CARRIER BASED PWM TECHNIQUE AND ADAPTIVE NEURAL NETWORK BASED ROTOR RESISTANCE ESTIMATOR FOR THE PERFORMANCE ENHANCEMENT OF VECTOR CONTROLLED INDUCTION MOTOR DRIVES

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ABSTRACT: In this paper, the carrier based Pulse Width Modulation (PWM) technique and neural network based rotor resistance estimator are proposed for vector controller Induction motor (IM) drives. The popular sine PWM is used for induction motor drive. The popular sine PWM has poor harmonic profile and (DC) utilization. The space vector modulation (SVM) technique overcomes the disadvantages of sine PWM. But SVM is computationally complex. Hence a simple PWM technique namely “carrier based PWM technique” similar to SVM is identified and proposed for vector controlled IM drive. The experimental set up is built up and the performance of carrier based PWM is validated using FPGA processor. The adaptive neural network based rotor resistance estimator in predictive mode is proposed for the vector controlled induction motor drive. The performance enhancement of the drive with carrier based PWM and rotor resistance estimator is comprehensively presented.

Keywords: Carrier based PWM technique; Rotor resistance estimator; MRAS; Adaptive neural network; Vector control; Induction motor drive.

تمكين تقنية تعديل عرض النبضة القائمة على الناقل ومقدار مقاومة الدوران القائم على الشبكة العصبية التكيفية من أجل تحسين الأداء للمحركات الحثية موجهة التحكم

أ. فينكاديسان

الملخص: قمنا باقتراح تعديل عرض النبضة القائمة على الناقل مقاوم الدوران القائم على الشبكة العصبية التكيفية للمحركات الحثية موجهة التحكم. وتسمى جيب زاوية جهاز تعديل عرض النبضة بسمة توافقية ضعيفة عند استخدام التيار المباشر. ويعمل استخدام تقنية تعديل اتجاه النطاق على التغلب على عيوب جيب زاوية تعديل عرض النبضة. لكن يُتعد تقنية تعديل اتجاه النطاق أمرًا معاقدًا من الناحية الحسابية. ومن ثم ، قمنا بتحديد تقنية بسيطة لتعديل عرض النبضة وهي "تقنية تعديل عرض النبضة القائمة على الناقل المشابهة لتقنية تعديل اتجاه النطاق", واقتريحا محرك حتى قابل للتحكم فيه. و قمنا بإعداد الكركب التجريبي والتحقق من مدى صحة أداء ناقل الدوران القائم على تقنية تعديل اتجاه نطاق الحركة باستخدام مالج تسبق قابل للبرمجة لانطلاق الدوران الداخلي. وتقترح تقنية مقاومة الدوران القائم على الشبكة العصبية التكيفية في الوضع التنبؤي للمحركات الحثية موجهة التحكم. وعملنا على عرض شامل لمقدار تحسين الأداء للمحركات الحثية موجهة التحكم مع تعديل عرض النبضة القائمة على الناقل ومقدار مقاومة الدوران.

الكلمات المفتاحية: تعديل عرض النبضة مقدار مقاومة الدوران نموذج مرجعي لنظام التكيف الشبكة العصبية التكيفية

متحكم الناقل المحركات الحثية موجهة التحكم.

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NOMENCLATURE

\[ v_{ds}^s, v_{qs}^s \quad - \text{d-axis Stator voltage, q-axis Stator voltage} \]

\[ i_{ds}^s, i_{qs}^s \quad - \text{d-axis Stator current, q-axis Stator current} \]

\[ \varphi_{dr}, \varphi_{qr} \quad - \text{d-axis Rotor flux, q-axis Rotor flux} \]

\[ R_s, R_r \quad - \text{Stator resistance, Rotor Resistance} \]

\[ L_s, L_r \quad - \text{Stator inductance, Rotor inductance} \]

\[ L_m \quad - \text{Magnetization inductance} \]

\[ T_s \quad - \text{Sampling Time} \]

\[ \omega_r \quad - \text{Rotor Speed (rad/sec)} \]

