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REACTIVE POWER MODEL REFERENCE ADAPTIVE SPEED-SENSORLESS SYSTEM WITH DIRECT TORQUE CONTROL TUNED WITH FUZZY NEURAL NETWORKS FOR IMPROVED SPEED CONTROL IN INDUCTION MOTOR DRIVES

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Abstract
This article investigates a reactive power based Model Reference Adaptive System (Q-MRAS) with Fuzzy Neural Network (FNN) facilitated Direct Torque Control for improved speed control of an Induction Motor Drive. A key component of the conventional DTC control scheme is the use of PID controllers and its derivatives. PID controllers were found to be a source of ripples. To mitigate its effect, in this work, a novel idea of replacing all the PI controls in the conventional speed control DTC models with FNN based controllers is investigated. The goal is to reduce complexity, reduce ripples in speed and boost low speed operation suitable for industrial needs. The proposed FNN controllers-based model is implemented using Matlab/Simulink. Comparisons are made between the results obtained from the proposed model and that from conventional models (Switching Table based DTC and SVM-DTC). Results showed that in the proposed FNN based DTC model, low speed operation (100 rpm) had 0.13 % speed ripple compared to 0.94 % in the conventional Switching Table based DTC and 0.23 % in the conventional SVM-DTC. This represents a reduction in speed ripple by 86.17 % in the proposed scheme compared to the Switching-Table DTC and by 43.48 % in the proposed scheme compared to the SVM-DTC scheme.

Keywords: Fuzzy Neural Network, Reactive Power-Model Reference Adaptive Scheme, Direct Torque Control, Speed Control, Squirrel-Cage Induction Motor.

1.0 INTRODUCTION

Induction motors are the most commonly used motor in industrial motion control systems as well as in home appliances (e.g. pumps, fans, blowers and so on) [1, 2, 3]. They are the preferred drive system in the industry with at least 90 per cent share because of their stand out characteristics such as having a simple and robust structure, low cost and can be operated under tough environmental conditions [4, 5]. The induction motor also has high reliability indices and high efficiency. Due to its simple and reliable design, the maintenance cost incurred on it is low. Moreover, it requires a direct connection to an AC power source which makes the inductor motor a good candidate for industrial applications[4, 6, 7].

The three-phase squirrel-cage Induction Motor is the most widely used motor because it offers more stability and better efficiency compared to single phase induction motors [8]. In spite of its popularity, the squirrel-cage rotor has two inherent limitations [9, 10]: firstly, it is not a true constant-speed machine and secondly, variable-speed operation is difficult.

Most of the contemporary control schemes of three-phase induction motor control are accompanied by speed sensors. In most cases, these sensors have a cost close to the cost of the motor. The implication is that the entire set up is very expensive. In industrial motion control, this sensor area is the weakest part and that translates ultimately to a reduction in the reliability of the whole system [11].

Recent studies have placed a lot emphasis on the elimination of the speed sensor without compromising the dynamic performance of the motor control system.

Ongoing researches on the sensorless operation of three-phase induction motor drives (because of advantages such as less maintenance costs, quieter operation: better noise immunity, reduction in the size of motor drive, simpler design and reduction in the complexity of the control system, elimination of sensor cable) is now of great interest [11, 12]. A typical sensorless scheme is the Direct Torque Control (DTC). A setback with the DTC scheme is the high ripple content which leads to inefficient power consumption. A source of ripples is in the use of classical PI controls. Tuning the controllers with AI methods which have a good track record of noise reduction is a field yet to be exploited fully. In order to actualise better results, implementing a FNN based DTC with Q-MRAS speed sensorless estimator is investigated.

1.1 LITERATURE REVIEW

Speed control methods used in induction motors can broadly be classified into two groups namely Scalar Control Methods (SCMs) and Vector Control Methods (VCMs) [13, 14, 15]. The SCMs are classified thus: Stator Voltage Control Method (SVCM), Supply Frequency Control Method (SFCM), Pole-Changing Control Method (PCCM), Rotor Resistance Control Method (RRCM) Stator Current Control Method (SCCM) and Stator Voltage/Frequency Control Method (SVFCM) [13] while the VCMs can be subdivided into two broad groups: Field-Oriented Control (FOC) Method and Direct Torque Control (DTC) Method.

The Stator Voltage/Frequency Control Method also known as the Volt-Hertz control or typically scalar control is the best of the SCMs [1]. Unfortunately, this control scheme cannot be used in industries where precision control is of prime importance [14]. This is as a result of the fact that the stator flux and torque are not directly controlled [16].

