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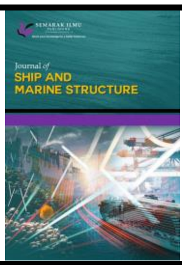

Performance Enhancement of Four Phase 8/6 Switched Reluctance Motor for Ship Propulsion System

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ABSTRACT

Nowadays, the use of electric propulsion in navy ships is not a unique idea in the field of marine industry. Power systems on board ships began with lights, advanced to electrified ship vessels that employed electrical motors as a propulsion system, and ultimately to the impression of All Electrified Ships (AES), which enabled all vessel sources of power to serve both the loads of auxiliary and propulsion systems. Because of the high demand for power generation in naval as well as in commercial ships, various generations of electrical motors must be used, and reformation in high power electronics aids in adjusting and driving the system. The control strategy for torque ripple suppression is presented and discussed in this study, and it is based on a Hysteresis controller to create a superior PWM and Cascaded Artificial Neural network (CANN). When compared to other approaches, CANN has been regarded as a promising method due to its generality, reduced complexity, stability, and accuracy. To demonstrate our technique, simulation results for torque ripple elimination at various speeds are examined. Finally, the pertinent findings are presented. Matlab/Simulink is used to create the simulation platform. The operational characteristics of the switching reluctance motor have been greatly improved. Furthermore, this study introduces the advantages of motors that could be used in vessel propulsion systems, as well as the significance of increasing the (8/6) type switched reluctance motors phases and by means of control strategies to address the major drawback in the motors, which is nothing but the torque ripples, and recommended to substitute SR motors rather than other machine which are used in vessel propulsion technology.

Keywords:
Ship Propulsion motor; Switched Reluctance Motor (SRM); All Electrified Ships (AES); Cascaded Artificial Neural Network (CANN); hysteresis current control; speed and torque control

1. Introduction

Nowadays, all electric ships play a vital role by providing a pollution free environment. It is a cutting-edge technology that allows the ship's capacity to be powered by the renewable source of energy, which runs the propeller [1]. All electric ships come into the picture for an emission free environment, it affects the global in terms of NOx and Sox emissions, which are more harmful to human life. Shipbuilders have begun to adopt renewable powered driven propulsion as an approach to reduce emission and fuel consumption costs. Fuel price fluctuations have also motivated the

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marine sector and ship owners in general to get familiar with renewable energy propulsion systems, as well as use highly electrified [2].

The purpose of employing an SRM for ship propulsion is to maintain a constant starting torque during the first acceleration phase. Around two techniques are there to overcome the torque ripple developed in the motor [3]. The first is to improve the motor design by modifying the structure of the stator and rotor sides, and the second is to apply advanced control. Many control solutions have been presented to cope with torque ripples [4]. However, because of the dual-phase structure and commutation from one phase to the next, torque ripple for this sort of motor has become a significant issue, particularly at low speeds, limiting the SRM's applicability as a servo drive [5]. Therefore, the motor's efficiency was enhanced to match the excessive power needs and attain the best performance. Because of its low reliability and simple design, the switching reluctance motor is receiving greater attention. Due to these characteristics, SR motors excel similar to adjustable speed motors [6].

R. Gobbi K. Ramar: The modulated reference current must be closely monitored and tracked by the current controller even during dynamic operations. [7] The reference phase present and peak current technique was monitored by the current control unit in order to improve torque torsion hysteresis. In this investigation, the hysteresis current controller switches at a consistent rate. The limit of the positive voltage range was maintained for two successive samples [8]. To decrease switch losses and increase condenser life, strong voltage cuts were used. Despite the fact that the hard switching approach used in the outgoing switch produces more noise than the soft-chopping mode does.

2. Electric Propulsion System

For more than decade, maritime transportation played a vital role in the history of human civilization. In the conventional propulsion system, the propeller is driven by the diesel engine with the help of heavy oil and alternative solutions are also possible with the help of an alternator coupled with the diesel engine to manage other loads in the ships. This system was given significant operating costs to the ship owners [8]. The biggest disadvantages are the high investment costs and the fact that fossil fuels pollute the environment. Fuel availability is decreasing in nature owing to increased demand.

To overcome the challenges associated with the conventional propulsion system, electrical propulsion systems are best suited in terms of less pollution and running costs of the ships. In the upcoming years, new advancements in the maritime sector will be the rising technology [9].

Hence, in place of spinning gears, the turbines directly drive the alternators with the help of an electrical motor coupled with the alternator in the electrical propulsion system. This motor changes the voltage and frequency required for the vessel propulsion system to run the ship at a low speed. Nowadays, especially in ship propulsion systems, variable frequency drive technology plays a vital role in the electric propulsion system which dominates the technology (refer to Figure 1) [10]. The purpose of a variable frequency drive system is to transform a fixed frequency line into a variable frequency drive in the motor terminals. These frequencies may vary to match the required speed of the vessel from time to time such as reaching and leaving the port and at various speeds of the vessels. Specially, the propulsion system required 75% of the generated electricity in the ship generation system [11].

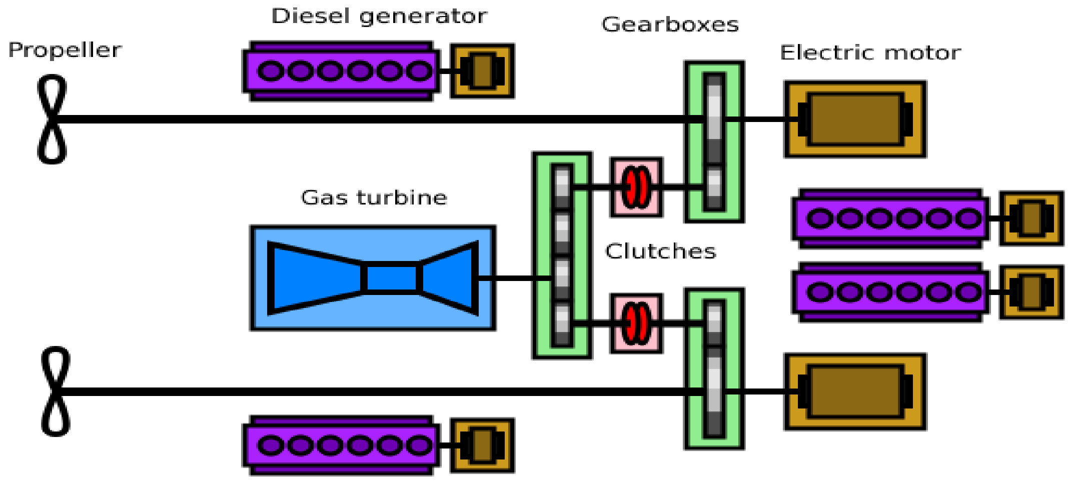


Fig. 1. Layout of ship main propulsion and electrical distribution [10]

The main advantages of an electric propulsion system are zero emission and fuel cost reduction. Each vessel required a minimum of fuel to reach a distance. If the speed of the ship decreases, then the fuel consumption is higher. To overcome the issue, electrified propulsion will do the best in terms of zero emission and fuel cost reduction.

2.1 Electrical Motors for Ship Propulsion Systems

In all electric ships, the motor drive is an important component which consists of the power control circuit and monitoring systems. The main function of a power control unit is to provide the necessary control which is required for the motor [12]. In the shipping industry, electrical motor technology plays a vital role because it transforms the mechanical form of energy into electrical that may be used for propeller, and also allows regeneration braking that to be transferred into an on-board power system. Figure 2 shows the classification of motors for electric ship propulsion systems.

