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High-performance speed control for three-phase induction motor based on reverse direction algorithm and artificial neural network

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ABSTRACT

This research proposes two approaches for determining the required frequency and modulation index for a pulse-width-modulation (PWM) system in a variable frequency drive (VFD) to control the speed of the three-phase induction motor. The first approach which is the reverse direction algorithm (RDA), uses a set of equations to calculate the necessary frequency and voltage for maintaining a constant motor speed under varying load conditions. The second one involves training a neural network (NN) on data collected by the RDA, which can then be used to continuously adjust the motor speed in real time to adapt to changing load torque requirements. Simulation and laboratory models for the three-phase induction motor are built and the proposed RDA-NN controller is examined. Results have proved that the proposed controller is effective in providing a stable and responsive motor speed control system.

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1. INTRODUCTION

Induction motors are increasingly used in the electro-mechanical energy conversion field thanks to their high performance, low cost and reliability [1]. Most of these applications require not only quick response but also speed control to maximize torque and achieve high efficiency. That is because when the load on an induction motor changes, the speed of the motor also changes. However, mechanical loads should be driven at a desired specific speed. The industry must keep the motor speed constant to achieve reliable and robust machine operation efficiency at different loads. In the past, the three-phase induction motors which used to be operated at a constant speed were difficult to control due to the inefficient conventional methods. Thus, a need arises to propose new speed control methods for the three-phase induction motors which the present study aims to address.

New control methods have allowed the development of advanced methods to control the speed of induction motors in the industry [2]. For example, Mobarra *et al.* [3] have developed a control algorithm for the alternating current (AC) compensator which drives the stator of the variable speed diesel generator. The speed is modified using a variable frequency drive in response to the load. The generator rotating stator is adjusted by the controller to enhance the operational efficiency taking into account load variation. The induction motor's performance could be improved by choosing the right control [4]. The speed control of a three-phase induction motor can be achieved by changing the supply frequency, the number of stator poles, or the rotor slip. The developed electromagnetic torque is proportional to the ratio of supply voltage and frequency. For maintaining a constant electromagnetic torque, this ratio has to be kept constant throughout the speed range [5].

Variable frequency drive (VFD) is used for this purpose [6], [7]. VFDs control the motor speed and motor torque by controlling the frequency and magnitude of voltages and currents supplied to the motor, through the pulse-width-modulation (PWM) [8]. Scalar and vector methods are used in variable frequency control for induction motors. They provide an acceptable response to variable speed and load situations [9]. In [10], the frequency control for induction motors is performed using curve fitting methods based on Polynomial, Fourier, and Gaussian models. It is expected that these methods could improve motor performance; the Polynomial curve fitting method has in particular shown the best performance. In [11], a multilevel inverter fed medium voltage VFDs is used to demonstrate the three control methods: scalar control (SC), indirect field oriented control (IFOC), and direct torque control (DTC). The DTC has shown a better dynamic response in comparison to SC and IFOC.

Khudier *et al.* [12] propose a programming logic controller (PLC) to regulate the VFD for a constant-speed induction motor subjected to load changes. The frequency varies from 50 to 59.2 Hz when the load current is changed from 0.095 to 0.774 A for a constant average speed of 1402.45 rpm. Advanced speed control for a five-leg voltage source inverter (FLVSI) that drives a dual three-phase induction motor system used in industry is proposed by Lim *et al.* [13], and the results guarantee stability.

In [14], a simple and elegant control algorithm has been proposed for realizing the DTC-space vector sinusoidal pulse width modulation (SVSPWM) that relies less on motor parameters. Because there is just one proportional integral (PI) controller required, there is a significant reduction in the computational work. In [15], various VFDs operating under induced voltage magnitude variation and voltage imbalance are compared for their efficiency outcomes using the same motor. In general, when the voltage imbalance increases, the efficiency of the VFD system decreases.

Azizipanah-Abarghooee and Malekpour [16] suggest an induction motor variable frequency drive to test its suitability for managing the smart grid's frequency. This controller allows the driver to reduce its power in response to a drop in grid frequency. Through a motor's speed rate limiter, the dynamic limitation of the drive caused by the inertia of the load is taken into account.