Again, on start-up or for directional change of rotation, flux oscillation is enormous producing high amplitudes whose value is variable during the transient states. Thus, the quality of torque and speed control is affected negatively leading to poor performance of the motor during such transient states. This limits its application to primary and ventilation systems [17].

For better dynamic performance, power microcontrollers and advanced control strategies are being implemented that use mathematical transformation to decouple the flux and torque. This facilitates the control of torque in transient state. Such decoupled torque and magnetisation control is commonly called Rotor Flux Oriented Control (RFOC) or Vector Control or Field Oriented Control (FOC) or Indirect Torque Control or Orthogonal Control or Transvector Control [18].

The FOC aims to achieve independent control of flux and torque via a suitable coordinate system [1]. From literature, it is adjudged to be the most popular of the VCMs because of the good performance it gives the motor [14, 19]. It has good performance like a DC motor but to achieve high torque response and speed accuracy, a feedback device is needed which is a limitation on the FOC [20]. To tackle the issues of accuracy inherent with the FOC, the DTC was invented by Takahashi and Nogushi and subsequently Depenbroch [21]. The key features of the DTC are [1, 16, 19, 21, 22]:

- No sensors (absence of mechanical transducers)
- Like the FOC, there is decoupled torque and flux control
- Low computational time and simple control structure/mechanism
- No PI control of torque and flux
- No current regulator
- No PWM pulse generator
- No coordinate transformation (DTC algorithms are in stator reference frame, so no need for coordinate transformation)

The elimination of all these simplifies the dynamics and actualisation of speed control which gives it a good advantage especially from an industrial perspective. Variants of the DTC include Sliding Mode Control (SMC) and Predictive Torque Control (PTC) which are implemented to reduce uncertainties in the system and also overcome system disturbance [23].

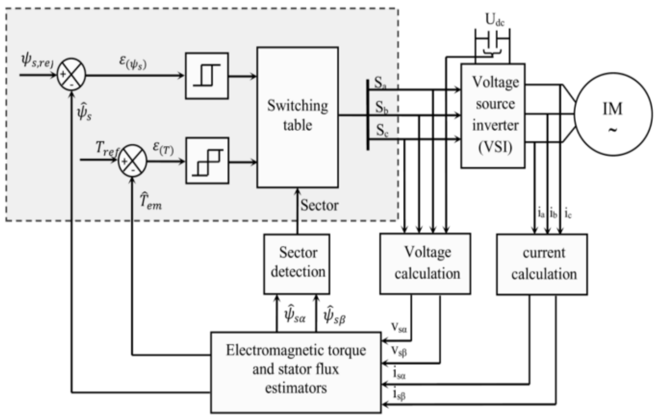


Figure 1: Block Diagram of Conventional Direct Torque and Flux Control [21]

Figure 1 shows the block diagram conceptualisation of the classical DTC scheme with details of the model shown in Figure 2.

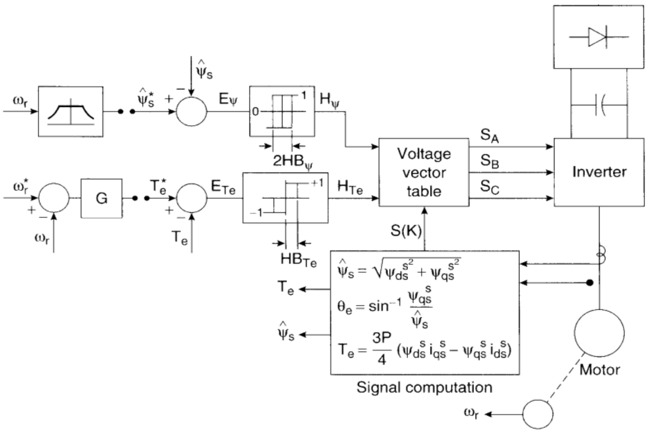


Figure 2: Detailed Block Diagram of Conventional Direct Torque and Flux Control [16].

