MODELLING AND PERFORMANCE ANALYSIS OF INDUCTION MOTOR UNDER DYNAMIC BRAKING OPERATION

THESIS

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OF

MASTER OF TECHNOLOGY

IN

[**POWER SYSTEM ENGINEERING**]

Submitted By:

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CANDIDATE’S DECLARATION

I, Harsh Agarwal, Roll No. 2K20/PSY/08, student of M. Tech (Power System Engineering), hereby declare that this Dissertation titled “Modelling and Performance Analysis of Induction Motor under Dynamic Braking Operation” which is submitted by me to the Department of Electrical Engineering, Delhi Technological University, Delhi, in partial fulfillment of the requirement for the degree of Master of Technology is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any degree, diploma Associateship, Fellowship or other similar title or Recognition.

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CERTIFICATE

I hereby certify that this Dissertation titled "Modelling and Performance Analysis of Induction Motor under Dynamic Braking Operation " which is submitted by Harsh Agarwal, Roll No 2K20/PSY/08, Department of Electrical Engineering, Delhi Technological University, Delhi in fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the thesis work carried out by the students under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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ABSTRACT

In today's world, industries are dependent upon induction motors due to their vast applications and economical aspects like robust nature, reliable operation, efficiency, lower cost, etc. The application of these motors in mills, conveyors systems, pumps, winders, wind tunnel operation, elevators, and so on. Due to their wide area of operation and usage, it is necessary to analyze and improve the braking part of these motors. So, it is very important to implement a braking system that can meet the requirement of industrial operations. Dynamic braking is achieved by developing a stationary magnetic field in the motor. The advantage of using dynamic brakes is ease in the regulation of speed and reduction in mechanical losses. A quick braking system means the motor should be coming to rest from its speed of operation within seconds or lesser. There can be multiple varying factors like different load torques, different braking time, different braking schemes or different machine parameters. That's the reason the implementation of an effective braking system has been an area of research over time. There are several conventional and long-known methods of braking of induction machines, which are widely known. In induction machines, the major issue has been the temperature rise as it determines the maximum loading.

An optimum braking scheme controls the stopping of motor drive in a smallest time with producing minimum heating and is hence cab be used effectively where regular and quick braking is required. A set of two improved dynamic braking schemes on 3 phase induction motor is implemented in this thesis, which is able to cover the drawbacks of the existing conventional braking system and hence eliminates the requirement for the implementation of a multistage braking scheme which is complex in nature that has been implemented by many scholars over the time. The

effectiveness of this braking system is analyzed under varying parameters. The power flowing in the motor during and after braking is also important to analyze its electrical model and losses at various stages. Thus, the power flow calculation from the input terminal to the power available at the shaft is done to analyze the power of the machine during the transients and steady-state braking. The effect of sudden braking on the motor drive on winding parameter and its thermal outcome is also analyzed in the SIMULINK environment. The performance of the braking system is studied and the ceasing limit due to different braking schemes is also estimated.

In this Thesis, a detailed analysis covering electrical and thermal modelling and implementation of improved dynamic braking of an induction motor is performed in SIMULINK environment.

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CHAPTER 1
INTRODUCTION

Induction machines belongs to most superior class of electromagnetic energy conversion devices over a decade or so, they are always in lime light for the research scholars over the globe without losing any attraction that they gained at the beginning. The reason being, they offer simplicity, safe and reliable modes of operation, Robust nature, efficient operation, and cost-effectiveness, etc. although their structural simplicity and robustness have assured continuous popularity of induction machines, but their sudden braking is still presenting some challenges that many industries and designers like to pursue and improve. Overall, A three-phase induction motor is an energy conversion device which changes its electrical power at input terminal into the mechanical power at output shaft. Structurally, a 3-phase induction machine is composed of a stator and a rotor. The 3-phase power supply is provided at the stator part, the rotor part derives its voltage and power in form of mechanical power from the stator side of winding via electromagnetic induction.

1.1 Working Principle:

Whenever a 3-phase stator winding is supplied from a balanced 3-phase alternating electrical power supply, a rotating magnetic field is thus produced in the motor windings. This rotating magnetic field starts rotating the stator windings at the synchronous speed, mathematically it is given by:

Synchronous Speed, $N_S=120 * \frac{f}{P}$ (1)

The Rotating magnetic field rotating at the synchronous speed through the air gaps and cuts the rotor conductors, which are not moving. Because of this relative motion in between the RMF and the conductors in stationary position an EMF gets induced in the rotor conductors of the motor. Because the rotor circuit is already closed due to the short circuit, a current starts flowing.