Intelligent control techniques are used to improve the performance of the three-phase induction motors subjected to load changes. To reduce the steady-state error and transient response of an induction motor's speed under varying load conditions, the fuzzy logic controller is proposed by Firdaus *et al.* [17]. Four families of machine learning algorithms (i.e. decision trees, support vector machines, k-nearest neighbors, and ensemble) were utilized in MATLAB for fault diagnosis of induction motors fed by VFDs. For each test, the motors' stator current and vibration signals are recorded concurrently under steady-state conditions, and the usefulness of both signals for defect identification is assessed. In the lab, two identical 0.25 HP induction motors are tested with various VFD output frequencies and motor loading under healthy, single and multi-fault circumstances.

Zemmit *et al.* [18] and Metha and Karvekar [19] have developed an improved DTC of a three-phase induction motor utilizing a PI controller modified using a genetic algorithm (GA) and fuzzy logic controller (FLC) to address the problems with conventional DTC that are characterized by high torque and flux ripples. Their results show improvements in torque and flux ripple. It has reduced the torque and flux ripple by more than 64.44% and 50%, respectively. Habib [20] present DTC using a traditional PI speed regulator based on fuzzy logic (FL) and an adaptive neuro-fuzzy inference system (ANFIS). Comparisons between the outcomes of the simulations using the ANFIS and FL intelligent regulators and a conventional DTC with 36 sectors are made. The proposed method is valid and reduces the electromagnetic torque as well as the total harmonic distortion (THD) value of the stator current and stator flux ripple, according to a comparison between DTC command and intelligent regulators.

An artificial neural network (ANN) control is proposed in [21] for a smooth start of a three-phase induction motor. The results of the proposed acceleration validate the effectiveness of the ANN controller under different loading conditions. To get the desired stability and the best response for getting the appropriate speed of the induction motor, a nonlinear model predictive control is applied [22]. An intelligent control algorithm using a PID controller-based back-propagation neural network (BP-NN) is proposed for the AC motor speed control. The results demonstrate the system’s adaptability, robustness and ability to intelligently regulate the speed of the AC motor [23]. Other meta-heuristic control approaches could also be used to enhance the smooth start of a three-phase induction motor [24], [25].

Considering the previous related research, this research contributes to knowledge on speed control of the three-phase induction motor through presenting two approaches: reveres direction algorithm (RDA) and neural network (NN) to determine both the supply frequency and supply voltage for the three-phase induction motor for a constant speed at variable load torques. When a load change is applied to the motor shaft, the RDA calculates the necessary frequency and the modulation index of the PWM inside the VFD to retrieve the rated speed. To calculate the required frequency and modulation index by RDA, the motor speed is recorded and recycled through a series of equations in the reverse direction of the motor's power flow. In the second stage, a real-time NN controller is proposed to retrieve the rated speed of the three-phase induction motor subjected to the load change. The NN is trained for a constant speed of the three-phase induction motor speed using the data set obtained from the RDA control stage.

The rest of the paper is organized as follows; a representation of the three-phase induction motor is presented in section 2. Section 3 describes the method; the proposed RDA and NN controllers. The results and discussions are given in section 4, and section 5 concludes the work.

2. REPRESENTATION OF THE THREE-PHASE INDUCTION MOTOR

Although the three-phase induction motors are fixed speed, they are widely used in industry due to their simplicity and low cost. The VFD provides the variable frequency for a variable speed induction motor [26]. The three-phase induction motor has two parts; the stator and the rotor. The per-phase equivalent circuit of the three-phase induction motor is shown in Figure 1 [27]. When the three-phase power supply voltage is applied to the stator winding, a rotating magnetic flux is produced in the air gap. Due to this rotating magnetic flux, an induced voltage is produced in the rotor circuit. The interactivity between the stator flux and rotor flux rotates the rotor at a speed less than the synchronous speed, causing a differential speed between the synchronous speed and rotor speed called rotor slip speed.

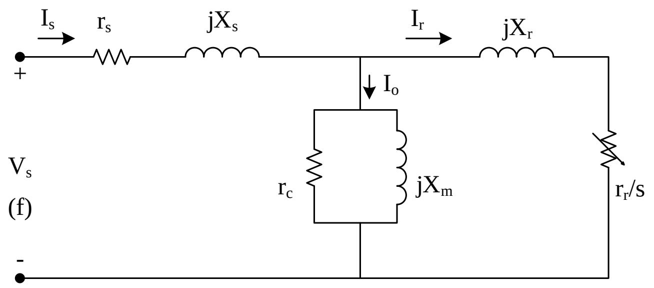

Figure 1. The per-phase equivalent circuit of the 3-phase induction motor

To analyze the three-phase induction motor, there are two methods to represent the motor: the actual variables model and the $d-q$ model. The advantage of the $d-q$ model is that it has fewer variables in the representative equations and the inductances are independent of the position of the rotor [28]. In the $d-q$ modelling of the motor, the three a, b, and c variables are transformed into two-axis variables to get the speed and torque expressions. The Park transformation for stator $P(\theta_S)$ is given in (1) [29].