The flux loop controller has two levels of digital output:

$$H_{\psi} = 1 \ \text{for} \ E_{\psi} > +HB_{\psi}$$
$$H_{\psi} = 0 \ \text{for} \ E_{\psi} < -HB_{\psi}$$

The torque loop controller has three levels of digital output:

$$H_{Te} = 1 \ \text{for} \ E_{Te} > +HB_{Te}$$
$$H_{Te} = 0 \ \text{for} \ -HB_{Te} < E_{Te} < +HB_{Te}$$
$$H_{Te} = -1 \ \text{for} \ E_{Te} < -HB_{Te}$$

The outputs of these hysteresis controllers in conjunction with stator flux position are fed as inputs to the switching state selection table or Look-Up Table (LUT) as shown in Figure 2. From the LUT, pulses (S_A,S_B,S_C) are generated for firing the inverter. In the classical DTC as proposed by [7], the stator flux position is divided into six different sectors and the angular position is gotten from $\theta_s(or\ \theta_e) = \tan^{-1}(\psi_{sq}/\psi_{sd})$.

The switching state selection table is shown in Table 1. The switching states of the inverter are based on the diagram shown in Figure 1 where "1" indicates that the upper limb switch is ON and "0" indicates that the upper limb switch is OFF.

Table 1: Switching State Selection Table

SECTORS							
S(1)	**S(2)**	**S(3)**	**S(4)**	**S(5)**	**S(6)**	H_{Te}	H_{ψ}
V_2 (110)	V_3 (010)	V_4 (011)	V_5 (001)	V_6 (101)	V_1 (100)	1	1
V_0 (000)	V_7 (111)	V_0 (000)	V_7 (111)	V_0 (000)	V_7 (111)	0	
V_6 (101)	V_1 (100)	V_2 (110)	V_3 (010)	V_4 (011)	V_5 (001)	-1	
V_3 (010)	V_4 (011)	V_5 (001)	V_6 (101)	V_1 (100)	V_2 (110)	1	0
V_7 (111)	V_0 (000)	V_7 (111)	V_0 (000)	V_7 (111)	V_0 (000)	0	
V_5 (001)	V_6 (101)	V_1 (100)	V_2 (110)	V_3 (010)	V_4 (011)	-1	

Source [24]

Improvements have been made in the DTC scheme. This can be divided into two groups: Non-Artificial Intelligence methods and Artificial Intelligence methods. Non AI based methods employ Lookup and Non-Lookup table based approaches while AI methods employ metaheuristic algorithms like Artificial Neural Networks, Fuzzy Logic, Genetic algorithms, Particle Swarm Optimisation, etc. This is shown in Table 2.

Selected recent works in speed control of DTC induction motors enumerating work done and shortcomings are shown in Table 3.

Table 2: Summary of Improvement Techniques in DTC

S/N	Performance term	Conventional DTC	SVM based DTC	SMC based DTC	DTC-MPC	ANN based DTC	FL Based DTC	GA based DTC
1	Algorithm complexity	Simple	Simple	Complex	Simple	More complex	More complex	More complex
2	Computational time	Low	Medium	High	Medium	High	High	High
3	Current THD	More distortions	Less distortions	Less distortions	Less distortions	Less distortions	Less distortions	Less distortions
4	Dynamics at low speed	Poor	Good	Good	Good	Very good	Very good	Very good
5	Parameter sensitivity	Insensitive	Sensitive	Insensitive	Insensitive	Insensitive	Insensitive	Insensitive
6	Precession	Low	Medium	High	Medium	High	High	Medium

7	Regulation	Hysteresis	PI conventi onal	SMC controller	Hysteresis	ANN	FLC	GA-PI
8	Switching frequency	Variable	constant	Almost constant	Constant	Constant	Constant	Almost constant
9	Switching loss	High	Low	Medium	Low	Low	Low	Medium
10	Torque and flux ripples	High	Low	Medium	Low	Very low	Very low	Medium
11	Torque dynamic response	Fast	Fast	Fast	Fast	Very fast	Very fast	Very fast

Source [1, 21, 25, 26]

Table 3: Recent works in Speed Control/Torque ripple reduction in DTC Induction Motor Drives

