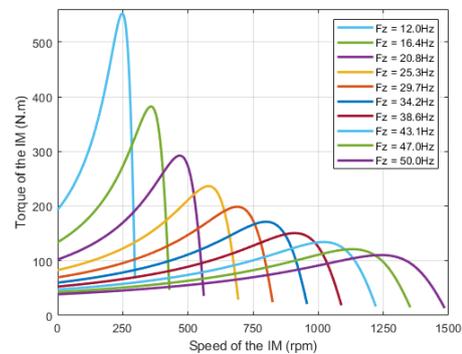

Fig. 1. Relation between maximum torque and speed under fixed voltage

However, there are some limits to this control method. Due to the rated voltage of the three phase

IM, it is not possible to exceed a certain level of voltage. After exceeding this level, the maximum torque is going to deteriorate drastically as shown in Fig. 1 and the motor's windings are going to damage.

The v/f constant control technique is still the most commonly utilized control technique in industrial applications. The main advantage of this method is its simplicity [14]. Therefore, it was adopted in this experimental setup for educational purposes.

III. CONTROL SYSTEM AND HARDWARE DESCRIPTION

In this part, the designed control system and the purposed experimental setup are examined. In this setup, an IM with attached encoder is used. The parameters of the IM are shown in Table 1.

Table 1. Motor parameters

Parameters	Parameter Value
Rated Frequency	50 Hz
Rated Power Factor	0.83
Rated Power	1 kW
Rated Speed	1400 rpm
Rated Voltage	400/230 V
Rated Current	2.65/4.6 A

The control unit is responsible for generating SPWM signals based on the received error that can be obtained by subtracting the measured value from the reference signal [15]. The measurement is obtained from the encoder attached to the IM's shaft. While the reference signal is applied by the user using the the built touch screen. The obtained error is fed to the proportional-integral (PI) controller which guarantees the error convergence to zero.

The output of the PI controller represents the slip angular frequency, which must be limited by certain threshold to ensure that the rated angular frequency will not be exceeded. This may occur when the tracking error is high especially when a new reference signal is applied.

Next, by adding the angular speed of the IM to the output of the saturation block, the compensated stator angular frequency (desired speed) can be obtained.

Finally, frequency, and voltage are determined using the stator angular frequency. The modulation index can be computed from Eq. (9), based on the rated stator angular frequency value to maintain a steady frequency to voltage ratio.

$$Modulation\ Index = \frac{\omega_S}{2*\pi*f} \qquad (9)$$

$$\sin(\theta)\,, \theta = \int 2\pi(f)\,dt \qquad (10)$$

The frequency is then multiplied by 2π and the result is integrated with respect to time to get the theta in Eq. (10). Then, the argument and the modulation index are fed to the SPWM block to generate six gate control signals to drive the three phase inverter. Finally, these signals are sent to the gate drives of the three-phase inverter. The proposed control method is shown in Fig.2.

The experimental setup consists of STM32H7 microcontroller, external monitor, DC source, three phase inverter, three phase induction motor, and oscilloscope for visualizing the current signals. The scheme of the experimental setup is given in Fig. 3.
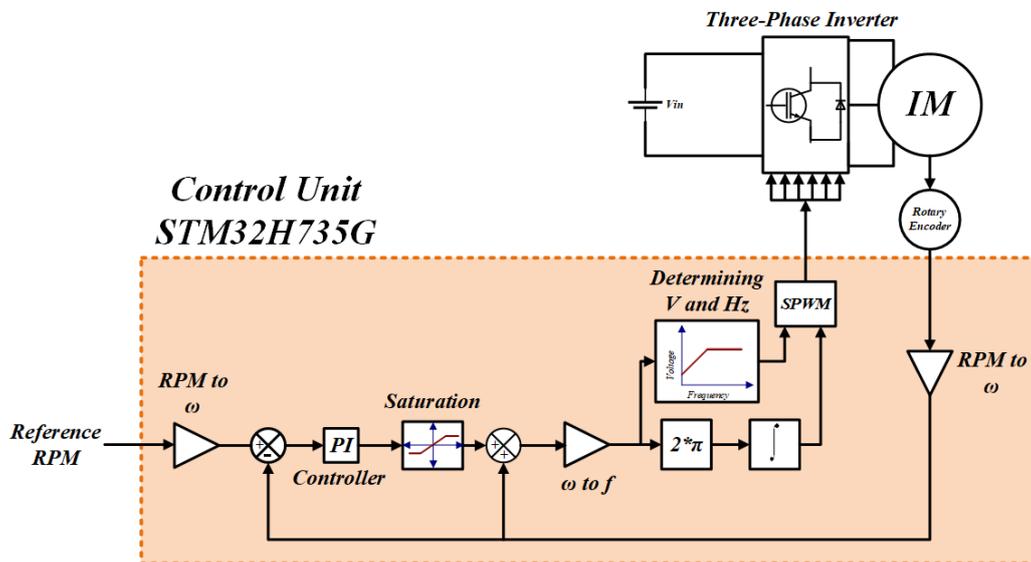