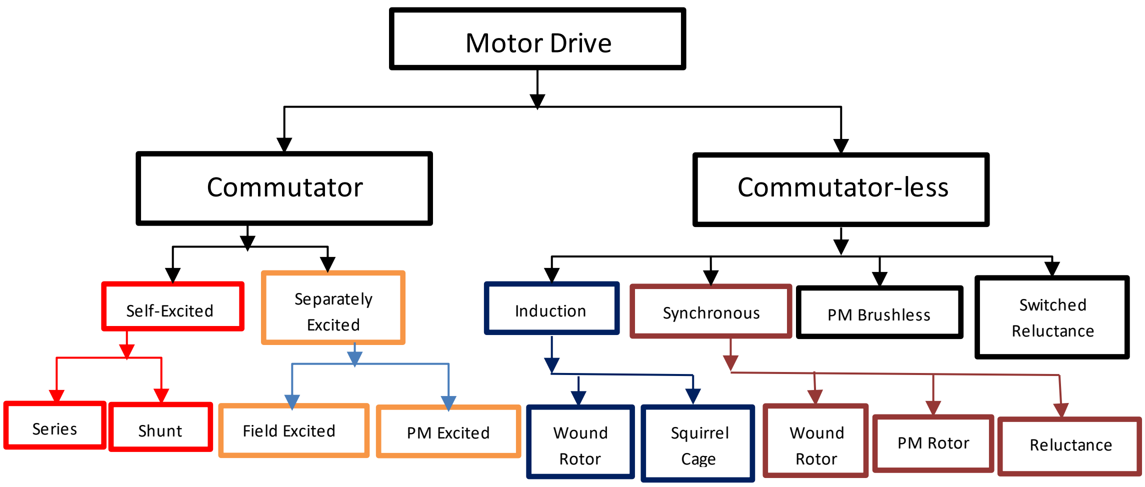


Fig. 2. Classification of motor for electric ship propulsion systems [12]

In electrical terminology, many motors are available in a wide variety of sizes and range. Such motors like BLDC motor, series motor, compound and shunt motor, synchronous motor with permanent magnets are the most commonly used motors in electrical propulsion systems. In the case of a DC motor, armature current must be supplied through brushes which reduces the reliability and causes unsuitable for high speed application and free maintenance [13]. Moreover, the benefits of DC motor like low operating cost, improved power density, increased efficiency and current induced electric motor in the latest advanced technology. Thus, dependability is strong, and maintenance is less expensive than switching, therefore, the absence of switches gives more attractive.

Due to less maintenance, excessive dependability and less running costs. Conventional motor control methods, such as variable frequency drive and variable voltage, may not provide the higher and expected efficiency. As the microchip technology increased, techniques like PWM control, direct torque control, field oriented control have been used to overcome the drawbacks of system complexity due to non-linearity. However, for light loads and during constant power in a constrained working range, these control approaches' efficiency is rather low [14]. Figure 3 shows the overview of the ship's electric power system.

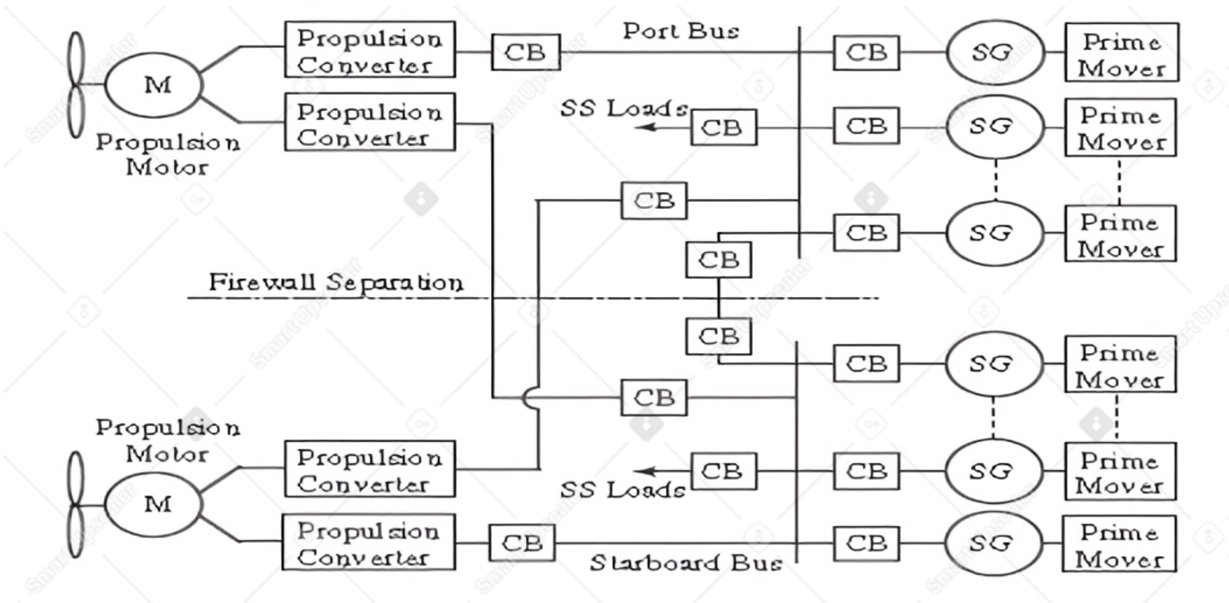


Fig. 3. Overview of the ship's electric power system [14]

Even though the post-graduate students from the school of naval architecture in the US looked at different electric motors for electric ship propulsion in 2013, they came to the conclusion that the switched reluctance motor is very poorly suited for the application of ship propulsion systems due to the rising cost of rare-earth metal, which is expensive to obtain and in short supply. Given its dependability and affordability, SRM is the most suitable marine propulsion system [15,16]. It is also the most suitable ship propulsion system.

2.2 SRM's Advantages and Disadvantages for Future Ship Propulsion Systems

SRM engines were typically not advised for propulsion and traction systems, but their use in ship propulsion has allayed many worries, even though it will have its limitations.

2.2.1 Merits

- The construction is simple, and the production costs are low.
- Its mutual inductance is minimal due to its simple wrap and one coil cycle per stator pole.

- It has a high level of dependability and robustness since it can keep operating although if one pole wrapping or one cycle fails.
- The SRM drive is simple and affordable since it runs on DC power.
- Because SRM does not preserve any magnetism after a phase is shut off, there are no voltage spikes concerned in the good functional zone.
- There are fewer losses because there aren't any eddy current or looping losses, as well as no rotor losses.
- SRM can replenish energy in the case of a ship halt. Moreover, since the ship's inertia keeps the blade and engine spinning, it might be utilised to recharge super capacitors, inductors, or other kinds of power storage.
- With the exception of motor drives, which have set torque vs. rotation speed that are tied to supply frequency, the value of torque must follow that path [17]. Thus, speed and torque may be adjusted individually, allowing the motor to operate at any position in the high torque boundaries as the heat increases to the suitable stage, as illustrated in Figure 4.
- Substantial torque may be created by SRM at low speeds (at first); this is suitable for hydrokinetic applications wherein power demand grows nonlinearly, eliminating the requirement for a gearbox [18].

2.2.2 SRM disadvantage

- As a result, acoustic noise and vibration are diminished, and an all-electric ship system's effectiveness is increased [24].
- The mass to average power is lower in comparison to other engines.
- High levels of movement and harmonic distortion
- The torque produced by SRM has a strong ripple.
- Because mechanical switching such as high power IGBTs is now mature, SRMs for power devices up to 4 MW may be developed and fabricated [19].