S/N	Authors	Work done	Limitation(s)
1	[27]	The authors proposed a DTC scheme controlled by a Fractional Order PI (FOPI) controller combined with DTC-SVM. The combination of DTC-SVM and FOPI results in better dynamic performance compared to the conventional DTC scheme with PI only according to [30]	The use of PI degraded the dynamic behaviour of the drive. This implies sizeable ripple content in torque and flux
2	[28]	Used an improved DTC of a doubly fed induction machine (DFIM) in motor mode based on SVM to tackle the issue of variable frequency which is a primary source of ripples in torque and flux in the conventional DTC. Results showed flux and torque reductions by 43 % and 42 % respectively while the harmonic distortion of stator and rotor currents were optimised by 60 % compared to the performance of the conventional DTC scheme	DTC here is applied to a DFIM. No guarantee on the suitability on the use of DFIM on induction motors
3	[29]	A PMSM driven by vector control variants such as SVM-FOC, SVMDTFC was investigated for constant load and speed variation. An NPCI was introduced into the design for better dc bus utilisation	Its performance on induction motor drives is not defined.
4	[30]	The authors used ANFIS-based torque controller to reduce torque ripples in switched reluctance motors used in conjunction with the Maximum Power Point Tracking method (MPPT) Perturb and Observe (P&O) algorithm order to extract the highest level of power from the panel.	The use of ANFIS in squirrel-cage motors is desired which is not implanted here. Thus, the use of an ANFIS-based controller is encouraged.
5	[31]	The authors applied artificial intelligence with rotor flux-based MRAS for sensorless operation tuned with the use ANN over a PI controller to boost low speed operation in a PMSM and minimise torque ripples.	Study is limited to synchronous motors. Its performance on the more rugged and industrial-suitable induction motor drives cannot be inferred.
6	[32]	The authors proposed MRAS based PPTC with online updating to facilitate the determination of weighting factors to track flux and torque errors.	Suffers from weak robustness and parameter variations with improved torque ripple reduction and good stator flux and rotor speed estimation.
7	[33]	The authors proposed an open-loop synchronisation (OLS) method for induction motor speed control to tackle DC offsets which cause large oscillations in the estimated quantities if unchecked. Performance of the OLS scheme is evaluated with distorted inputs and compared with that of a PLL scheme	Provides acceptable operation in low speed range. However, it gives estimation Errors during acceleration and deceleration processes.

2.0 METHODOLOGY

The conventional DTC method employs PI, PID or their adaptive versions whose parameters change slowly with change in motor's operating conditions. Again, with PIDs comes the challenge of accurate parameter selection for the controller. The conventional fixed gain PI and PID controllers are sensitive to parameter variation, noise and system non-linearities as a result of changing operating conditions, thus, making the control complex.

From the review of the literature of existing speed control schemes of induction motors, several limitations are identified especially in the DTC scheme which is adjudged to be the most advanced [34]. Generally, AI techniques have proven to be very effective when it comes to weakening the strength/impact of noise signals and disturbances. The DTC model, whereby the torque (and flux) can directly be controlled, easily synchronises with AI topologies. This can aid in estimation in the midst of high ripples and variations. Hence it is adopted for this article.

The following are the limitations encountered with the conventional DTC scheme:

- Presence of high torque and flux ripples
- Possibility of Electromagnetic Interference (EMI)
- High complexity (in terms of operation)
- Varying switching frequency
- General parameter variation problem
- Poor performance at low speeds

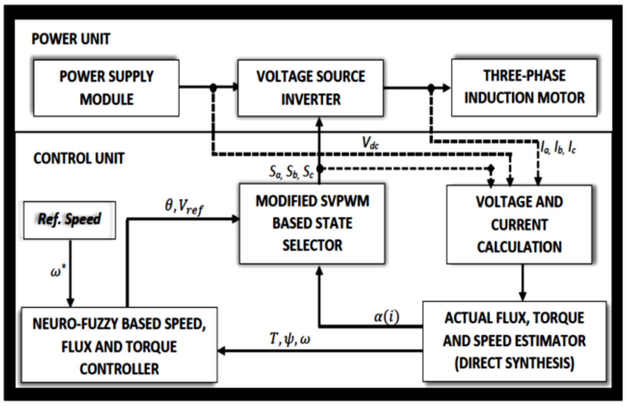


Figure 3: Block Diagram of Proposed Control Scheme

In the quest to improve on the efficiency of the DTC scheme in terms of ripple content and low speed operation, the following modifications are suggested in this article (these modifications are depicted in the block diagram shown in Figure 3):

1. ANFIS based flux and torque controllers with SVPWM to reduce complexity
2. ANFIS based speed controller to optimise tuning time
3. Reactive power based Q-MRAS with an ANFIS based adaptation mechanism for improved speed estimate.

The complete detailed diagram of the Matlab/Simulink implementation of the proposed scheme enhanced with the improvements highlighted in the methodology is shown in Figure 4. The SVPWM setup for pulse generation for firing of inverter switches is shown in Figure 5.