Subsequently, the rotor conductors are not having a current passing through them and also they are positioned in the magnetic field that has been developed by the stator windings of the machine. As a result, the rotor conductors start experiencing a motorized force. The combined effect of all these motorized forces on all the rotor conductors now produces a mechanical torque that starts rotating the rotor in the same direction as the direction of the rotation of the magnetic field. Hereafter, in such a fashion the three-phase input electrical power is transformed into output rotational power available at the shaft.

According to Lenz's law, the rotor has to be moving in the same direction as that of the direction of the rotation of the stator field, i.e., the direction of flow of the rotor currents in the conductors will be in such a way that the current tries to oppose the source fabricating them. Here, in the induction motor, the main cause generating the rotor currents is the relative speed between the RMF and the rotor conductors. Thus, to remove this gap in the relative speed between the two, the rotor starts running to catch the synchronous speed in the similar direction that of the RMF.

1.2 Advantages and Disadvantages of Three Phase Induction Motor

Advantages and Dis-advantages of the Induction Motor are discussed in Table 1.

Table 1. Advantages and Dis-advantages of Induction Motor

Advantages	Dis-advantages
Simple and rugged construction	They are constant-speed motors.
less maintenance	Poor starting torque
Better efficiency	High In-Rush Current
Less expensive	operate under a lagging power factor
Has self-starting Torque	Operation at a very low power factor during light loading conditions.

1.3 Need Electrical Braking?

Majorly there are two classifications of the Braking namely, Mechanical and Electrical Braking. Under the Mechanical Braking scheme, the rotation of the induction motor is diminished only by the mechanical methods but in the Electrical Braking is considered as more captivating than the mechanical braking schemes because of the fact that the whole braking schemes is dependent upon currents flow and torque directions. So, one can infer that braking is a process of reducing the rotor speed of an induction motor. The requirement of a braking system can be realized at practically every imaginable area, it can be inside the motor usage in a production factory, it may be a light or heavy industrial application zone or be it in field of trains and engines or the most widely used vehicles. Far and wide, the use of Mechanical and Electrical braking scheme is unavoidable.

The requirement and application for Electrical Braking can be pictured by some of the basic examples. Let's say, a loaded hoist is being lowered down or an unloaded one is being lifted up, in both the cases here, the total electro-mechanical torque will support the motion.

Therefore, in a steady-state operation for both the cases can be attained by accumulating a mechanical braking system (it can be just like when somebody is moving down in sloped road by his/her vehicle, they need to keep applying Breaks for attaining a consistent speed otherwise the vehicle will start accelerating). But, regrettably, the usage of Mechanical Braking scheme have several disadvantages:

- It requires regular maintenance and replacement of its Braking Shoes.
- It reduces the life of Mechanical Brakes.
- The Braking produces lot of wasted energy in form of heat.

This demands for a smart technique for implementing Braking system. Here, an Electrical Braking is able to provide the same. The disadvantages occurred in the Mechanical Brakes can be overcome by the application of Electrical Braking system in which the Motor is set to operate as a Generator mode which changes the mechanical energy at rotor part of the machine or vehicle into electrical energy and at the same time producing an electromechanical torque in the direction to clash with the motion. But to enhance and improve the reliability and for emergency time in case of unexpected failure, Mechanical Braking scheme are also available sideways with the Electrical Brakes.

Now approaching to another situation. Let's assume that it is needed to decrease the speed of an induction Motor. So obviously, there is a need to decelerate the Motor. As it is known that deceleration of the Motor happens if the load torque is higher than the Motor torque. For such an application wherever, the Load torque is continuously in the picture, just by simply dropping the Motor current will cause reduction in the Motor torque and therefore, as a result the Motor torque will now become lesser than the applied torque and hence braking will be implemented in the machine. But, what if in an application, where the applied Load torque is not available all the time. Thus, for the obtaining a braking in such cases, one require either of Electrical or Mechanical Braking.