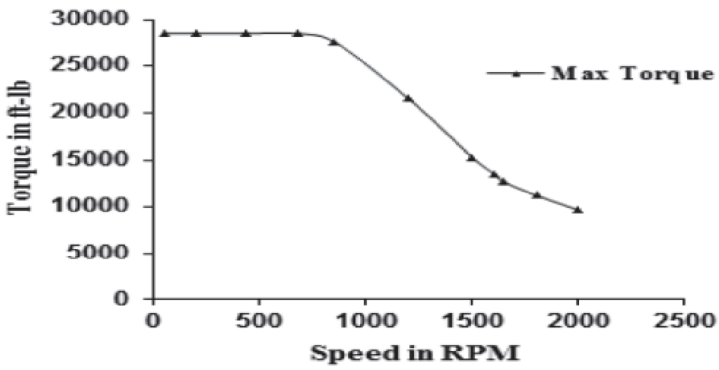


Fig. 4. Max torque–speed curve of SRM for 2 MW, 950 rpm [19]

3. Switched Reluctance Motors

A variable reluctance motor operates on both sides separately. Even though both the rotor and stator have observable poles, only one has copper coils. The rotor is constructed from a stack of pertinent laminate made from aluminum or titanium alloy [20], with no coils, magnets, or cage unwinding. The switching resistance machine functions by minimizing resistance and creating torque. Figure 5 shows how to build an 8/6 SRM in both matched and unaligned modes.

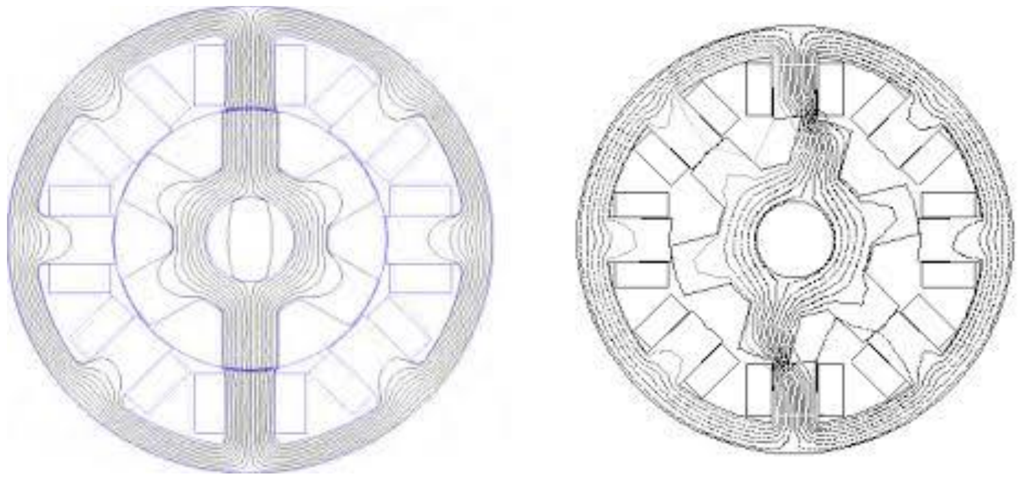


Fig. 5. 8/6 SRM at (a) unaligned view and (b) aligned view

Because the air-gap is highest in completely unaligned conditions, greater reluctance and lesser inductance. As soon as a phase is launched, the resulting flux pushes the closest rotor pole to an aligned position with the lowest reluctance and highest inductance, thus closing the channel between the stator poles. This shift in reluctance leads to continuous torque in a machine having more than one phase.

3.1 Mathematical Design

3.1.1 SRM mathematical modelling

The SRM is a rotating machine with distinct rotor and stator parts. The gadget is therefore considered to be twice as prominent. It consists of a magnetic rotor and a blade with an interesting winding. The basis of torque production is the forcing of pole pairs to realign with stimulating poles to reduce stator flux interconnections created by a given supply stator current, hence no magnetic flux is needed. The electrical properties of SRM will be described by the motor equation. According to Faraday's rule, the flux linked in the plastic wrap is dependent on the voltage waveforms across connections of a phase of an SRM circuit.

$$V_j = RI_j + \frac{\partial \varphi_j(i,\theta)}{\partial i}\frac{di}{dt} + \frac{\partial \varphi_j(i,\theta)}{\partial \theta}\frac{d\theta}{dt}, \quad \text{here } j = 1, 2, 3 \tag{1}$$

$$V_j = RI_j + L(\theta)\frac{\partial i}{\partial t} + i\frac{\partial L(\theta)}{\partial \theta}\omega \tag{2}$$

$$\omega = \frac{\partial \theta}{\partial t}$$

After mutual inductance effects and excluding saturation, flux in each phase is given below

$$\varphi_j(\theta, i_j) = L(\theta) i_j \tag{3}$$

The following energy is associated with four phases (n = 4)

$$W_{total} = \frac{1}{2}\sum_{j=1}^{4} L(\theta + (n - j - 1)\theta_s) I_j^2 \tag{4}$$

The motor torque and phase inductance displaced by angle s are as follows

$$T_e = \frac{\partial W_{total}}{\partial \theta} = \frac{1}{2}\sum_{j=1}^{4} \frac{\partial L(\theta+(n-j-1)\theta_s)}{\partial \theta} I_j^{\ 2} \tag{5}$$

The motor torque and phase inductance displaced by angle θ_s are as follows

$$J\frac{\partial \omega}{\partial t} = T_e - T_l - f\omega \tag{6}$$

Where friction coefficient is denoted by f, voltage terminal is V, instantaneous inductance (θ), phase current is I, moment of inertia by J, phase winding resistance is R, T_1 is denoted as torque load and T_e is total torque.

3.1.2 Mathematical stages of ANN

Nonlinear and complicated interactions may be learned and modelled using artificial neural networks. The main equation for ANN is as follows: After learning from the initial inputs, ANN may condense and infer previously unknown correlations on previously unseen data, enabling the model to generalise and forecast on previously unseen data.

$$Y = \sum(weight * input) + bias \tag{7}$$

A basic unit of a neural network is a node, with a set bias value and number of inputs. The signal is multiplied by the weight value as it arrives. During the training step, each weight value is modified by its input. The bias is a one-dimensional additional input for neurons with a connection weight [19]

$$z = x_1 * \omega_1 + x_2 * \omega_2 + \cdots + x_n * \omega_n + b * 1 \tag{8}$$

Results and imports from the human brain fall between 0 and 1 in a linear equation. Nonlinearity is introduced by the input layer. Gaussian or logistic input vectors are frequently used for binary classification problems (output values range from 0 to 1). It is easy to calculate the sigmoid function's derivative. Using the SVM classifier [18], simple values are converted to complex values

$$\hat{Y} = a_{out} = sigmoid\ (z), \tag{9}$$

While sigmoid is the perceptron used to a weighting factor of signals and biases, and Y is the result.

4. Improve the Entire Electric Ships System's Performance

The electrically driven engine is a crucial element of the All Rechargeable Ships idea. Modern naval and corporate ships are flocking to SRM due to the benefits outlined above. High starting torque fluctuations, vibration, and noise are major difficulties with this motor for ship launch systems. However, these problems remain the fundamental limitations of employing these motors in a variety of applications. For many years, several scholars have been researching these problems. Most of the research is focused on finding solutions to the problem by developing drives that reduce torque rippling and regulate thrust force [20] direct torque control, direct near instant torque regulation. Wave Torque Direct power control is demonstrated in minimising of direct speed controller using an Artificial Processor and Field Focused Control Approach. Scientists have tried to reduce vibration in SRM for many years using any methodological approaches (as stated earlier) or alternate solution device design ideas such as deciding the optimum magnetic loop main objective is to lessen low speed torque shockwave [21], rotor framework architectural style [20], and assists in describing a novel alternator pole face idea with a quasi-air space and a pole foot attached to the rotor pole's transverse face [22,23]. The impact of employing multi-phase SRM or a greater amount of rotor poles on vibration and noise is investigated in this work. As a result, acoustic noise and vibration are diminished, and an all-electric ship system's effectiveness is increased [24].