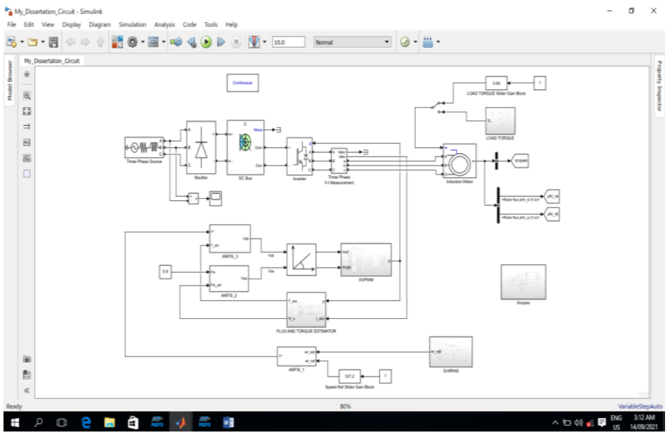
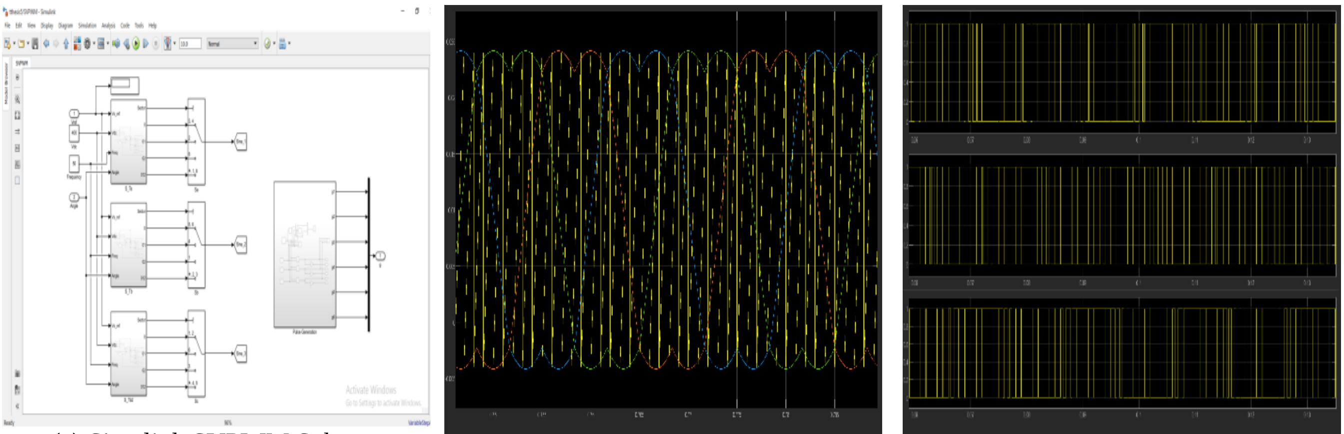


Figure 4: Complete Simulink Setup of Proposed System with Q-MRAS



(a) Simulink SVPWM Subsystem (b) SVPWM waveform (c) SVPWM firing pulses to inverter

Figure 5: Space Vector Pulse Width Modulation Implementation

The mathematical model for the Q-MRAS in Figure 6 is thus:

1. Reference Model (RM):

$$Q^* = V_{qs}I_{ds} - V_{ds}I_{qs} \qquad (1)$$

2. Adaptive Model (AM):

$$Q=\left(\frac{L_m}{T_rL_r}\right)\left(\Psi^s_{dr}I^s_{qs}-\Psi^s_{qr}I^s_{ds}\right)+\left(\frac{\omega_rL_m}{L_r}\right)\left(\Psi^s_{dr}I^s_{qs}-\Psi^s_{qr}I^s_{ds}\right)+\sigma L_s\left(\Psi^s_{dr}I^s_{qs}-\Psi^s_{qr}I^s_{ds}\right) \quad (2)$$