Stopping is a situation for braking where the final rotor condition of the induction motor is fetched down to zero or standstill. In the applications where one want regular, rapid, smooth or urgent stopping/braking, one should look towards Electrical Braking as it has lesser effects on the mechanical parts of the machine. For illustration, consider a sub-urban electrical traction train quick breaks are regularly required. Usage of Electrical Braking permits a soft break which doesn't originate any inconvenience to the on-board passengers and it also increases the mechanical life of the railtrack and the train wheels and thus saves also the money on wear and tear.

1.4 Classification of Electrical Braking

- Regenerative braking
- Plugging Braking
- Dynamic braking
    - AC dynamic breaking
    - Capacitor Self-Excitation Braking
    - DC dynamic braking
    - Zero Sequence braking

1.5 Regenerative Braking

The power (input) of an induction motor is given as :

$$Pin = 3*V*I_s * Cos(\varphi_s) \quad (2)$$

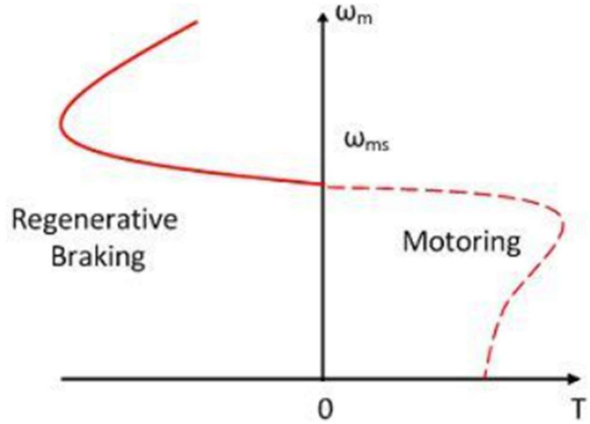


Fig. 1. Regenerative Braking [16]

Here, φ_s is the phase angle between stator phase voltage V and the stator phase current I_s. Now, for obtaining a motoring operation $\varphi_s < 90^o$, and for braking operation $\varphi s > 90^o$. When the speed of the motor is more than the synchronous speed, the relative speed between the motor conductors and air gap, the rotating field gets reversed, as a result, the phase angle becomes greater than 90^o and the power flow reverses and thus a regenerative braking takes place. The nature of the speed Vs torque curves are shown in the Fig. 1. It the source frequency is fixed then the regenerative braking of induction motor can only take place if the speed of the motor is greater than synchronous speed, but with a variable frequency source regenerative braking of induction motor can occur for speeds lower than synchronous speed. The key advantage of this kind of braking can be said that the generated power is use fully employed and the main disadvantage of this type of braking is that for a fixed frequency sources, braking cannot happen below synchronous speeds.

A typical application of regenerative braking is its use in electric traction systems such as trains or trams. There are often thousands of tones on the move and this constitutes significant inertia. If this energy can be converted into electrical energy and slow down a train or tram, a lot of saving in electricity costs can be achieved. The brake shoes used in a mechanical system will also save on wear and tear.

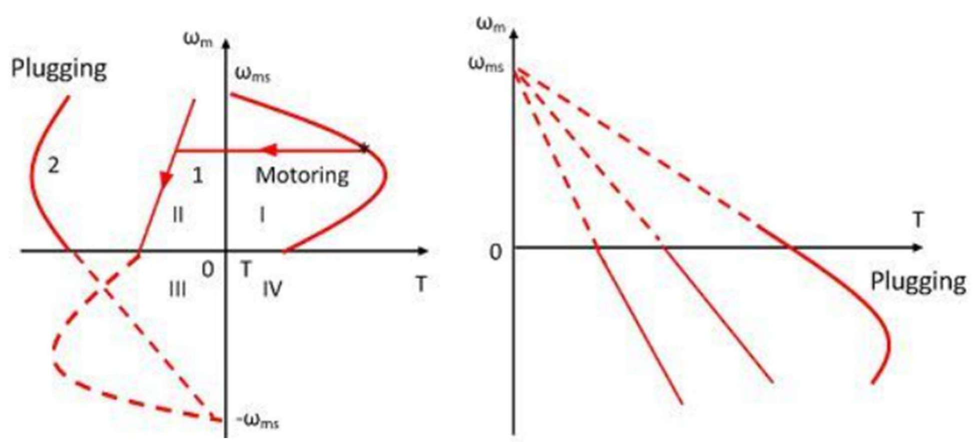
As a vehicle slows down the vehicle and requires mechanical braking, which reduces the effectiveness of the system. At some point, the generated electrical energy is not enough to feed back to the supply line and the system needs to be disconnected from the grid. Occasionally, the system may also use dynamic braking as a deceleration process. The usage of regenerative braking is limited by the cost of installing additional equipment on the machine and the lack of a way to stop the machine completely and keep it in a stationary position. In AC work, it is mainly used to control the overhaul loads. Consider a crane that lowers heavy loads.