$$\begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix} = P(\theta_S) \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{1}$$

where

$$P(\theta_S) = \frac{2}{3}\begin{bmatrix} cos(-\theta_S) & \cos\left(-\theta_S + \frac{2\pi}{3}\right) & \cos\left(-\theta_S - \frac{2\pi}{3}\right) \\ \sin(-\theta_S) & \sin\left(-\theta_S + \frac{2\pi}{3}\right) & \sin\left(-\theta_S - \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{2}$$

Similarly, the transformation for the rotor can be obtained by replacing θ_S by $(\theta_S - \theta_r)$. Also, the electro-magnetic torque can be represented in $d-q$ form as in (3):

$$T_e = \frac{3}{2} P L_m \left(i_{qs} i_{dr} - i_{ds} i_{qr}\right) \tag{3}$$

where θ_r: Rotor angle, θ_S: Stator angle, P: No of poles, and L_m : Mutal inductance.

3. METHOD: SPEED CONTROL OF THE THREE-PHASE INDUCTION MOTOR

This section presents a thorough description of the proposed methodologies and data analysis procedures. Two phases are proposed to control the speed of a three-phase induction motor by restoring it to its rated speed following a torque change. In phase one, an RDA is proposed and explained in subsection 3.1. This algorithm determines the motor's necessary supply frequency depending on speed, torque, power, and slip. The required voltage for the motor is calculated using the constant relationship between supply frequency and voltage. The RDA is proven as a high-performance control for the induction motor as demonstrated in subsection 3.1.

In the second stage of this research, an NN technique is proposed as an online mode controller to restore the rated speed of the three-phase induction motor after the load torque change. This technique provides a quick response to load torque changes made to the motor shaft. The data set is acquired from the first phase and is utilized to train the ANN for real-time control of motor speed subjected to load fluctuation since the results achieved in the first phase utilizing RDA are accurate and highly perfect.

3.1. Reverse direction algorithm for a constant speed at variable load conditions

A change in the motor load causes a speed variation on the motor. The speed of the three-phase induction motor depends on the stator frequency, the number of stator poles and rotor slip. When the load torque is changed, the rotor speed, air-gap power (P_2), and mechanical power (P_m) are changed.

In this work, RDA for a constant speed at variable load conditions is used to determine the supply frequency required for a constant speed at variable load conditions. When a load change is applied to the motor shaft, the RDA calculates the necessary frequency and the modulation index of the PWM inside the VFD to retrieve the rated speed. In order to calculate the required frequency and modulation index by RDA, the motor speed is recorded and recycled through a series of equations in the reverse direction of the motor's power flow. This RDA employs the equations related to the speed, torque, power, slip, and supply frequency of the motor. The steps below explain how the speed of the motor is controlled by RDA after being subjected to a load change.

- Record the rotor speed (ω_r) and electromagnetic torque (T_e), when the load torque is changed.
- Determine the air-gap power (P_2) and mechanical power (P_m) of the induction motor according to (4) and (5):

$$P_2 = T_e \times \omega_s \tag{4}$$

where ω_s is the synchronous speed at a rated frequency.

$$P_m = T_e \times \omega_r \tag{5}$$

- Use the air-gap power (P_2) and mechanical power (P_m) to determine the rotor slip, as demonstrated in (6).

$$S = 1 - \frac{P_m}{P_2} \tag{6}$$

- Substitute the rotor slip in (7) to calculate the required synchronous speed for retrieving the rated speed of the motor. When the slip in (5) is changed, the synchronous speed in (7) is adjusted to new values if the load torque changes while maintaining a constant rotor speed.

$$N_s = \frac{N_r}{1-S} \tag{7}$$

- Substitute the new value of the synchronous speed in (8) to find the new supply frequency required for the desired motor speed.

$$f = \frac{p \times N_s}{60} \tag{8}$$

where p is pole-pairs.