3. Adaptive Speed Mechanism:

$$\widehat{\omega}_r=\left(K_p+\frac{K_i}{s}\right)(Q^*-Q) \quad (3)$$

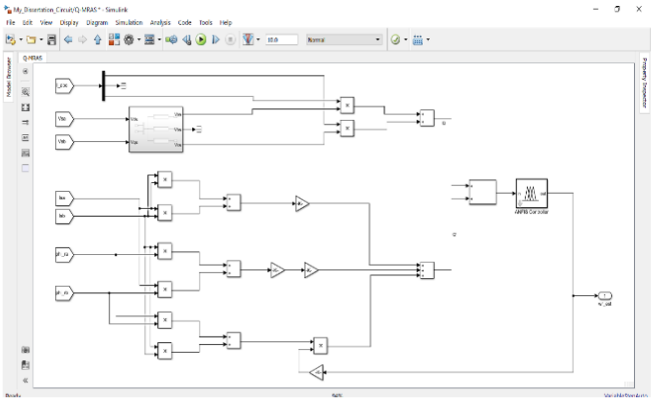


Figure 6: Simulink setup of Q-MRAS

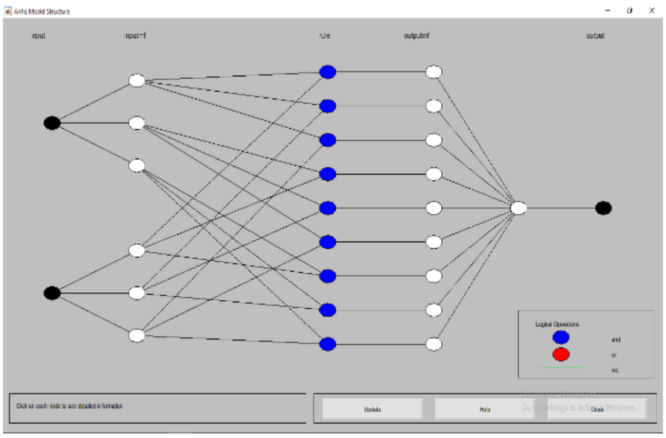


Figure 7: ANFIS network structure

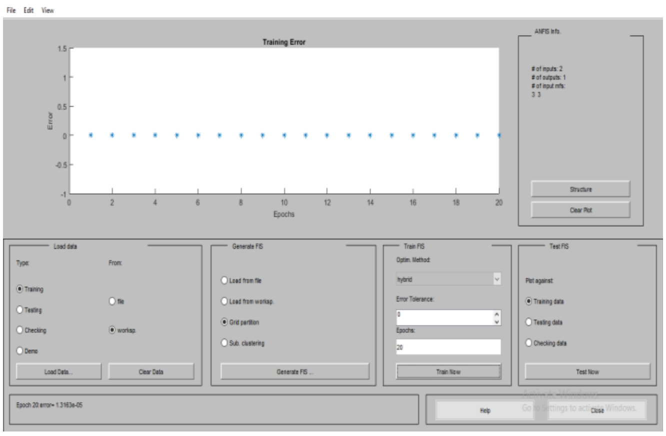


Figure 8: ANFIS Editor showing training

The PI controller in equation (3) is tuned with ANFIS. The procedure is as follows:

- Export data from Q^*, Q and $\widehat{\omega}_r$ to the workspace.
- Open ANFIS editor (Neuro-Fuzzy Designer) using the M-script command >>anfisedit
- Select Sugeno type from New FIS, load data and train the network
- Save the network and export to workspace
- Use the Fuzzy logic toolbox to load network in Simulink

Figures 7 and 8 show the ANFIS architecture used for the research and the training error data respectively.

3.0 RESULTS AND DISCUSSION

For evaluating and validating the methodology, the performance criteria include:

- Start-Up behaviour
- Behaviour towards changes in reference speed
- Behaviour of design towards unknown load torque
- Response towards parameter variation and ripples

Figure 9 shows the Simulink setup of an induction motor without a speed controller (open-loop) for variation in load torque.