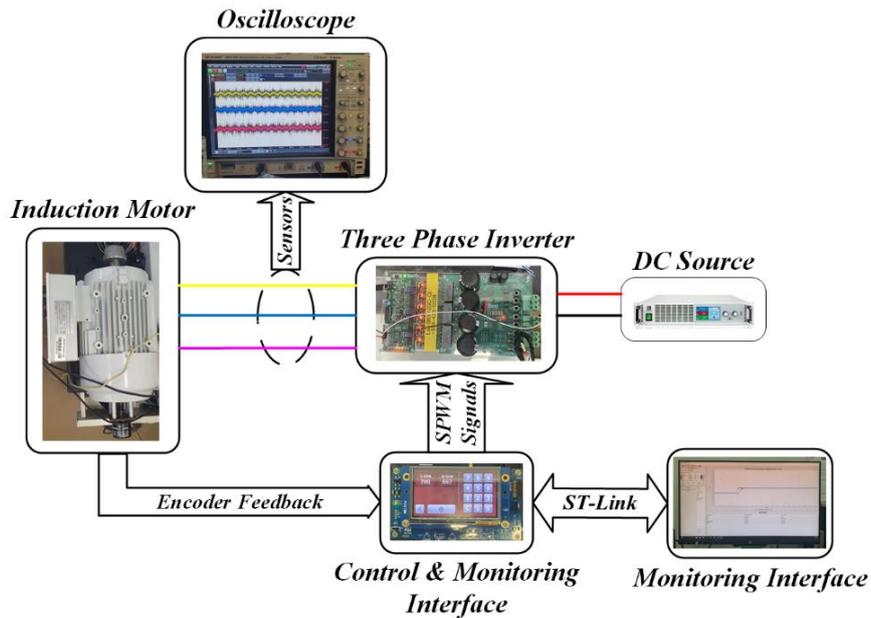Fig. 2. Block diagram of the designed experimental set

Fig. 3. Experimental Setup

With the proposed test setup, students can adjust control parameters such as frequency, modulation index, and rpm through the touchscreen. They can also select open and closed loop modes as shown in Fig. 4 and Fig. 5 respectively. Moreover, proportional (K_p) and integral (K_i) gains can be tuned online using the STM Studio tool as shown in Fig. 6.
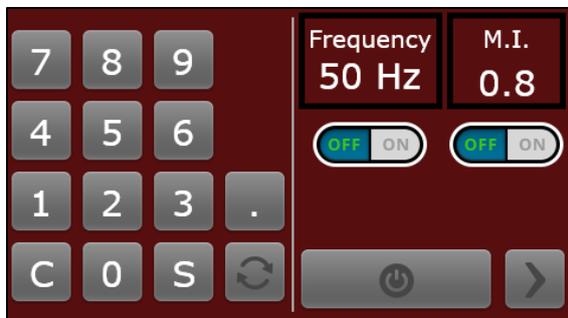