Superscript e - Synchronous Reference Frame
Superscript s - Stationary Reference Frame

1. INTRODUCTION

Three phase induction motor drives are popularly employed for variable speed control applications in many industries. This is due to their ease in maintenance (Abdelkarim Ammar et al. 2017; Ahmed A.Z. Diab 2014; Venkadesan A et al. 2016; Venkadesan A et al. 2017; Witold Pawlus et al. 2017). Now-a-days, for high performance applications, vector control provides good alternative as compared to scalar control methods. Various pulse width modulation techniques are used to generate pulse for three phase inverter in vector controlled IM drives. Out of which, space vector modulation technique (Benchabane et al. 2012; Bimal K. Bose 2005; Durasukumar G et al. 2012; Govindasamy et al. 2014; Hannan M. A. et al. 2017; Mahmoud Gaballah et al. 2013; Sabah V.S et al. 2015) is attaining popularity because it has the advantages of having better DC utilization and better harmonic profile as compared to sine-PWM technique. The space vector modulation technique is computationally rigorous and complex as it involves many mathematical calculations (Govindasamy et al. 2014; Hannan M.A et al. 2017; Sabah V.S et al. 2015). The carrier based PWM technique with a common mode voltage injection method is proposed for a three phase inverter Keliang Zhou et al. 2002). In the paper by Keliang Zhou et al. (2002), it is mathematically proved that the carrier based PWM technique with the common mode voltage injection method performs similar to SVM technique. But the carrier based PWM technique is simple for on-line digital implementation. In the paper Keliang Zhou et al. (2002), the application of the technique is not demonstrated in vector controlled IM drives. The same technique is proposed for open loop speed control of multilevel inverter fed permanent magnet motor Shriwastava R.G et al. (2016) and not demonstrated in vector controlled IM drives.

In this paper, the same technique is proposed for vector controlled IM drive. The proposed carrier based PWM technique with the common mode voltage injection method technique (CB-PWM-CMV) is also implemented in FPGA (SPARTAN 6 board). The performance of CB-PWM-CMV is also validated experimentally. The vector control especially indirect type, is sensitive to rotor resistance variation (Chitra A et al. 2015; Karanayil B et al. 2007). Hence, rotor resistance estimation using a neural network approach is proposed to track variation in the rotor resistance. The neural network based rotor resistance estimator is proposed for sine PWM based vector controlled IM drive Chitra et al. (2015). In the proposed work, neural network based rotor resistance estimator is proposed for CB-PWM-CMV based vector controlled IM drive. Also in the paper (Chitra A et al. 2015; Karanayil B et al. 2007), the adaptive NN is used in simulation mode. But the proposed Adaptive NN based rotor resistance estimator is used in predictive mode. The idea of using adaptive NN in predictive mode is inspired from the speed estimator proposed by Maurizio Cirrincione et al. (2005). In the paper by Maurizio Cirrincione et al. (2005), it is applied for speed estimation. In this proposed work, it is applied for rotor resistance estimation which is novel in this paper.

2. VECTOR CONTROLLED IM DRIVE

The vector control is preferred for high performance applications. The advantages of vector control are well presented in Krishnan R (2007). The indirect vector controlled IM drive with proposed PWM technique (CB-PWM-CMV) and rotor resistance estimator is shown in Fig. 1. For closed operation, the actual speed is compared with the reference speed. The speed error is processed through the PI controller. The torque

![Figure 1. Indirect Vector Controlled IM Drive showing the Rotor Resistance Estimator.](image-url)
command \( T_e^* \) is generated. The reference flux producing component of current \( i_d^* \) is generated from the reference flux \( \theta_{\text{ref}} \) using equation (1). The reference torque producing component of current \( i_q^* \) is generated using the equation (2). The slip frequency \( \omega_s \) is obtained using equation (3). The transformation angle \( \theta_e \) is obtained using the equation (4). The actual three phase stator current is transformed to actual flux producing component \( i_d^* \) and actual torque producing component \( i_q^* \). The \( i_d^* \) is compared with \( i_d^* \) and \( i_q^* \) is compared with \( i_q^* \) to produce the corresponding command voltage \( V_d^* \), \( V_q^* \). The reference three phase voltage \( V_d^* \), \( V_q^* \), \( V_a^* \) is generated using the command voltage and transformation angle through d-q transformation theory. The three phase duty cycle profiles are generated using the CB-PWM-CMV. The duty cycle profile/control signal is compared with the triangular signal to generate the switching pulses to the inverter.