1.6 Plugging Braking

Plugging in induction motor braking can be achieved by reversing the applied phase sequence of the supply fed to the motor or by swapping the supply connections of any two phases of the stator part with respect of input power supply terminals. And thus, the operation of the machine gets shifted from motoring mode into plugging type of braking mode. During plugging braking the slip is (2 – s), if the original slip of the running motor is considered as ‘s’, then mathematically it can be represented in the following way:

$$S_n = \frac{-\omega_{ms} - \omega_m}{-\omega_{ms}} = 2 - s \qquad (3)$$

But, this type of braking is a abrupt and forceful method for taking a motor to a zero speed or standstill. The authentic time taken for the braking generally depends on the net quantity of inertia in the associated machine.



(a). 1- Natural Characteristics, 2- With external resistance in rotor

(b). Plugging (IV quadrant) with extra-large resistance

Fig. 2. Plugging Braking [16]

From the Fig. 2, one can see that the torque is not zero at zero speed. Therefore, when it is necessary to stop the motor, the power must be cut off at a speed close to zero. The motor is wired to rotate in the opposite direction and the torque is not zero at zero or any other rotational speed, so the motor first brakes to zero and then gently accelerates in the direction opposite.

In direction to use the plug method as a stopping scheme, means shall be provided to remove all electrical energy stored in the motor at the time of change of direction. This can be achieved with a single pole friction inverter mounted on the drive shaft of the induction motor.

1.7 Dynamic Braking of Induction Motor

There are four classifications of dynamic braking:

1.7.1 AC Dynamic Braking

This type of induction motor braking is achieved when the motor is operating on single-phase power by disconnecting any one of the three phases from the supply, and leaving it open or connected to another phase. When the disconnected phase is left open, it is called a two-conductor connection, and when the disconnected phase is connected to another phase of the machine, it is called a three-load connection. Brake operation can be understood easily. When the motor is running on single-phase power, the motor is energized in the forward and negative order, the net torque generated by the machine is the sum of the torque due to the positive and negative sequence voltages.

At high resistance, the actual torque becomes negative and braking occurs. From the Fig. 3 the two and three load connections can be understood.

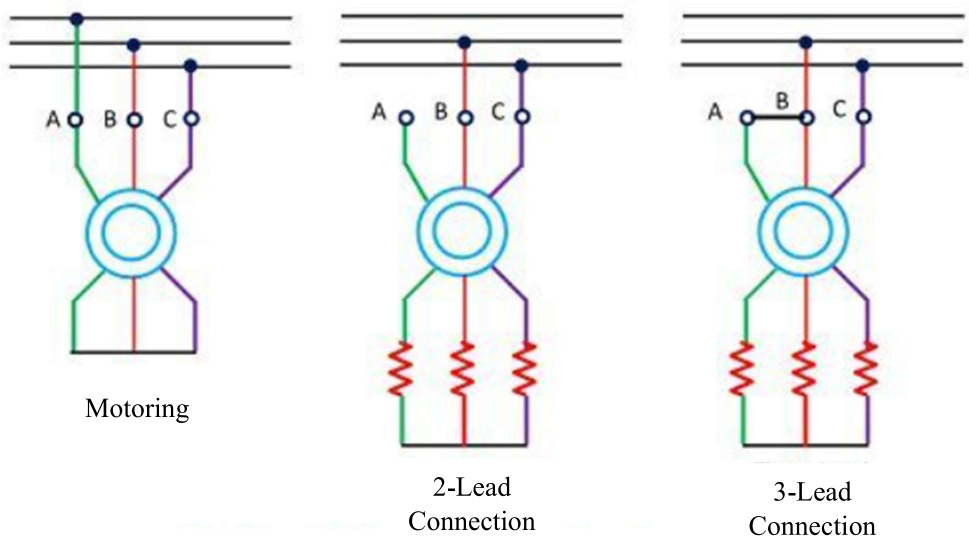


Fig. 3. AC Dynamic Braking [16]