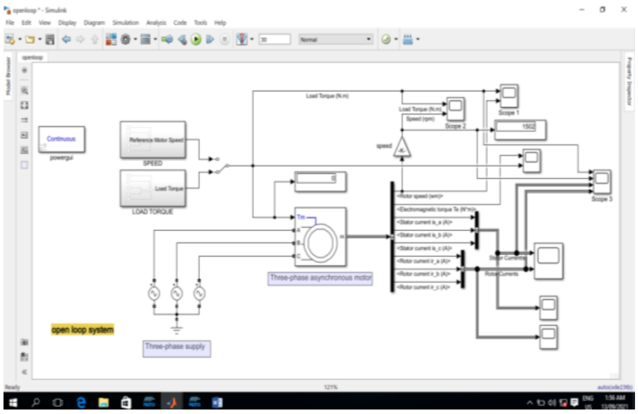


Figure 9: Open-loop Implementation of Induction Motor for Load Variation

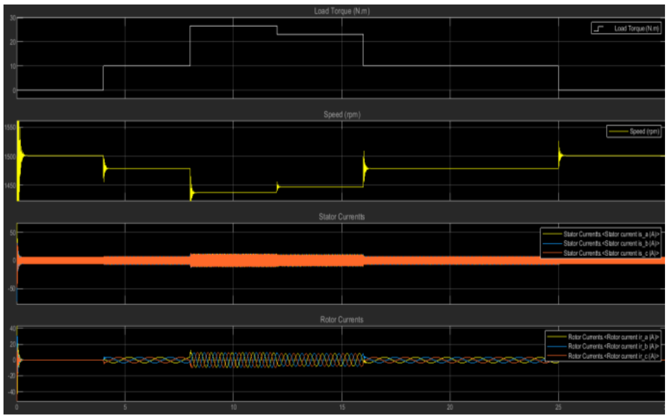


Figure 10: Load Variation Effect on the Speed of an Induction Motor

The motor is subjected to different load torques (0 Nm at 0s, 10 Nm at 4s, 26.72 Nm at 8s, 23 Nm at 12s, 10

Nm at 16s and 0 Nm at 25s) and the speed profile of the motor is observed (anticipatedly the reverse of the load curve). Figure 10 shows the variation of speed with load torque (display of Scope 3 in Figure 9). Clearly, the motor speed has an inverse relationship with the load torque. This is the default behaviour of an induction motor.

The simulation results are presented in Figures 11, 12 and 13. Figure 11 shows the changing load profile. Figure 12 shows the speed response/behaviour in two conventional systems(Hysteresis and SVM designs) and compared with the proposed design under high speed operation. Figure 13 shows the speed response/ behaviour in the two conventional systems (Hysteresis and SVM designs) and compared with the proposed design under low speed operation. Figure 13 is zoomed to show the ripples in the three systems.

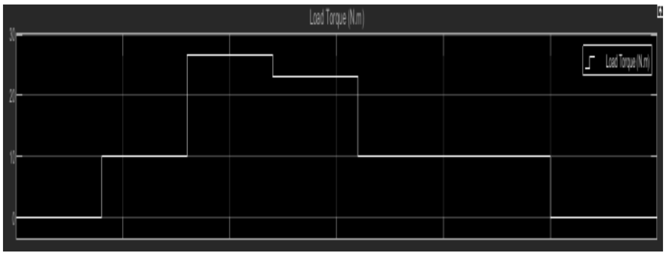


Figure 11: Load Torque Variation

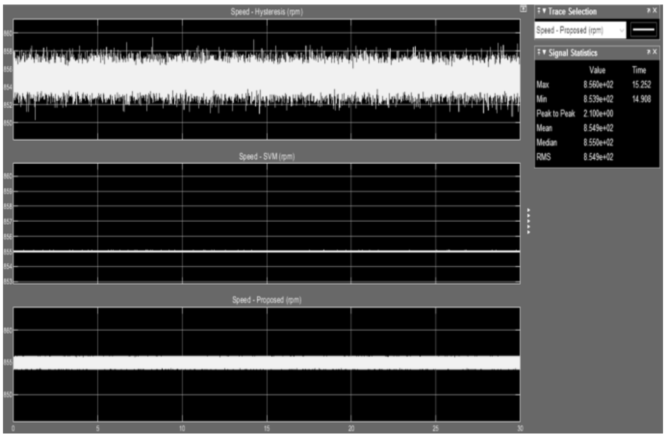


Figure 12: Switching Table (Hysteresis), SVM and Proposed DTC speed behaviour under varying Load Torque (Figure 11) with speed set at 855 rpm (High Speed Operation)

The data shown in Tables 3 to 5 is extracted from the signal statistics (right most column of Figures 12 and 13) for set speeds of 100 rpm and 855 rpm. The tables show the speed values with ripple content under varying load torque for the three systems under investigation – Hysteresis, SVM and the Proposed methodology. The maximum and minimum signal values represents the highest and lowest ripple value points on the speed wave form respectively. The peak to peak value represents the difference between the highest point and lowest points. The mean, median and rms values are indicators of the average value of the speed.

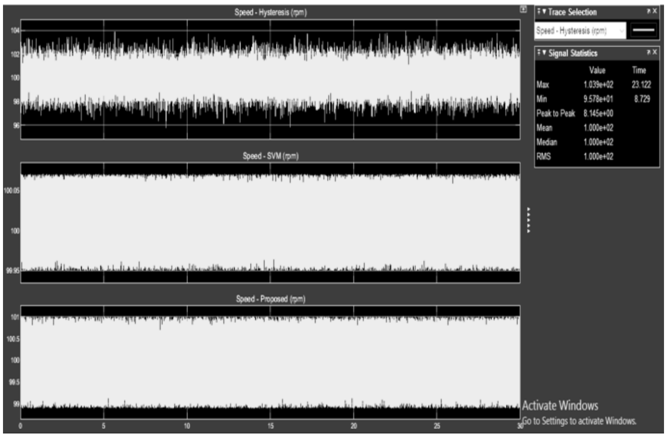


Figure 13: Switching Table (Hysteresis), SVM and Proposed DTC speed behaviour under varying Load Torque (Figure 11) with speed set at 100 rpm (Low Speed Operation)