\[
i_d^* = \frac{\theta_{\text{ref}}}{L_m} \tag{1}
\]

\[
i_q^* = \frac{4}{3} \left[ \frac{L_r T_e^*}{L_m \theta_{\text{ref}}} \right] \tag{2}
\]

\[
\omega_s = \frac{i_d^* R_e}{i_d^* L_s} \tag{3}
\]

\[
\theta_e = \int (\omega_s + \omega_e) dt \tag{4}
\]

2.1 Carrier Based PWM With Common Mode Voltage Injection Technique

In the carrier based PWM with the common mode voltage injection technique, the common mode voltage is injected into the fundamental sinusoidal reference signal. The resultant signal is used as the modulating signal and it is compared with the carrier signal for the generation of switching pulses to the inverter. The addition of the common mode voltage provides lower harmonic distortion, higher fundamental output voltage Srirattanawichaikul W et al. (2011). The common mode voltage can be generated using three phase sinusoidal reference voltages as (5). The duty cycle for each phase can be generated using (6).

\[
v_{\text{cmv}}^* = \frac{\text{Max}(v_a^*, v_b^*, v_c^*) - \text{Min}(v_a^*, v_b^*, v_c^*)}{2} \tag{5}
\]

\[
D_p = v_p^* + v_{\text{cmv}}^*, \ P \in \{a,b,c\} \tag{6}
\]

Where \( m_a \) is the modulation index. The range of \( m_a \) is 0<\( m_a \leq 1 \) for under modulation ranges. The Fig. 2 shows the block diagram for the extraction of the duty cycle profile. The equations involve only simple arithmetic operations. The equations are simple, less complex and give ease in digital implementation.

![Figure 2. Duty Cycle profile Generation using CB-PWM-CMV Technique.](image)

The performance of the proposed CB-PWM-CMV technique is compared with the SVM and Sine PWM technique in terms of DC bus utilization, harmonics profile, efficiency and complexity. The motor is operated with \( m=0.9 \), frequency=50Hz under a rated load condition. The performance comparison is shown in the Table 1.

<table>
<thead>
<tr>
<th>( V_{\text{DC}} ) (volts)</th>
<th>Method</th>
<th>( V_{\text{Fundamental}} ) (volts)</th>
<th>( V_{\text{output}} ) (%)</th>
<th>% Efficiency</th>
<th>Computational complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>582.5</td>
<td>Sine PWM</td>
<td>455.6</td>
<td>79.10%</td>
<td>78.20%</td>
<td>Simple</td>
</tr>
<tr>
<td></td>
<td>SVM</td>
<td>528</td>
<td>63.68%</td>
<td>83.43%</td>
<td>Complex</td>
</tr>
<tr>
<td></td>
<td>CB-PWM-CMV</td>
<td>528</td>
<td>63.68%</td>
<td>83.43%</td>
<td>Simpler than SVM</td>
</tr>
</tbody>
</table>

Table 1. Comparison of CB-PWM-CMV with Sine PWM and SVM.
Figure 3. (a) Duty cycle profile of CB-PWM-CMV (b) $\max(V_a, V_b, V_c)$ (c) $\min(V_a, V_b, V_c)$ (d) Common mode voltage.
The Sine PWM is simple, but has poor DC bus utilization and harmonic profile. The SVM has better DC bus utilization of 15.89% as compared to sine PWM. It has an output voltage THD of 63.69% which is lesser as compared to sine PWM. The efficiency of the drive with SVM and Sine PWM is also computed in Table 1. For efficiency calculation, the electrical input power of the drive is computed using discrete 3-phase Positive-Sequence Active and Reactive Power block in MATLAB Simulink. It is seen that the efficiency of the drive is improved with SVM as compared to the drive with sine PWM. But conventional SVM is computationally complex which involves many sector calculations. The proposed CB-PWM-CMV shows a similar performance as that of SVM but it is simple and less complex. Hence, the proposed PWM technique has better DC bus utilization, a better harmonic profile and a better efficiency. Besides, it is computationally simple and offers easy on-line digital implementation.