The air-gap flux of the motor is proportional to the ratio of the supply voltage (V_s) to the frequency (f). For smooth speed control, constant air-gap flux is required. Also, a high torque may be obtained for all levels of speed. This can be accomplished by maintaining a constant ratio of (Vs/f). Therefore, if there is a change in the load torque, it is important to change V_s and f simultaneously. To produce this inside VFD, the frequency of the reference signal and modulation index are controlled. The RDA control is applied on the three-phase induction motor for a constant speed at variable load torque conditions. Table 1 shows the RDA response for load torque changes made to the motor shaft. The rated motor speed to be maintained is 1,467 rpm at a rated torque of 9N.m. The proposed RDA controller demonstrates its superior capability in maintaining the rated motor speed in the face of the load torque changes as shown by the results.

Table 1. RDA results for load torque changes made to the three-phase induction motor

Case No.	Load torque TL (Nm)	Before Control Action					After Control Action						
		Input current (A)	Electro-magnetic torque, Te (Nm)	**Rotor speed (rpm)**	Air-gap power, P2 (W)	Mech. power, Pm (W)	New stator freq. (Hz)	New supply voltage (V)	Input current (A)	Electro-magnetic torque, Te (Nm)	**Rotor speed (rpm)**	Air-gap power, P2 (W)	Mech. power, Pm (W)
1	0.495	1.4777	0.9628	**1497**	151.242	150.937	48.9988	440.9889	1.4624	0.9535	**1467**	149.768	146.470
2	2.330	1.592	2.796	**1491**	439.2	436.5	49.1944	442.7493	1.595	2.788	**1467**	438	428.3
3	3.165	1.679	3.63	**1488**	570.2	565.7	49.2856	443.5702	1.669	3.623	**1467**	569.1	556.5
4	4.495	1.852	4.958	**1484**	778.8	770.4	49.4344	444.9095	1.848	4.958	**1467**	778	760.8
5	6.495	2.18	6.956	**1477**	1093	1076	49.6683	447.0145	2.179	6.953	**1467**	1092	1068
6	7	2.2728	7.4603	**1475**	1171.9	1152.3	49.7297	447.5670	2.2766	7.4578	**1467**	1171.5	1145.6
7	12.330	3.442	12.78	**1454**	2008	1946	50.4642	454.1776	3.456	12.79	**1467**	2009	1965
8	14	3.8757	14.4504	**1445**	2269.9	2187.4	50.7442	453.1457	3.9039	14.457	**1467**	2270.9	2220.4
9	16	4.4488	16.4467	**1434**	2583.4	2470.5	51.1347	456.6325	4.5334	16.456	**1467**	2585.0	2528.1
10	17	4.764	17.44	**1428**	2740	2609	51.3628	458.6699	4.75	17.46	**1467**	2742	2682

3.2. Neural network control

As a second phase in this work, the NN is proposed as a real-time controller to retrieve the rated speed of the three-phase induction motor subjected to the load change. It is trained to control the voltage and frequency of the VFD to keep the motor speed constant. The NN is trained via MATLAB-Simulink environment. The NN is trained using the RDA data set that was obtained in subsection 3.1. The motor rotor speed (rpm), mechanical power (W), and motor input current (A), for 100 cases of load torque, are the input data to the NN. The outputs of the trained ANN are the frequency of the reference signal and the modulation index that are needed for the VFD to restore the motor speed.

A feed-forward NN is used in this work as shown in Figure 2. The hidden layer contains ten neurons, the input layer includes three neurons, and the output layer includes two neurons. The training algorithm used is Levenberg-Marquardt. It requires more memory but less time for training.