4.1 Cascaded ANN Controller

The choice of a suitable controller is vital for enhancing the converter's dynamic performance and delivering the necessary error correction. The charging stations in this scenario are optimised via a cascaded control technique. The cascaded ANN control strategy, as shown in Figure 6, entails connecting two ANN controllers in series, with the output from the first controller serving as the input to the second. Although the ANN controller generally has a high computational speed, it has the drawback of being less exact. As a result, a cascaded ANN control technique is used to improve the accuracy of the controller. The output layer, input layer, hidden layer, and are the three fundamental layers of the ANN in Figure 6. Each layer is entirely interconnected even though there are no paired neurons inside it.

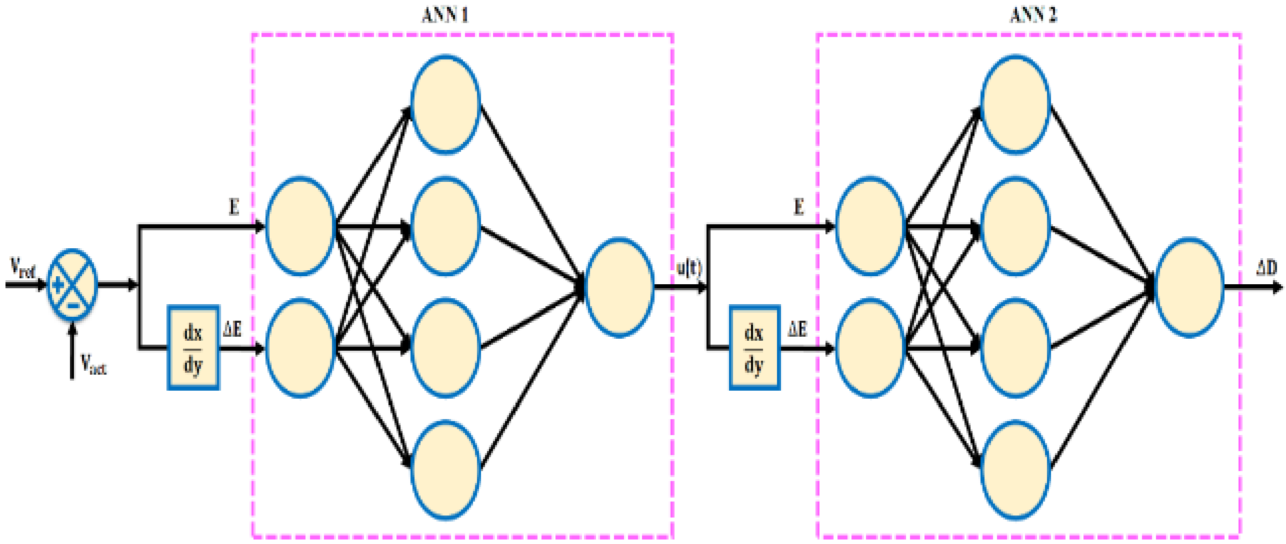


Fig. 6. Structure of cascaded ANN structure

The duty ratio of the converter is the primary output, and the magnitude and change in error are provided into the cascaded ANN controller. Once more, the duty ratio range for the following ANN controller is determined by the output of the first ANN controller. As a result, the accuracy of the cascaded ANN controller in figuring out the necessary change in duty ratio instruction is enhanced. Using pulses produced by the PWM generator, the cascaded ANN controller regulates the switching operation of the converter to produce a stable and continuous output.

5. Methodology Proposed

Transient response affects the computational efficiency of a variable reluctance motor (SRM), which is dealt with by adopting SRM modelling built on a cumulated artificial neural network (CANN). The schematic diagram of the CANN-based management system for a shifting resistance motor is shown in Figure 7. Current flow cannot be used to power SRM; rather, a converter is needed.

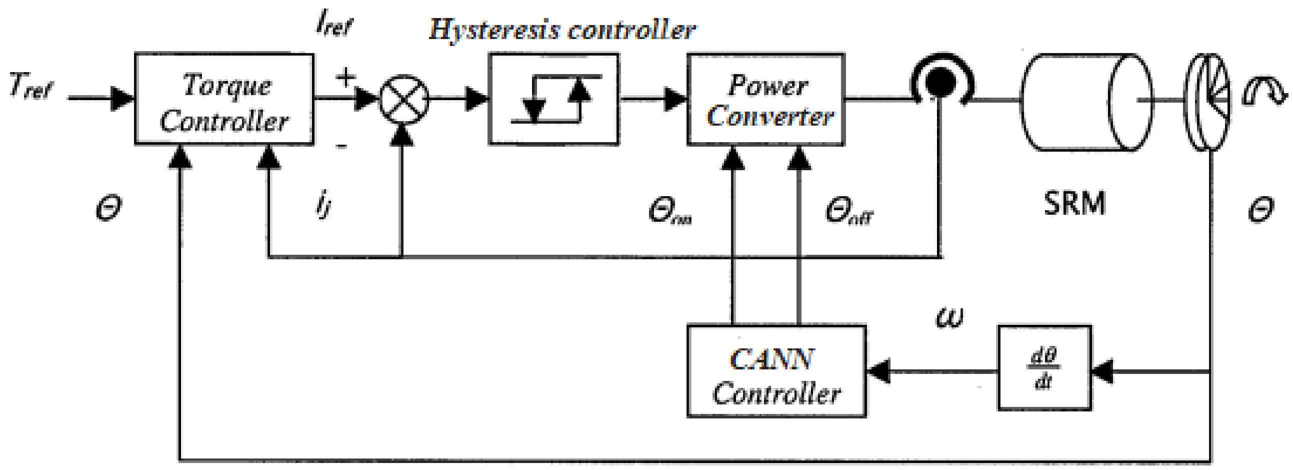


Fig. 7. The proposed control block diagram for the torque ripple minimization technique

Figure 8 depicts the SRM model, which is cantered on a four-leg, four-phase BR conversion. Each leg is made up of two rectifiers and two IGBTs. The SRM winding is coupled to a positive supply voltage in the aggressive condition through an IGBT switch. Positive voltages flow in phase windings during conductance periods, and inversely, even when there is no conductivity. The potential glycogen is returned to the DC source via transistors [22].