The experimental set up is built up to validate the performance of CB-PWM-CMV. The prototype Laboratory setup is shown in Fig. 4. The CB-PWM-CMV is implemented on Spartan-6 FPGA board. The clock frequency for FPGA implementation is chosen as 20MHz. The reference sinusoidal signals are stored in a look up table with 8-bits precision as an integer. The duty cycle profiles are generated with 8-bits precision from the reference sine signals using the proposed CB-PWM-CMV technique. The VHDL coding is developed to realize the CB-PWM-CMV.

The gate pulses are given to the three phase inverter through the pulse driver circuit and opto-isolator to drive the induction motor. The switching is chosen as 10kHz. The single phase bridge rectifier [DB107], Buffer IC [CD4081], Opto-isolator [6N137] are used for hardware implementation. Two coupling capacitors of 330 μF connected in parallel (equivalent capacitor value is 660 μF) are used. The dead time for the inverter is chosen as 6μs.

The performance of CB-PWM-CMV fed induction drive is tested for various operating conditions. The sample results obtained are presented. The modulating waveform and switching pulses obtained from the FPGA processor are shown in Fig. 5(a) and Fig. 5(b) respectively. The inverter output voltage obtained for modulation index=0.96 and frequency=50Hz is shown in Fig. 6(a). The inverter output voltage obtained for modulation index=0.48 and frequency=25Hz is shown in Fig. 6(b).

The two-level inverter is used in this paper. Hence, two levels are obtained in the output line-line voltage. It is observed that as soon as the ratio of m/f is reduced to 50%, the fundamental output voltage magnitude and frequency of the line-line voltage is also reduced to around 50%. The effect of variation in the fundamental output voltage magnitude and frequency for various m/f ratios is reflected in the rotor speed. Since the rotor speed can be easily measured using tachometer, the rotor speed for various m/f ratios is shown in Table 2. The measured speed increases proportionally with increase in m/f ratio. From this table, it is shown that the drive performs very well under a practical condition with CB-PWM-CMV for various m/f ratios.

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**Figure 4.** Hardware setup of SVM based inverter fed IM drive with FPGA controller.
Figure 5. (a) Modulating waveform (b) Pulses to IGBT switches.

Figure 6. (a) Inverter output voltage (L-L) for m=0.96, f=50 Hz (b) Inverter output (L-L) for m=0.48, f=25 Hz.
2.2 Adaptive Neural Network Based Rotor Resistance Estimator

The design of an indirect vector controller, to a large extent, depends on the accuracy of the rotor resistance. The slip frequency depends on the knowledge of rotor resistance which is evident from (3). The transformation angle or flux angle depends on the slip frequency which is evident from (4). In real time, the rotor resistance may vary up to 100 due to the rotor heating Karanayil B et al. (2007). Any mismatch between the rotor resistance of motor and the rotor resistance value in the vector controller leads to the loss of the decoupled control (Chitra A et al. 2015; Karanayil B et al. 2007). Hence to track variation in the rotor resistance, the rotor resistance estimator using Model Reference Adaptive system (MRAS) with adaptive neural network scheme is proposed. For simulation study, the motor is modeled in d-q frame to introduce variation in the rotor resistance.

The proposed MRAS scheme for rotor resistance estimation is shown in Fig. 7. The MRAS uses a voltage and a current model for rotor resistance estimation. The output from both models is d and q-axis rotor fluxes in stationary reference frame. It is well known that the voltage model is independent of rotor resistance and the flux estimated will be independent of the rotor resistance. Hence, the voltage model is used as a reference model. Accordingly, the equations (10) and (11) do not contain rotor resistance. The three phase voltages and currents are measured and transformed into d and q axis stationary reference frame and given as inputs to the voltage model.