1.7.2 Capacitor Self-Excitation Braking

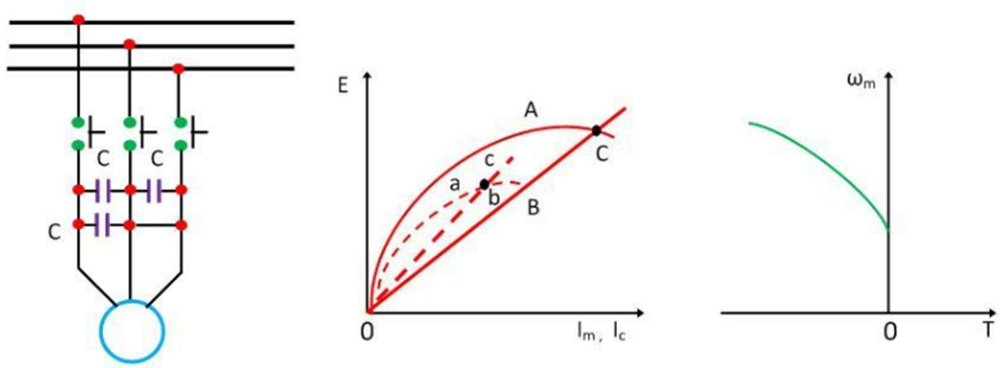


Fig. 4. Self-excitation Braking using Capacitors [16]

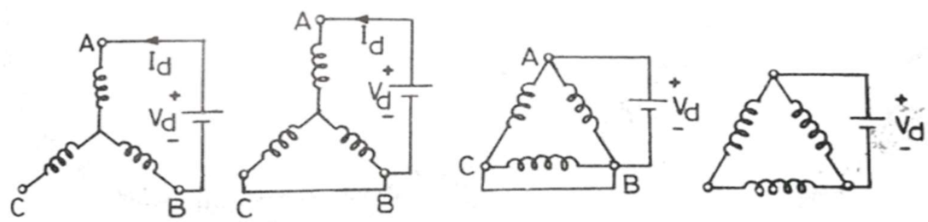
The Fig. 4. Present the circuit diagram and different characteristics of self-excited brake using capacitor. As it can be seen in the figure, in this method the capacitors are kept fixed connected to the power terminals of the motor. The value of the capacitors is chosen according to their ability to supply enough reactive current to excite the motor and make it act as a generator.[4-6] Thus, when the motor poles are disconnected from the source, the motor acts as a self-excited generator and the torque and field generated are in the opposite direction and the braking action of the induction motor occurs. In figure (b), curve A represents the no-load magnetization, curve B shows the current flowing through the capacitors.

The speed-torque characteristics in self-excited braking are shown in figure (c). To increase the braking torque and take advantage of the generated energy, external resistors are sometimes connected across the stator terminals.[7-8]

1.7.3 DC Dynamic Braking

This type of electrical braking is achieved, when the stator side of a dynamic induction motor is detached from AC source and coupled to a DC supply. Two and three lead networks are the two normal type of configurations for the star and delta associated stators as shown in

Fig. 5.



(a) (b) (c) (d)

(a) and (d) are two-lead connections; (b) and (c) are three lead connections

Fig. 5. DC Dynamic Braking [16]

When the AC power is disconnected and the D.C. power is passed through the terminals of the induction motor, a stationary magnetic field is created due to the d.c. current flowing, and when the motor's rotor rotates in this field, there is a partial armature in the rotor winding, and thus the machine acts as a generator mode and the generated energy is dissipated in the resistance of the rotor circuit and dynamic braking of the induction motor is obtained.

1.7.4 Zero Sequence Braking

In this type of braking scheme, all the three stator supply side phases are set to get connected in a series combination and a single phase AC or DC power supply is connected across them as shown in the Fig. 6. This type of assembly is termed zero-sequence as the currents flowing in all the stator windings of the motor are in same phase or co-phasal. If the connected supply at the stator side is AC type in nature, the resultant field produced is stationery in the phasor space and pulsating at the frequency of the power supply, when the connected power supply is DC type in nature, the resultant field produced is also stationery and is of the fixed magnitude. The foremost advantage of this type of induction motor braking has been that all the stator phases gets loaded in uniform way. It does not have any need to use large rotor resistances as that is needed in AC dynamic braking scheme. The circuit diagram for the braking scheme and the speed torque plot are also shown in Fig. 6.