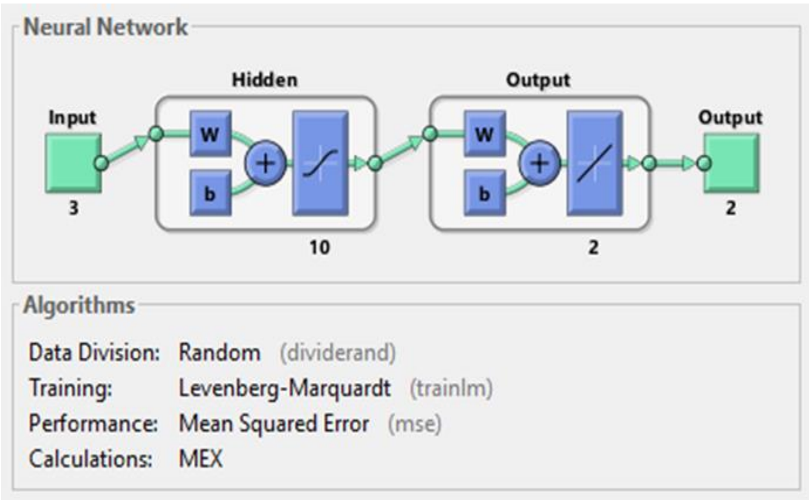

Figure 2. ANN structure used in this work

Figure 3 shows the ANN's performance during the training, validation and test stages. The model's capability to generate the desired output is determined by the regression factor (R). It ranges from 0 to 1. If it reaches 1, it means that the ANN's training produces the best results. As shown in Figure 3, the regression factor obtained throughout this training procedure is one for training, validation, testing, and for all, leading to the finest training. Additionally, Figure 4 displays the mean squared error (MSE) against the periods. It is shown that the best validation performance is 0.081722 of MSE at epoch 21.

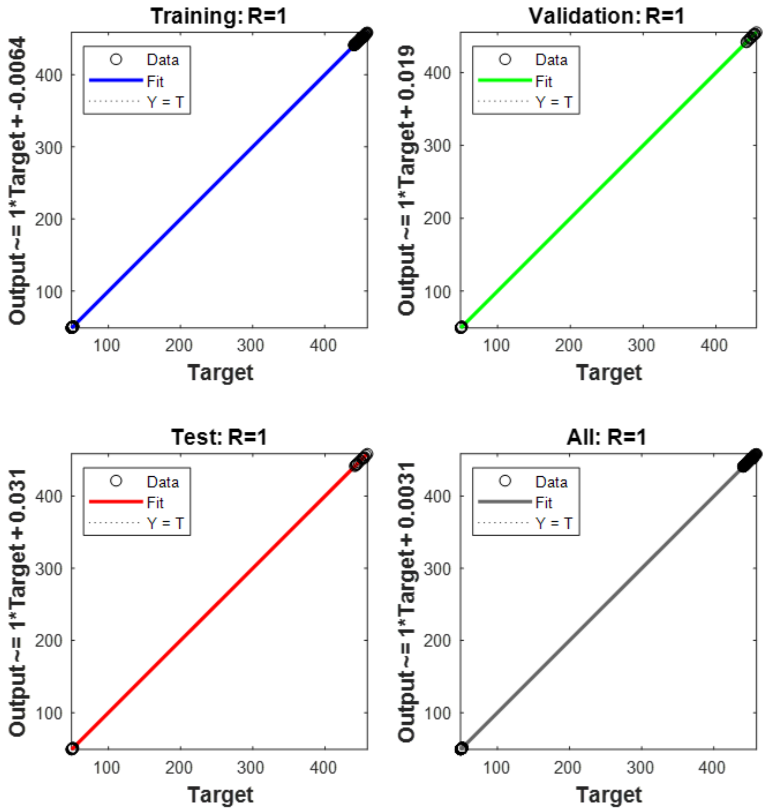

Figure 3. Performance of ANN training in terms of regression factor (R)

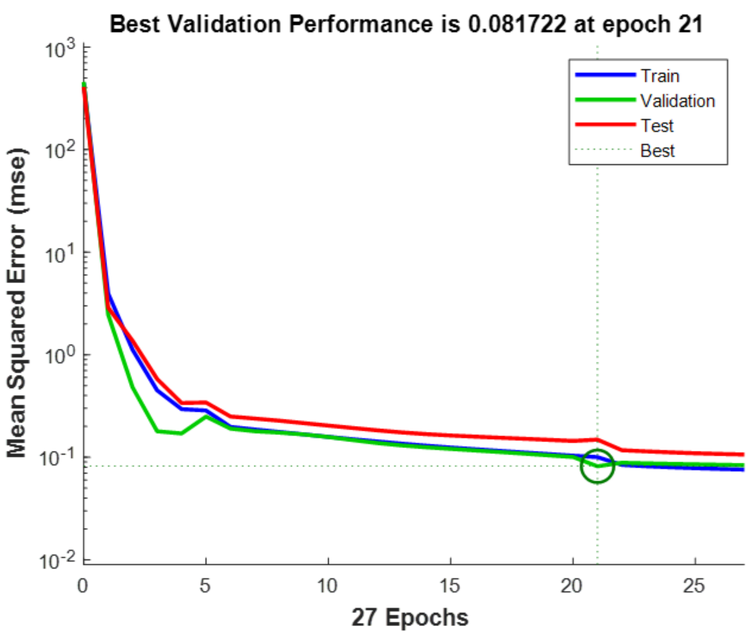

Figure 4. Performance of NN training in terms of MSE

4. RESULTS AND DISCUSSION

A 450 V, 3-Phase, 2-pole, 50 Hz induction motor is used. It has a nominal power of 1.38 kW. The rated speed and the rated torque of this motor are 1467 rpm and 9 N.m respectively. The values of other parameters of this motor are listed in Table 2.