The current model is dependent on the rotor resistance and the flux estimated will be dependent on the rotor resistance. Therefore, the current model equation can be used as the adaptive model. Consequently, the equations (12) and (13) contain rotor resistance. The three currents and rotor speed are measured. The three phase currents are transformed into d and q axis stationary reference frame. As a result, the inputs to the current model are d and q axis current and rotor speed.

The current model equations (12), (13) are represented as a two-layer neural model and used as the adaptive model because it is dependent on the rotor resistance. The weight of the adaptive NN model is the function of the rotor resistance (R_s). The error between the reference model flux and the adaptive model flux is back propagated to adjust the weights of the adaptive model to estimate the rotor resistance. The error between the reference and adaptive model is minimized using the BPM (Back Propagation with Momentum Algorithm).

The discrete form of Current model equations can be obtained using backward Euler’s rule. Using this rule, the rate of change of rotor flux can be expressed as in (14)

\[
\frac{\psi_{dr}^s}{dt} = \frac{\psi_{dr}^s(T) - \psi_{dr}^s(T-1)}{T_s}
\]

The discrete form of Current model equations can be obtained using backward Euler’s rule and are given in (14) and (15)

\[
\psi_{dr}^s(T) = W_1 \psi_{dr}^s(T-1) - W_2 \psi_{dr}^s(T-1) + W_3 i_{dr}\psi_{dr}^s(T-1)
\]

\[
\psi_{dr}^s(T) = W_1 \psi_{dr}^s(T-1) + W_2 \psi_{dr}^s(T-1) + W_3 i_{dr}\psi_{dr}^s(T-1)
\]

Equations (14) and (15) can be represented as a two-layer neural network with a linear activation function (Fig. 8). This is used as the adaptive model. It contains four inputs \{ \psi_{dr}^s(T-1), \psi_{dr}^s(T-1), i_{ds}(T-1), i_{qs}(T-1) \} and two outputs \{ \psi_{dr}^s(T), \psi_{dr}^s(T) \}. The adaptive model is used in a predictive mode instead in simulation mode. In predictive mode, the past values of rotor flux required as the input for the adaptive model is obtained from the reference voltage model itself rather than from the adaptive model as in simulation mode. This gives ease in digital implementation of the adaptive model and overcomes the problem of instability Maurizio Cirrincione et al. (2005). The inputs and outputs are connected through the weights w_1, w_2, w_3. The weight w_2 is kept constant. The other two weights w_1 and w_3 are proportional to the R, they are updated using BPM.
to minimize the error $E (17)$.

The BPM is coded in MATLAB.m-file. The learning rate ($\alpha$) and momentum factor ($\eta$) are chosen as $5 \times 10^{-5}$ and $2 \times 10^{-5}$ respectively. The $E$ is chosen as $1 \times 10^{-6}$. The weights of NN are updated using (20) and (21).

\[ E = \frac{1}{2} [\epsilon(T)]^2 = 0.5 [s^2(\phi r) - s^2(\phi r)]^2 \]  
\[ \Delta w_1(T) = \alpha \left[ \epsilon_i^2(T) + \epsilon_i^2(T-1) \right] \]  
\[ \Delta w_3(T) = \left[ \epsilon_i^2(T) + \epsilon_i^2(T-1) \right] \]  
\[ w_1(T) = w_1(T-1) + \alpha \Delta w_1(T) + \eta \Delta w_1(T-1) \]  
\[ w_3(T) = w_3(T-1) + \alpha \Delta w_3(T) + \eta \Delta w_3(T-1) \]  

where,

\[ \epsilon_i^2(T) = \epsilon_i^2(T) - \epsilon_i^2(T) \]  
\[ \epsilon_i^2(T) = \epsilon_i^2(T) - \epsilon_i^2(T) \]  
\[ \epsilon_i^2(T) = \epsilon_i^2(T) - \epsilon_i^2(T) \]  
\[ \epsilon_i^2(T) = \epsilon_i^2(T) - \epsilon_i^2(T) \]  
\[ \epsilon_i^2(T) = \epsilon_i^2(T) - \epsilon_i^2(T) \]  
\[ \epsilon_i^2(T) = \epsilon_i^2(T) - \epsilon_i^2(T) \]  