Fig. 4. Open loop control interface

Fig. 5. Closed loop control interface

Fig. 6. Adjustment of K_i and K_p parameters

In open loop mode, the frequency and modulation index are given separately by the user. While in the closed loop mode, they are computed by the control algorithm. For the close loop control, the user can set the reference speed and observe the response of the measured speed. In both modes, transient response, controller's gains effect, and real time charts can be monitored online using STM Studio. Fig. 7 and Fig. 8 show some examples related to the online monitoring system.
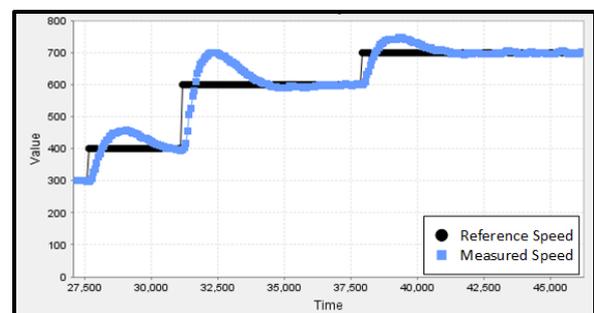

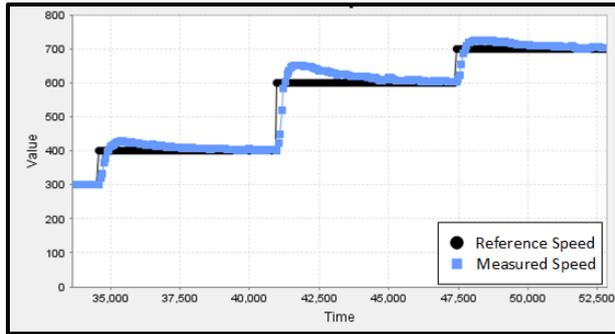Fig. 7. Tracking performance with $K_p = 6$

Fig. 8. Tracking performance with $K_p = 3$

At startup, the microcontroller will initialize all components such as timers, interrupts, and peripherals. Then, the user can choose the control method to be investigated. If the closed loop is selected, he/she can set the reference speed and monitor the results until the stop button is pressed. On the other hand, if the open loop is selected, the user can apply the frequency and modulation index seperately. These steps are shown in Fig.9.
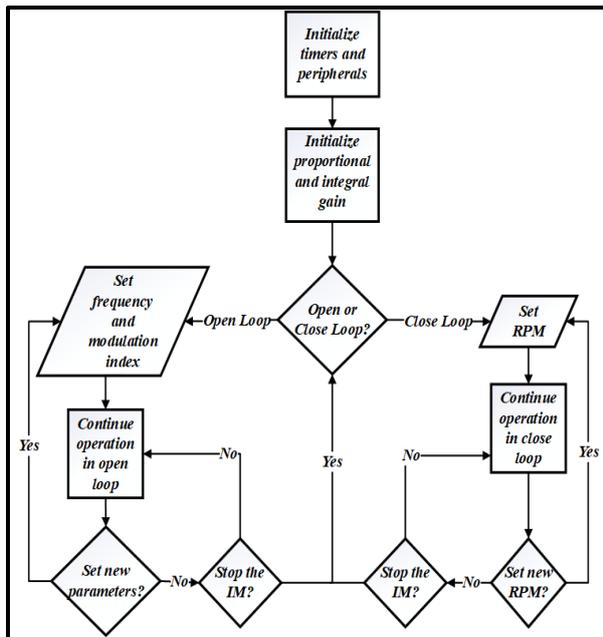

Fig. 9. Flowchart of the designed experiment set

IV.   EXPERIMENTAL RESULTS

In this section, two case studies will be presented to show the flexibility and the advantages of the proposed set. The first case represents the open loop control, while the second one represents the closed-loop control.

•   Case Study 1: Open Loop Control

In the first experiment, students can control their IM's with the open-loop interface. In order to have a better understanding of the open-loop control, students can observe the effects of frequency and voltage (modulation index) on speed and torque.