Table 2. The template values of the three-phase induction motor

The parameter	Value
Rated voltage	450 V
Supply frequency	50 Hz
Nominal power	1.38 kW
Stator resistance (R1)	2.45 and
Rotor resistance (R2)	2.7222
Leakage inductance for stator (Ls)	1.56 mH
Leakage inductance for rotor (Lr)	1.56 mH
Mutual inductance (Lm)	0.5634 H
Number of pole pairs	2
Moment of inertia	0.0131 kg.m2
Friction factor	0.002985 N.m.s
Rated speed	1467 rpm
Rated torque	9 N.m.

4.1. Simulation results

In this work, the NN technique is proposed as an online mode controller to restore the rated speed of the three-phase induction motor after the load torque changes. The block diagram simulation is shown in Figure 5. Different load torques are applied to evaluate the effectiveness of the proposed NN controller for the three-phase induction motor's real-time speed control. The proposed NN controller determines the necessary frequency and the modulation index of the PWM inside the VFD when a load change is applied to the motor shaft, varying the speed. The 3-phase induction motor receives the output of the VFD at the new frequency and voltage to restore to the rated speed. The proposed NN controller's and RDA control's actions for various load changes are shown in Table 3. The results demonstrate the higher capability of the proposed NN to recover the rated speed as well as the closeness between the two proposed controllers; NN and RDA. Furthermore, the results show that the load torque variations could recover up and down by roughly twice as much as the rated torque.

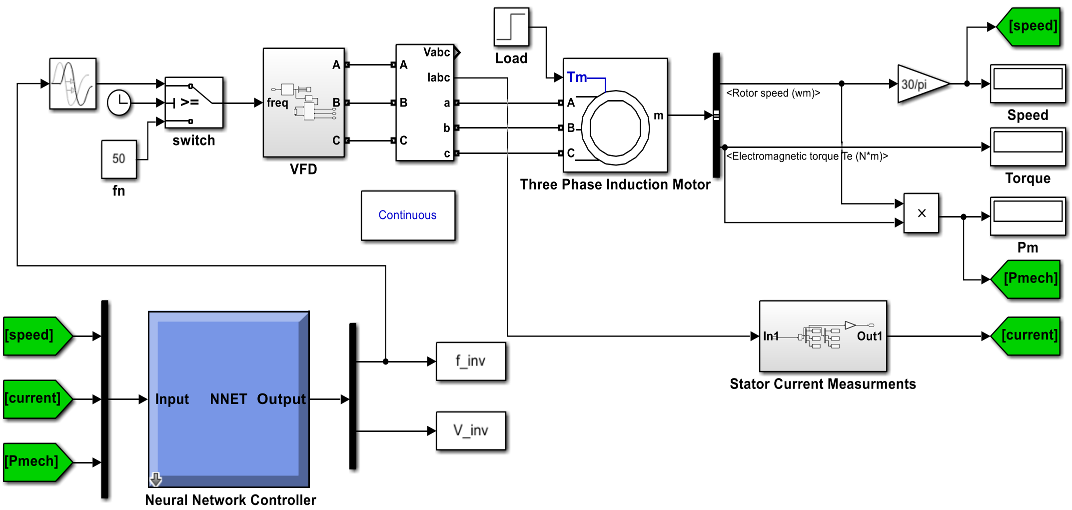

Figure 5. The block diagram simulation

To test the dynamic response of the three-phase induction motor, a simulation model of the motor is built. Several case studies have been conducted to test the response of the motor to load changes based on the NN controller. The test case scenario is as follows: starting the induction motor with the rated condition (rated speed of 1467 rpm at rated torque of 9 N.m) during the time interval from 0 to 1.5 sec, then making a load change at 1.5 sec, and finally initiating the NN controller at 2.5 sec. Figure 6 shows the motor speed response when the load torque is changed to 2.33 N.m. It is lower than the rated torque and the motor speed is increased. When the NN controller is activated at 2.5 sec, new frequency and the modulation index are applied to the PWM and the rated speed is recovered. Figure 7 shows the motor speed response when the load torque is increased to 12.33 N.m, which is greater than the motor's rated torque, as well as how the NN controller retrieves the motor's rated speed.