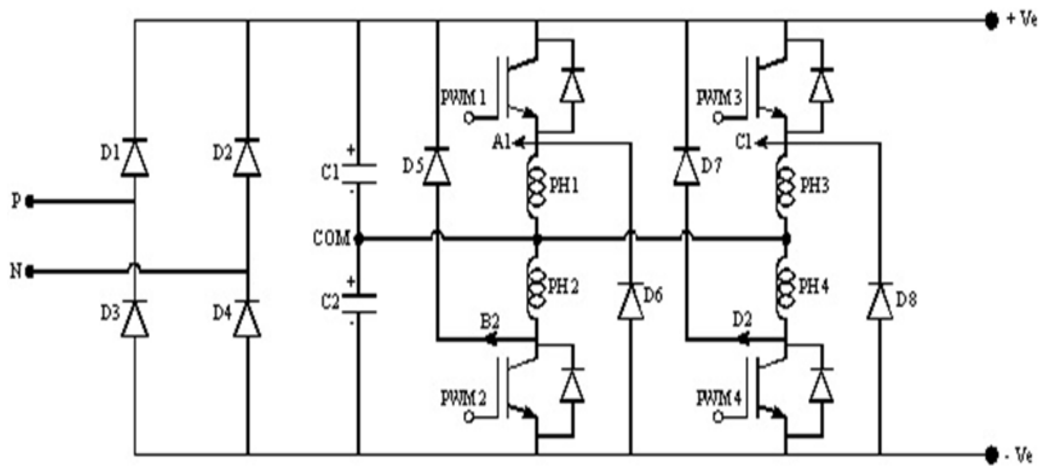


Fig. 8. Four Phase BR Converter Circuit diagram

The converter controls the motor's speed in large part by precisely turning on the required stator windings. Input is given by the hysteresis band that will be powered by a power converter which accepts gate pulses. The hysteresis band determines the switching frequency of an IGBT. For three-phase current hysteresis control, reference current is used. The position sensor regulates the motor windings' on and off phases. Using the sum block, the noise is mixed with the real motor speed and supplied into the CANN-based speed block, the output of which is coupled to the position of the speed sensors. Similarly, noise is added separately to the motor's real three-phase current, and the three-phase current is then fed into the CANN-based three-phase current blocks in Figure 9.

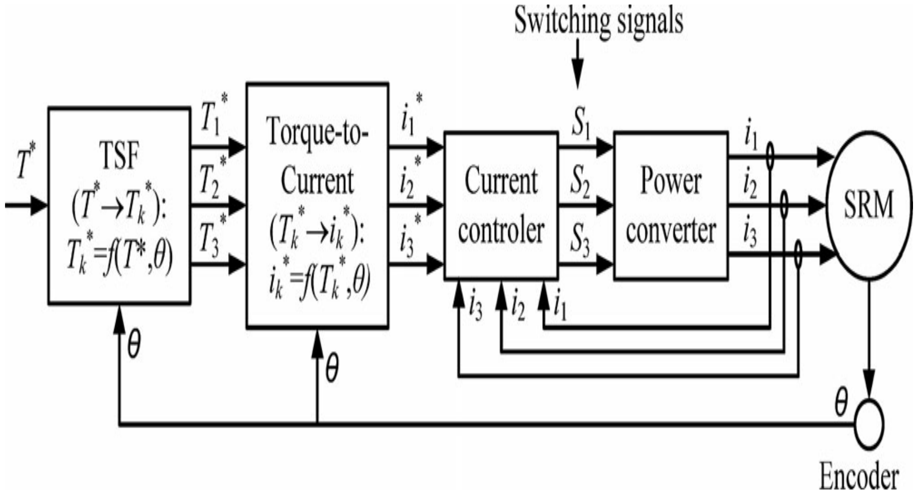


Fig. 9. Block diagram of SR motor based hysteresis current controller

Three hysteresis controllers are utilised to regulate phase currents individually and create IGBT drive signals by comparing CANN-based 3-phase currents with references. A CANN-based SRM is used to get the required outcome.

5.1 Proposed System Working

The SPLIT RAIL CONVERTER is fed by the single-phase diode bridge rectifier, which transforms the input AC voltage source to DC voltage. Based on the position sensor information from the SR motor, this converter will convert direct current voltage to variable alternating current voltage. The position sensor signals may be used to compute the real speed of the SR motor. The current sensor detects the four separate phase currents, which are referred to as the SR motor's real current. The torque sharing function block divides up the SR motor's total torque into separate phase torques. The corresponding current and flux are discovered once the torque has been extracted; this current serves as the reference current.

The Hysteresis Current Controller compares the reference and actual currents, and the C.ANN controller then adds the error to produce PWM pulses that are sent to the BR converter switches. The hysteresis current controller reduces current ripples. By comparing the reference and real speeds and feeding the error into it, the C.ANN controller lowers speed error and enables the motor to run at a consistent speed even when the load fluctuates. In other words, the PI controller will keep the voltage to the SR motor constant by adjusting the PWM pulse width, and the voltage to the motor won't change. In response to an increase in current, the hysteresis current controller widens the PWM pulses to the BR converter, boosting the voltage to the motor while decreasing the current. The torque ripples in the SR motor were lessened as a result of the decrease in current.

6. Results and Discussion

This study explores the simulation results. Figure 10 depicts the Simulink model of the recommended systems of 10 KW four stages 8/6 SRM with 1500 r.p.m. Figure 11 depicts a Simulink model of a retro control strategy.