The rotor resistance can be obtained either from $w_1$ or $w_3$ (Chitra A et al. 2015; Karanayil B et al. 2007).

\[ R_s = \frac{L_s}{L_m T_r} \]  
\[ R_s = \frac{L_s}{L_m T_r} \]  

The effect of sampling time on the performance of the proposed rotor resistance estimator assumes importance for on-line digital implementation. Hence, the same is tested for various sampling time. The drive is operated with the speed of 148 rad/s under 100% load torque. The rotor resistance is increased to 50%. The switching frequency of the inverter is chosen as 10kHz. Hence the switching time is 100µs.

Figure 7. NN-MRAS scheme for rotor resistance estimation.

Figure 8. Two-layer neural network.
The steady state error is computed between the actual and estimated rotor resistance for various sampling time and presented in Table 3. Lesser sampling time leads to more accuracy but increases computation time as the number of samples per cycle is more. On the other hand, larger sampling time decreases computation time but it decreases accuracy as the number of samples per cycle is less. In this paper, the sampling time is chosen same as the inverter switching time for study.

The estimator is tested for a step change in rotor resistance. The actual and estimated rotor resistance for step variation (24) is shown in Fig. 9(a). The sample weight evolution plot for step change is also shown in Fig. 9(b). It is understood that the network learns to estimate the rotor resistance. The weight and the rotor resistance are linearly related. The step change is the extreme case condition. It is used to show the capability of the proposed estimator to estimate $R_r$ even in the extreme case condition.

But in the practical real time, the rotor resistance varies slowly. Accordingly, the proposed estimator is tested for trapezoidal variation (25) in the $R_r$ and also with exponential variation Beguenane R et al. (1999) as in (26). The result obtained for trapezoidal variation and exponential variation is shown in the Fig. 9(c) and Fig. 9(d) respectively. The NN-MRAS tracks the variation in $R_r$ for the various rotor resistance variation profile very well with good accuracy.

$$R_r(t) = \begin{cases} R_{r, nom} & 1 < 1.5 \text{sec} \\ R_{r, nom} + \Delta R_{r, nom} & 1 < 1.5 \text{sec} \end{cases}$$

(24)

$$R_r(t) = \begin{cases} R_{r, nom} & (t < 1 \text{sec}) \text{or}(t > 4 \text{sec}) \\ \frac{R_{r, nom} - (R_{r, nom})_t}{(R_{r, nom})} - R_{r, nom} & 1 \text{sec} \leq t \leq 2 \text{sec} \\ \frac{R_{r, nom} + \Delta R_{r, nom} - R_{r, nom}}{2 \text{sec} \leq t \leq 3 \text{sec}} \\ \frac{(R_{r, nom} - t)}{3 \text{sec} \leq t \leq 4 \text{sec}} \\ R_{r, nom} - (R_{r, nom} + \Delta R_{r, nom}) & 3 \text{sec} \leq t \leq 4 \text{sec} \end{cases}$$

(25)

$$R_r(t) = R_{r, nom} + (1 - e^{-1.2t})$$

(26)

The estimated $R_r$ value for various %changes in $R_r$ is consolidated and presented in the Table 4 along with the steady state error for 100% and 50% load torque. It is found that the proposed estimator tracks, the change in $R_r$ with good accuracy.

### 2.3 Adaptable Neural Network Based Rotor Resistance Estimator

The performance of the drive with and without a rotor resistance estimator is studied. The motor is operated with the speed of 148 rad/sec, torque of 7.5 Nm and rotor flux of 0.9 Wb. The step change in rotor resistance is effected at 1.5 sec. Without the $R_r$ estimator, the rotor flux, torque and three phase stator current are shown in the Fig. 10 (a), Fig. (b), Fig. (c) respectively. It is observed that without the rotor resistance estimator, the error in the rotor flux is found to be 16.66% and the actual flux deviates from the reference flux. The ripple in the machine torque is found to be 30.46% and oscillates about the load torque which is evident from Fig. 10(b). The sinusoidal shape of the three phase stator current gets distorted. This type of response is not desirable in high performance drives. With the rotor resistance estimator, the actual rotor flux tracks the reference flux with the error of 0.133% after about 0.4sec as soon as the step change in rotor resistance is applied at 1.5sec which is evident in Fig. 11(a). With the rotor resistance estimator, the ripple in the machine torque is reduced significantly to 3.382% which can be observed in Fig. 11 (b).