To further enhance the motor speed response during load changes and the NN controller actions, a damper with a natural frequency of 5 Hz and a damping ratio of 0.55 is proposed. The motor speed response for a load torque of 17 N.m, with and without a damper, is shown in Figures 8 and 9, respectively. The results show an improved speed response of a very small overshoot and few oscillations.

The results in Figures 6 to 9 further demonstrate that the NN controller, based on oscillation and low steady-state error, provides high performance for the three-phase induction motor speed control when compared to the methods in the literature. Also, the results show the effectiveness of the NN controller, which is trained using RDA equations, as opposed to the majority of approaches described in the literature [30]–[32] which rely on heuristic algorithms for controller training.

Table 3. Comparison between NN controller and RDA controller for induction motor speed control

Case No	Load torque change and rotor speed before correction		Control action using NN controller			Control action using RDA controller		
	TL (Nm)	Rotor speed (pm)	New stator Freq. (Hz)	New supply voltage (V)	Rotor speed (rpm)	New stator freq. (Hz)	New supply voltage (V)	Rotor speed (rpm)
1	0.495	1497	48.9800	441.2000	1466	48.9988	440.9889	1467
2	2.330	1491	49.1900	442.8000	1466	49.1944	442.7493	1467
3	3.165	1488	49.2700	443.7000	1466	49.2856	443.5702	1467
4	4.495	1484	49.4300	445.0000	1467	49.4344	444.9095	1467
5	6.495	1477	49.6800	447.1000	1467	49.6683	447.0145	1467
6	7	1475	49.7400	447.6000	1467	49.7297	447.5670	1467
7	12.330	1454	50.4700	452.6000	1467	50.4642	454.1776	1467
8	14	1445	50.8400	452.8000	1468	50.7442	453.1457	1467
9	16	1434	51.1300	456.5000	1467	51.1347	456.6325	1467
10	17	1428	51.2100	458.4000	1466	51.3628	458.6699	1467

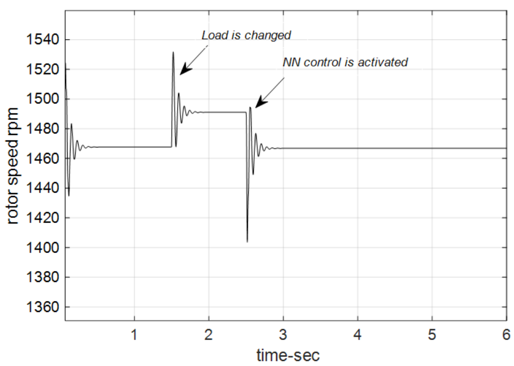

Figure 6. Motor speed response to a load torque of 2.33 N.m, employing the NN controller

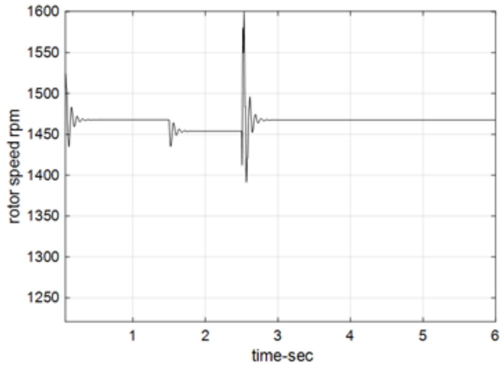

Figure 7. Motor speed response to a load torque of 12.33 N.m, employing the NN controller

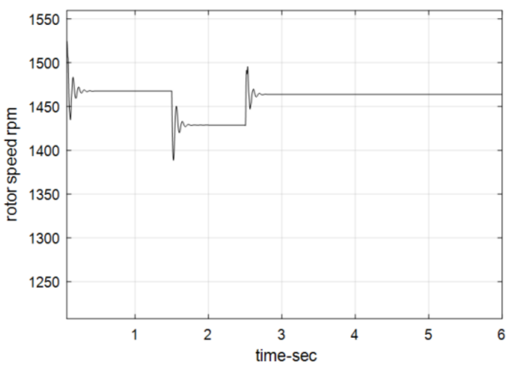

Figure 8. Motor speed response to a load torque of 17 N.m, employing the NN controller without a damper