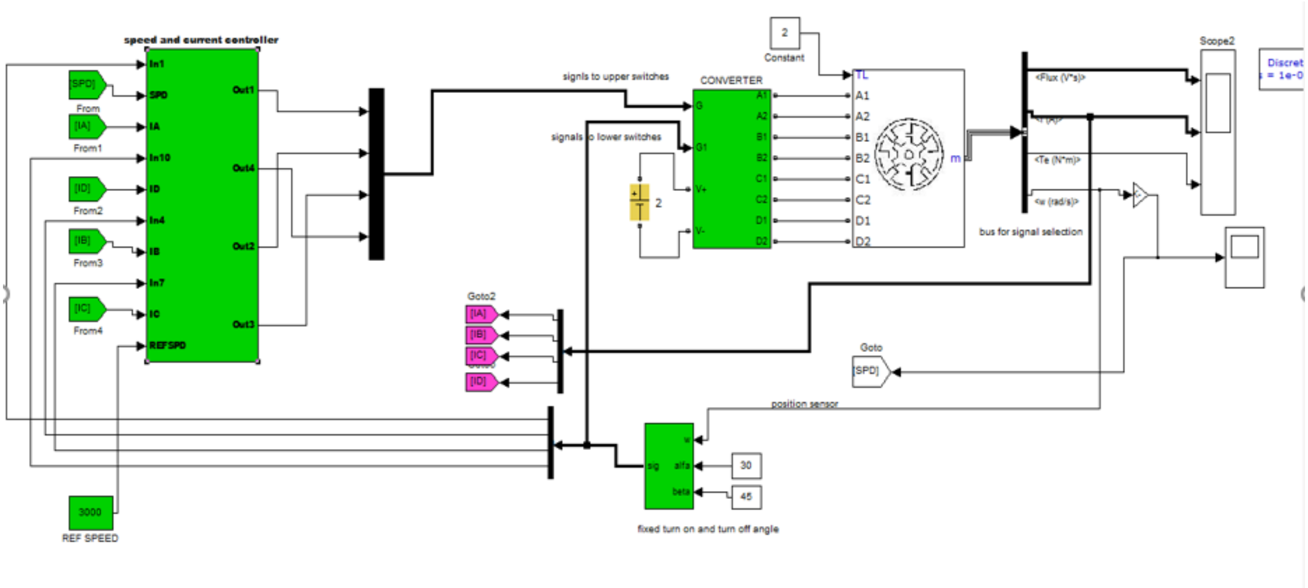


Fig. 10. Simulink Model of Four Phases 8/6 SRM

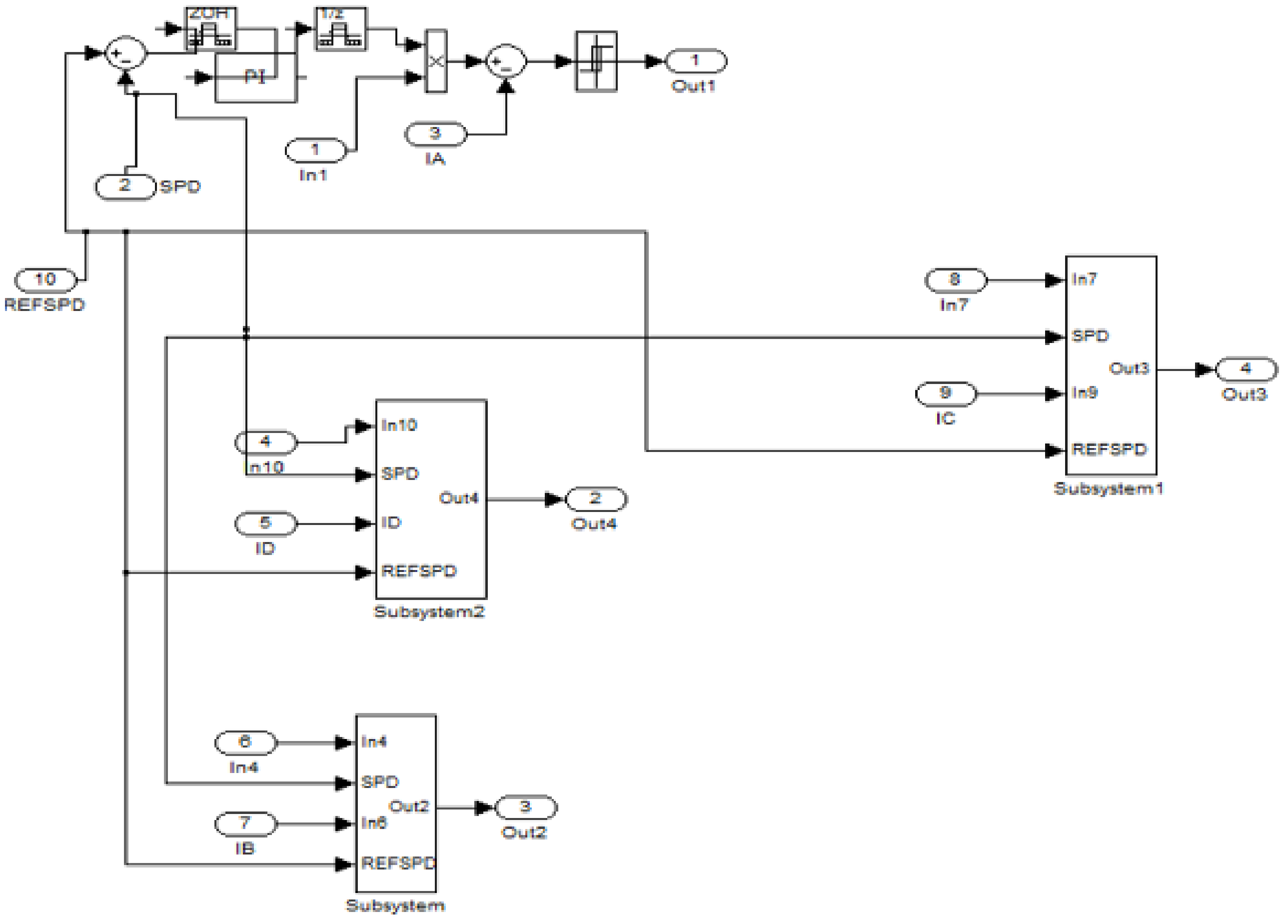


Fig. 11. Simulink model of a Hysteresis Current Controller

The SRM is supplied by the Bridges Resonant power converter and has four legs, each with two bidirectional switches and two IGBTs, are given in Figures 12 and 13 depict the cascaded ANN simulation results.

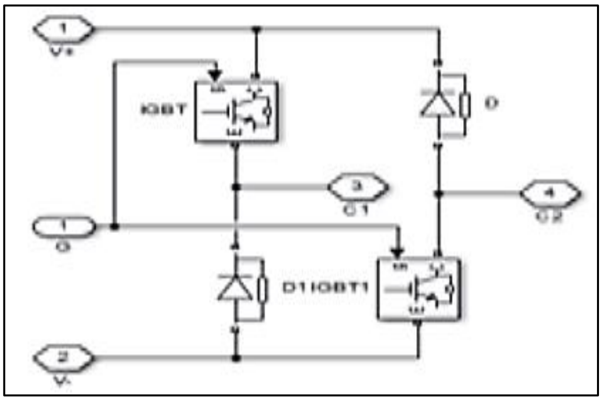


Fig. 12. BR converter simulation for SRM converter

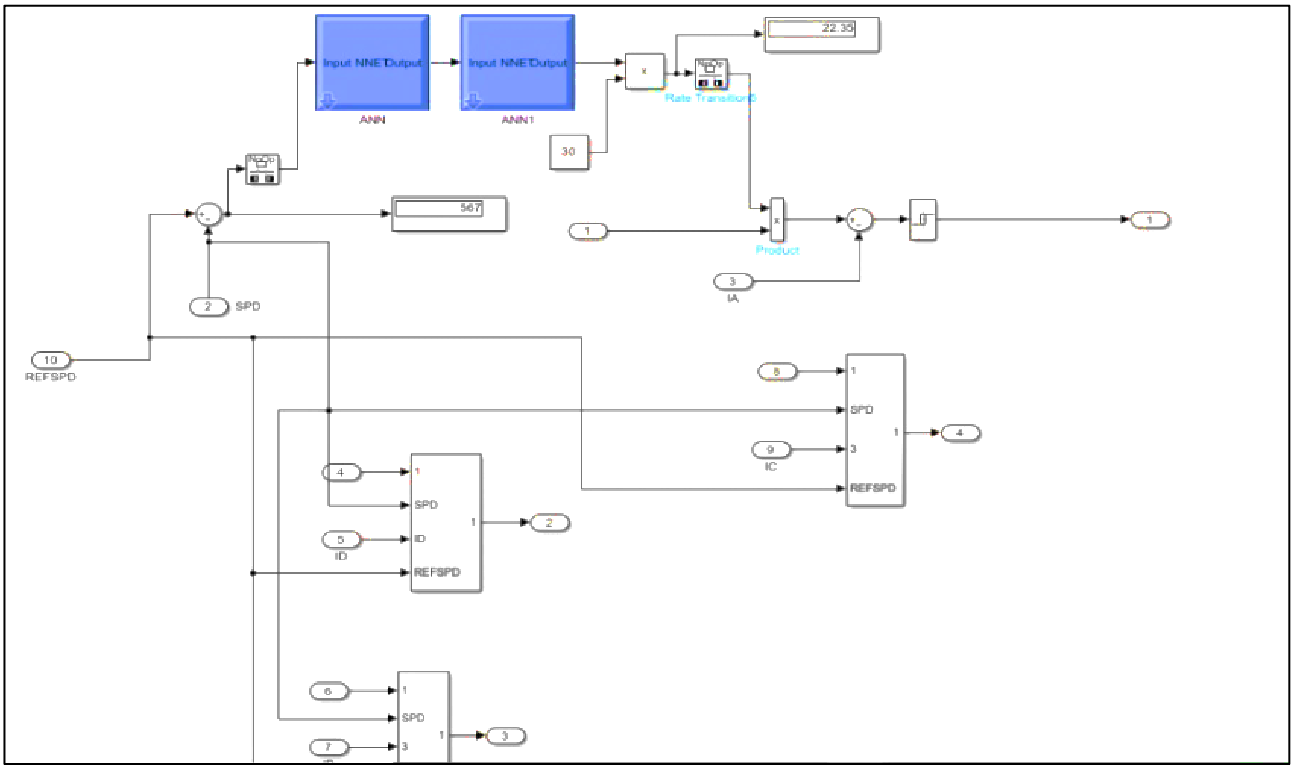


Fig. 13. Simulink model of cascaded ANN structure

Figure 14 illustrates the PWM to BR converter's pulses. The pulses instantly and directly influence the torque. The pulse switching frequency is 25 KHz. The DC tension is changed into AC tension. This voltage is then used to power the four-phase SR motor.