The sinusoidal shape of the current is maintained which can be observed from in Fig. 11(c). Hence, the performance of the CB-PWM-CMV based vector controlled IM drive is significantly enhanced with rotor resistance estimator.

### Table 3. Effect of sampling time on the rotor resistance estimator

<table>
<thead>
<tr>
<th>Sampling Time</th>
<th>Actual $R_r$ (ohms)</th>
<th>Estimated $R_r$ using Proposed NN-MRAS Scheme (ohms)</th>
<th>% Steady State Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>50μs</td>
<td>9.127</td>
<td>9.123</td>
<td>0.043826</td>
</tr>
<tr>
<td>100μs</td>
<td>9.114</td>
<td>9.114</td>
<td>0.142435</td>
</tr>
<tr>
<td>200μs</td>
<td>9.052</td>
<td>9.052</td>
<td>0.821738</td>
</tr>
<tr>
<td>300μs</td>
<td>8.958</td>
<td>8.958</td>
<td>1.851649</td>
</tr>
<tr>
<td>400μs</td>
<td>8.828</td>
<td>8.828</td>
<td>3.275994</td>
</tr>
<tr>
<td>500μs</td>
<td>8.657</td>
<td>8.657</td>
<td>5.149556</td>
</tr>
</tbody>
</table>

### 3. CONCLUSION

A carrier based PWM technique and Neural Network based rotor resistance estimator are proposed for the performance enhancement of induction motor drives. The CB-PWM-CMV technique is computationally less complex and gives ease in digital implementation as compared to space vector modulation technique. The CB-PWM-CMV technique is shown to improve the efficiency of the drive as compared to Sine-PWM. The CB-PWM-CMV technique is implemented on Spartan-6 FPGA processor and experimentally validated.

A neural Network based Model Reference Adaptive system in prediction mode is proposed for the rotor resistance estimation. The proposed NN-MRAS is shown to estimate $R_r$ with good accuracy which is evident from Table 4. With rotor resistance estimator, the performance of the drive is significantly improved. Hence, it is concluded that the performance of the drive is enhanced significantly with CB-PWM-CMV and rotor resistance estimator.
Figure 9. (a) Rotor resistance for step variation (b) Weight evolution plot for step variation (c) Rotor resistance for trapezoidal variation (d) Rotor resistance for exponential variation.
Figure 10. Without Rr Estimator: (a) Rotor Flux (b) Torque (c) Current.
Figure 11. With Rr Estimator: (a) Rotor Flux (b) Torque (c) Current.
Table 4. Rotor resistance estimation using NN MRAS for various % changes in rotor resistance.

<table>
<thead>
<tr>
<th>% Variation in R&lt;sub&gt;r&lt;/sub&gt;</th>
<th>Actual R&lt;sub&gt;r&lt;/sub&gt; (ohms)</th>
<th>Estimated R&lt;sub&gt;r&lt;/sub&gt; using Proposed NN-MRAS Scheme (ohms)</th>
<th>% Steady State Error</th>
<th>Estimated R&lt;sub&gt;r&lt;/sub&gt; using Proposed NN-MRAS Scheme (ohms)</th>
<th>% Steady State Error</th>
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**CONFLICT OF INTEREST**

Author declares no conflicts of interest.

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**REFERENCES**


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Appendix 1

Induction Motor Parameters: 3 phase, 4 poles, 1100W, 415V, 50Hz, 7.5Nm.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>$R_r$</td>
<td>6.085Ω</td>
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<tr>
<td>$L_{sl}$</td>
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