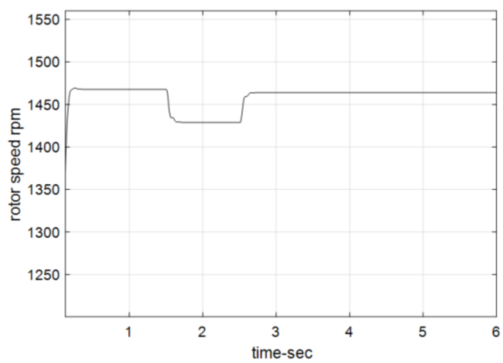

Figure 9. Motor speed response to a load torque of 17 N.m, employing the NN controller with a damper

4.2. Laboratory model of the three-phase induction motor

This section demonstrates the experiments conducted. A three-phase induction motor laboratory model was built to investigate and verify the suggested RDA-NN technique's ability to control the motor speed at varying load torques. The laboratory setup is shown in Figure 10 and the ratings of the squirrel cage three-phase induction motor are; power: 300 W, voltage: 220/380 V, D/Y current: 1,38/0.8 A, Δ/Y frequency: 50 Hz $Cos\varphi$: 0.74, and speed: 2.800 rpm. For this laboratory test, the desired speed is fixed at 2,400 rpm. The oscilloscope measures for the motor speed under varying load torque are displayed in Figure 11. The load torque varies between 0 and 1.1 N.m., and the speed remains constant at the desired value of 2,400 rpm. Results have shown that when a varying torque is applied to the motor, the RDA-NN controller can keep the motor running at the desired speed.

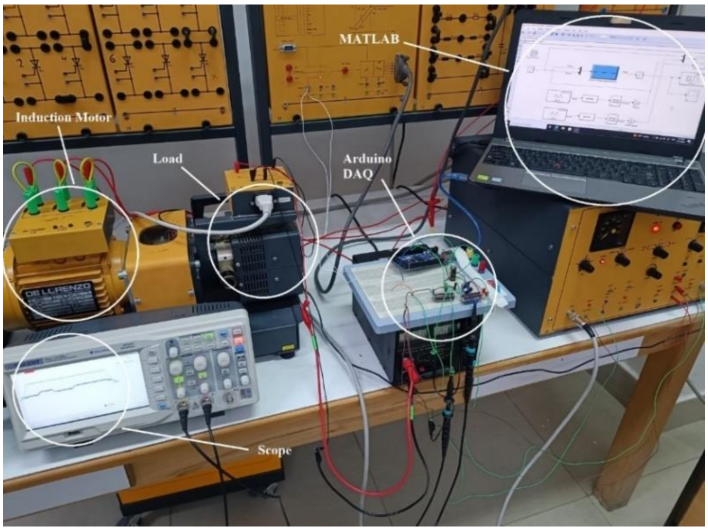

Figure 10. The three-phase induction motor laboratory setup

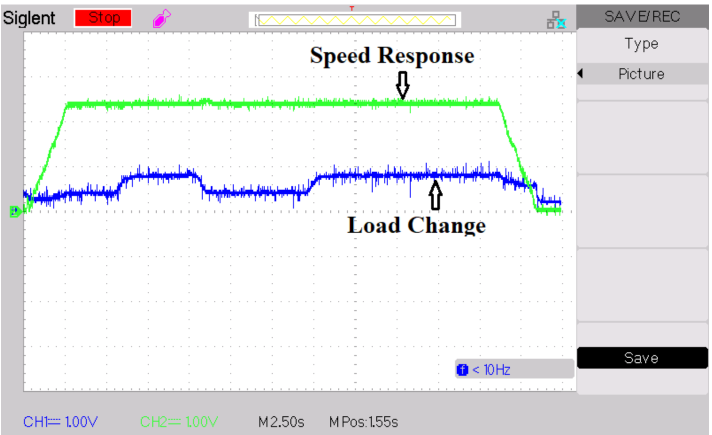

Figure 11. Motor speed response to a varying load torque

5. CONCLUSION

In this work, two controllers are proposed to determine the required supply frequency for the three-phase induction motor in order to maintain a constant speed at variable load torques. Using the RDA, a set of equations is proposed to calculate the required supply frequency and voltage for a constant motor speed at different load changes. Moreover, an NN-based real-time controller is employed in online mode to control the motor speed. The NN is trained using the RDA data set. The training, validation, and test stages show the best performance for the NN based on the regression factor and mean squared error compared to the previously reported control approaches. An acceptable range of supply frequency is determined by RDA and NN controllers and applied to the three-phase induction motor to control its speed for a wide range of load torque changes. In addition, simulation and laboratory models are built for the three-phase induction motor to verify the effectiveness of the proposed RDA-NN controller.

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