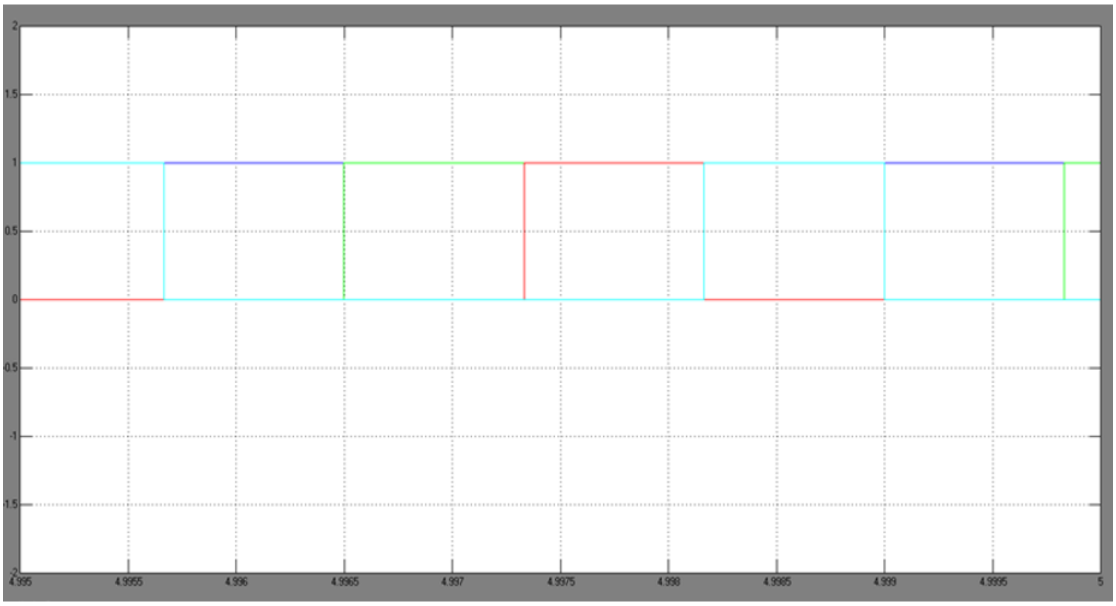


Fig. 14. Proposed system PWM pulses to the converter

Figure 15 displays the current, torque, and flux waveform of the SR motor. The machine initially uses a lot of power because of the nature of the material. Higher orders of ripple currents might generate noise in the torque due to this as well.

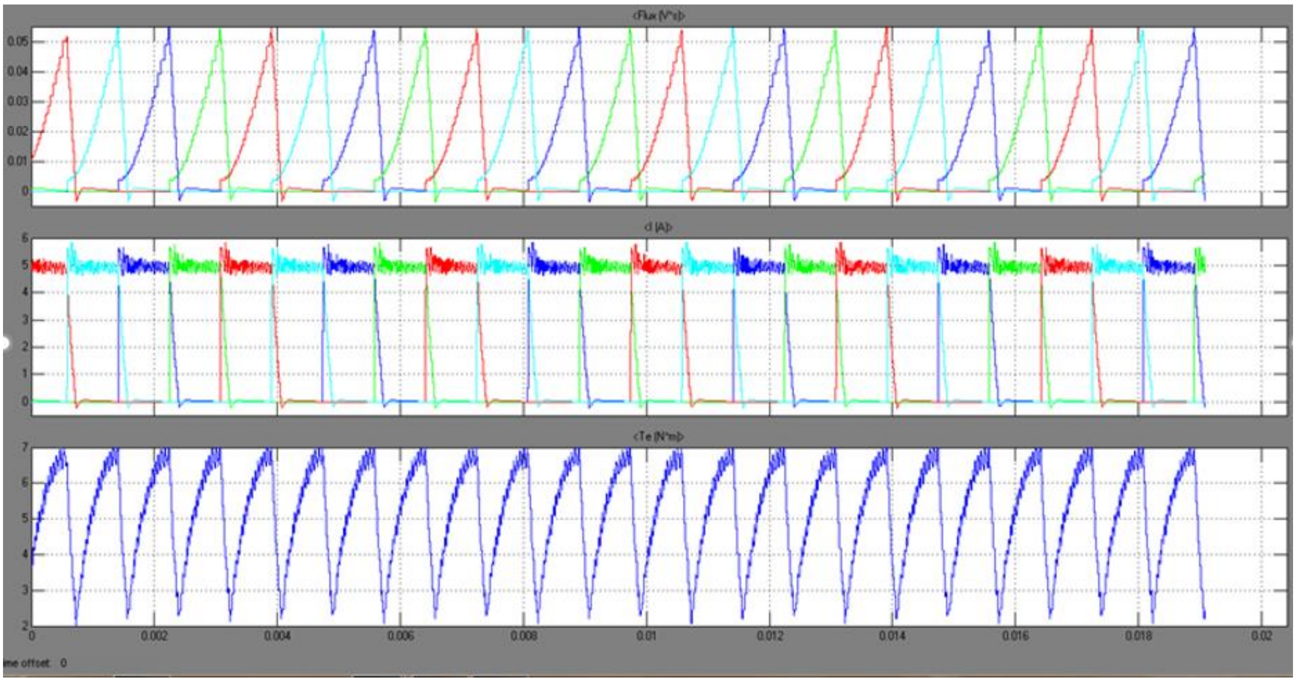


Fig. 15. Simulation waveform for flux, current and torque

The step change parameter for speed control is shown in Figure 16. Speed is set with 1500 RPM as an initial value and settled at 2000 RPM as shown in the speed waveform for the proposed system in Figure 17. The speed response of the SR motor with and without step change is shown in Figures 17(a) and 17(b). Torque improvement from the proposed and existing system is shown in Figure 18, which is 7 N-m when compared to the existing system.