Table 3: Signal Statistics for Hysteresis Based DTC

	100 rpm	**855 rpm**
Maximum signal value	1.039e+02	8.596e+02
Minimum signal value	9.578e+02	8.509e+02
Peak to peak value	8.145e+00	8.725e+00
Median value	1.000e+02	8.55e+02
Mean value	1.000e+02	8.550e+02
RMS value	1.000e+02	8.550e+02

Table 4: Signal Statistics for SVM Based DTC

	100 rpm	**855 rpm**
Maximum signal value	1.001e+02	8.551e+02
Minimum signal value	9.995e+01	8.550e+02
Peak to peak value	1.200e-01	1.200e-01
Median value	1.000e+02	8.55e+02
Mean value	1.000e+02	8.550e+02
RMS value	1.000e+02	8.550e+02

Table 5: Signal Statistics for Proposed Scheme

	100 rpm	**855 rpm**
Maximum signal value	1.010e+02	8.560e+02
Minimum signal value	9.890e+01	8.539e+02
Peak to peak value	2.625e-01	2.100e+00
Median value	9.994e+01	8.550e+02
Mean value	9.995e+01	8.549e+02
RMS value	9.995e+01	8.550e+02

Results statistics show 0.12 % speed ripple at high speed (855 rpm) and 0.13 % speed ripple at low speed (100 rpm) in the proposed scheme compared to speed, flux and torque ripples of 0.94 %, 2.33 % and 0.25 % on average in Switching Table based DTC and 0.23 %, 0.46 % and 0.25 % respectively on average in SVM-DTC at 100 rpm (Low speed) and 855 rpm (High speed).

Reduction in speed ripples is $\left(\frac{0.94-0.13}{0.94} \times 100\% = 86.17\ \%\right)$ for Switching Table DTC and $\left(\frac{0.23-0.13}{0.23} \times 100\% = 43.48\ \%\right)$ for SVM-DTC.

4.0 CONCLUSION

In this work, all the PI controllers were implemented with the use of the FNN (ANFIS).

Results showed reductions in speed ripple by 86 % in the proposed scheme compared to Switching table DTC and by 44 % in the proposed scheme compared to the SVM-DTC scheme at low speed operation. The use of FNNs to replace the hysteresis flux and torque controllers and PI controllers reduces drive complexity. This represents an improvement when compared to the classical design. The cornerstone of the research has been the implementation and validation of speed control of a DTC scheme for induction motor drives with reduced complexity and ripple content compared to two contemporary designs: SVM-DTC and switching table based DTC.

Table 6: Machine Parameters for Induction Motor Used

S/N	Parameter	Value
1	Nominal power, P	4 KW
2	Rated voltage, V	400 V
3	Rated current, I	3.7 A
4	Rated speed, n_m	1430 rpm
5	Efficiency, η	82.5 %
6	Power factor, pf	0.72
7	Stator resistance, R_s	3.5 Ω
8	Rotor resistance, R_r	2.1 Ω
9	Stator inductance, L_s	0.3419 H
10	Rotor inductance, L_r	0.3513 H
11	Mutual inductance, L_m	0.324 H
12	Pole pairs, p	2
13	Torque hysteresis bandwidth, ΔHB_T	0.045 Nm
14	Flux hysteresis bandwidth, ΔHB_Ψ	0.025 Wb
15	Rated torque, T	9 Nm
16	Rated flux, Ψ_s	0.9 Wb
17	Weighing factor, k	0.95
18	Inertia, J	0.0155 kg m^2
19	Friction coefficient, f_c	0.0025 Nms
20	Blondel's coefficient, $\sigma = 1 - \frac{L_m^2}{L_s L_r}$	0.874
21	Rotor type	Squirrel-cage

5.0 RECOMMENDATIONS

The details of the Simulink block of an induction motor to relate the outputs of rotor speed and electromagnetic torque to its input parameters (load torque, input or stator voltage/current) is very unclear. More work needs to be carried out on the characterisation of the induction motor in Simulink for the generation of a more comprehensive model. Again, the experimental demonstration of the research work should be the target of a future study.

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