STM Studio is used to monitor the speed while the current waveforms can be monitored by an oscilloscope as shown in Fig.10 and Fig.11. Where each channel has a 0.2 A/ div and the time scale is 20ms/div.
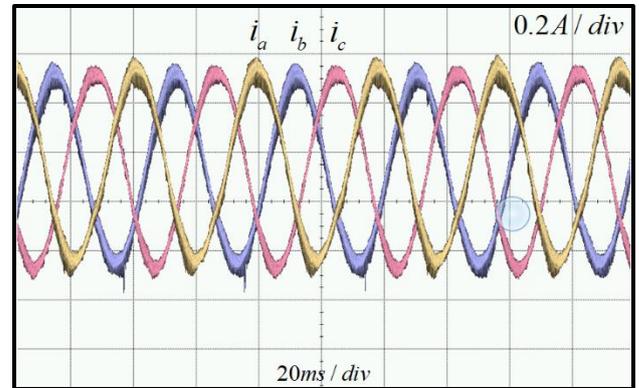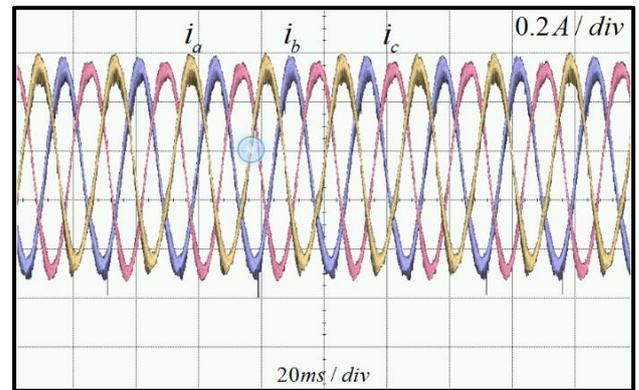

Fig. 10. Phase currents for 25 Hz

Fig. 11. Phase currents for 40 Hz

For Fig. 10, the frequency is 25 Hz and the modulation index is 0.5. While in Fig. 9, the frequency is 40 Hz and the modulation index is 0.7. If the modulation index is decreased and the frequency is held fixed, students are going to see that the motor is stopped. This occurs due to the lack of torque applied to run the motor since an approximately constant voltage to frequency ratio is required. As a result, students are going to notice that this behavior of the IM is aligned with the theoretical part.

•   Case Study 2: Close Loop Control

In the second experiment, students can use the closed-loop interface to control the speed of the IM. The student can observe speed response and the effects of proportional and integral gains.

This experiment aims to enable the students to monitor the effects of controller's gains on the response as shown in Fig. 7 and Fig.8. Where the proportional gain was changed online from 3 to 6 and the effects (such as overshoot) can be observed clearly. Moreover, the student can observe the

current required for different speeds as shown in Fig.12. Where the scale is 2A/div for Y axis, and 20 ms/div for the X axis, and the results are given numerically in Table 2.

Students can use this experiment for better understanding of the physical motor and system behavior. This would boost their ability to understand the effects of parameters, controller's gains, and applied reference signal on the speed and current responses.
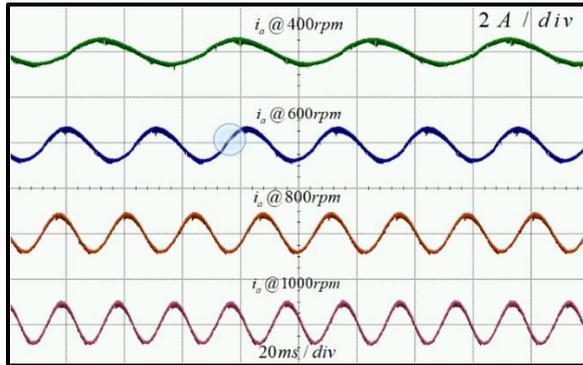

Fig. 12. The behavior of phase current for different speeds

Table 2. Waveform Properties

Wave	Current (mA)	f (Hz)	Modulation Index	RPM
Green	112	20	0.2	400
Blue	140	30	0.26	600
Orange	155	41	0.32	800
Pink	171	50	0.38	1000

V. CONCLUSION

In the presented paper, an experimental setup for AC motor drives was proposed, implemented, and validated to assist theoretical science in control and drive educational subjects. Specifically, the basic theory of IM drives.

The proposed setup provides multiple advantages in terms of effective education, cost, simplicity, flexibility, run-time tuning, parameters control, and real time response monitoring. Multiple examples and case studies were also proposed to enrich students' abilities to conduct hardware experiments.

All possible scenarios, parameters, and modes can be easily implemented by the students. The motor response, speed behaviour, and current response can be monitored online as shown in the performed expirements.

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