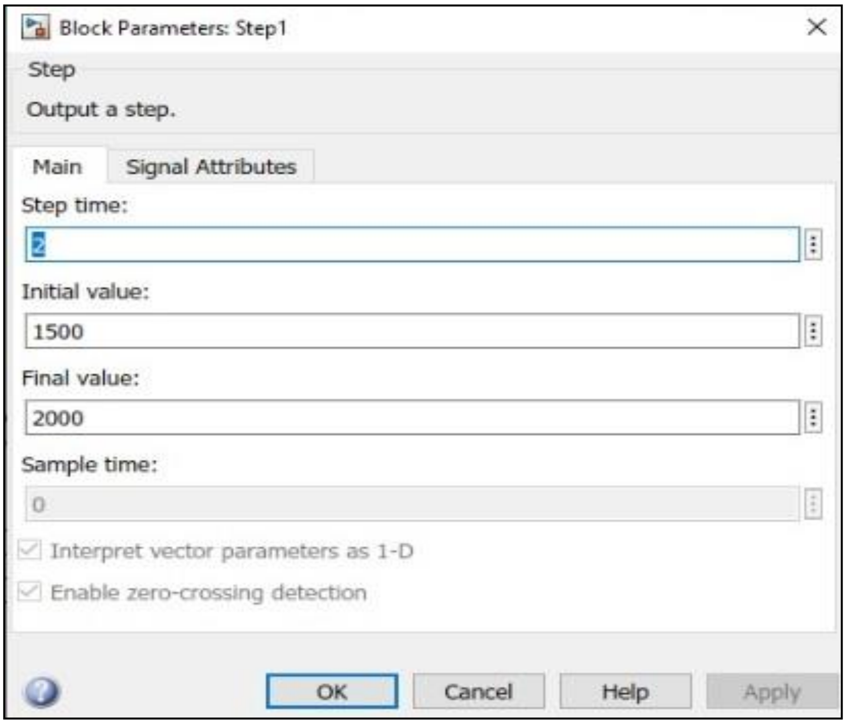
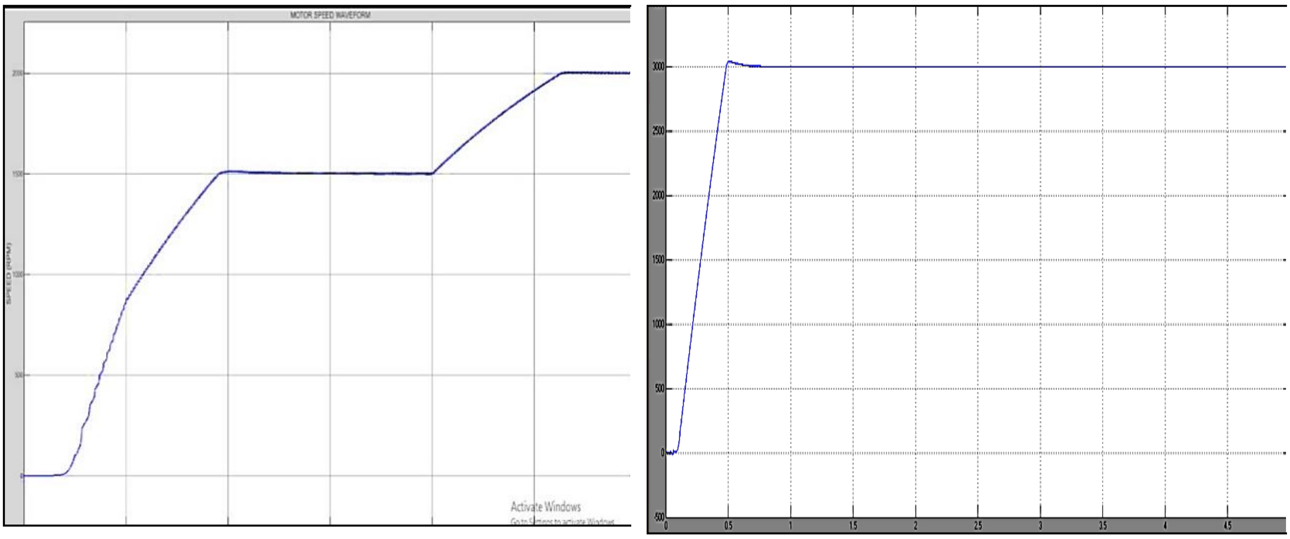


Fig. 16. Step change parameter for speed control



(a) (b)

Fig. 17. Speed waveform using Cascaded ANN controller (a) Speed response of SR Motor with step change and (b) Speed response of SR Motor with step change

6.1 Torque Improvement

Figure 18 shows the torque improvement from the proposed system to the existing system. Existing system: 6.2 Nm, proposed system:7 Nm

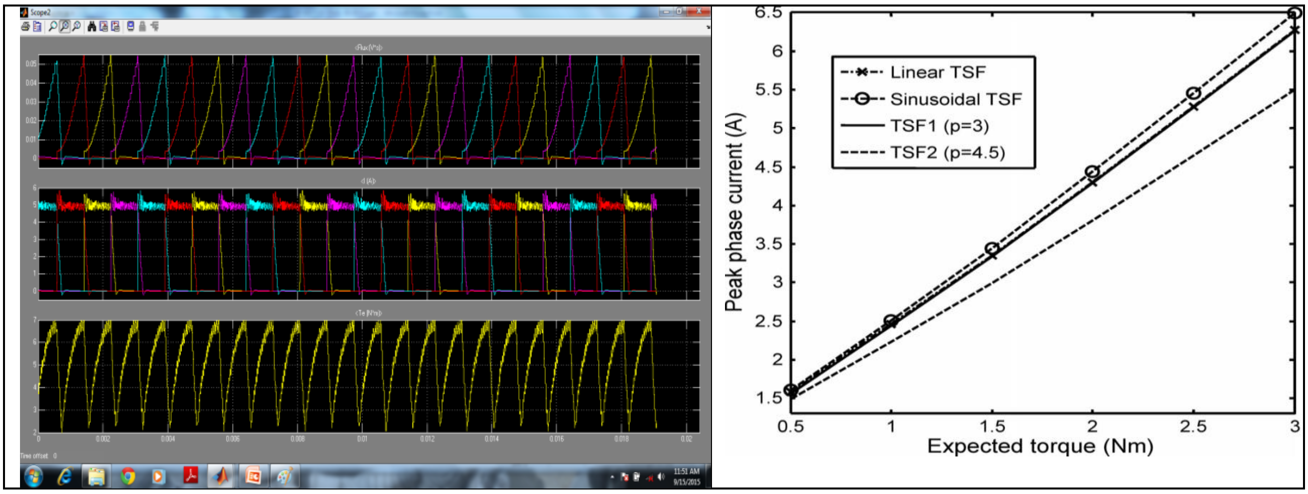


Fig. 18. Torque improvement from proposed system to existing

Table 1
Compares the suggested approach to others already in use

Considerations	Suggested method	PI controller	Basic model of SRM
Accuracy	Accuracy has Improved	It is less accurate when compared to ANN	Accuracy is inaccurate
Conversions	Conversions take less time and have less torque ripple.	Conversions are slower as compared to ANN.	Conversions are slower as compared to ANN.
Generalization	Good generalization enhanced performance over time when retrained.	There is no need to transfer the generality property, and no time improvements are available.	No simplification stuff
Model Speed	The computation period is short, and the operation is quick.	Long calculating period	Slow
Performance	Improved performance for SRM nonlinear features	Performance falls short of expectations.	Performance is Poor
Regression	Regression is near to one, indicating that performance and rapid parameter changes in ANN are legitimate.	There is no regression property, SRM demands rapid parameter changes, and the PI controller requires gradual parameter changes.	Nil
Complexity	Because there is no mathematical model, it is less complicated.	Because a mathematical model is provided, it is complicated.	Difficult than ANN and PI controller
Constancy	Better constancy	Fewer stable	Less steady

6.2 Efficacy of the Suggested Method

By contrasting the proposed CANN-based SRM approach with other current systems, its effectiveness is shown. A contrast is shown in Table 1.

7. Conclusion

Cascaded ANN is used in this study to enhance the performance in terms of current, torque and speed. The simulation results demonstrated the practicality of the devised strategy for reducing torque ripple, particularly in the low-speed area. Nevertheless, SRM runs at high speeds, and the phase current's rate of change limits any torque-ripple improvement. So, an improved model of cascaded ANN-based SRM significantly reduces torque ripples, leading to improved performance. As a result, simulation results show the viability and use of an improved SRM model as well as the capability of the Cascaded ANN algorithm to minimise torque ripples. High-speed applications can be controlled (stopped and loaded). A high-power density is advantageous for high-speed motors since it is a crucial component of traction motors used in ship propulsion. Furthermore, CANN outperforms SRM due to its quick convergence, robustness, stability, and suitability for nonlinear situations.

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