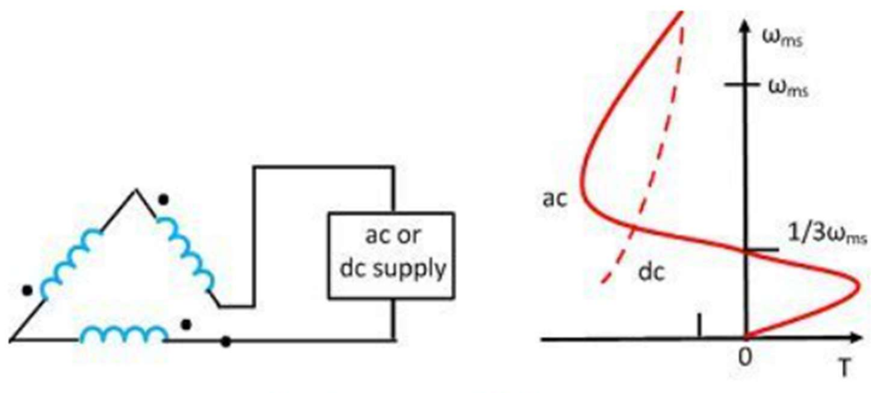


Fig. 6. Zero Sequence Braking [16]

CHAPTER 2

LITERATURE REVIEW

C. F. Evert, "Dynamic braking of squirrel-cage induction motors," in Electrical Engineering, vol. 73, no. 2, 1954, pp. 162-162.

In this paper, an application using direct current to the three-phase induction motor have been used in order to develop a negative torque to implement braking scheme in the motors due to production of stationary magnetic field around the peripheral space of the stator windings. As the rotor bars cuts through the magnetic flux generated, a voltage is produced across the rotor side of the machine and resulting current due to this voltage is responsible to produce deaccelerating torque in the machine.

R. Singh, S. Umashankar, D. Vijaykumar and D. P. Kothari, "Dynamic braking of induction motor - Analysis of conventional methods and an efficient multistage braking model," 2013 International Conference on Energy Efficient Technologies for Sustainability, 2013, pp. 197-206.

In this paper, a thorough study and analysis is done on the multistage braking model including capacitive self-excitation braking scheme, DC-Injection scheme and magnetic braking scheme implemented altogether to achieve a quick emergency braking for the induction motor. The effect of changing the machine parameters along with terminal capacitance is closely observed and a combination of conventional braking schemes is implemented.

E. C. Ejiogu and Y. Tanno, "Capacitor self-excitation braking of the induction motor," Proceedings of IECON '93 - 19th Annual Conference of IEEE Industrial Electronics, 1993, pp. 891-895 vol.2

In this paper, a decaying vector-controlled component method has been used to analyse the transients during the braking operation. Here, the saturation characteristics has also been taken into the account for the braking. Finally, the experimental and the simulation results obtained are compared and the application related issues and problems that needed to be solved have been discussed briefly.

P.L. Rongmei, Shimi S.L, Dr. S. Chatterji, Vinod K. Sharma, "A Novel Fast Braking System for Induction Motor," International Journal of Engineering and Innovative Technology (IJEIT) Volume 1, Issue 6, June 2012, pp 65-69.

In this paper, a reliable, improved and quick braking scheme for three phase induction-motor has been designed using combinations of conventional braking schemes. In scheme one, a combination of capacitive self-excitation braking along with magnetic braking is used to produce deaccelerating torque. In scheme two, combination of capacitive self-excitation braking along with DC injection is implemented. In scheme three, a combination of capacitive self-excitation braking, magnetic braking and DC injection is used. In scheme four, capacitive self-excitation braking, magnetic braking and zero-sequence braking has been implemented using a rectifier circuit for DC current injection. The last scheme is expensive as compared to other schemes. In all the schemes, Capacitor self-excitation braking is used as primary braking.

R. Subramanian and C. Chellamuthu, "A fast method of braking of induction motor by self-excitation," in IEEE Transactions on Energy Conversion, vol. 7, no. 2, 1992, pp. 315-321

In this paper, an effective braking is achieved by connecting different values of terminal capacitances at the stator side of the motor. Also, the stator frequency is inversely proportional to the capacitive reactance used at the stator terminal. As the machine is operating in negative slip a negative torque slows down the motor and thus braking is achieved. As the machine slows down the energy is dissipated in form of electrical losses in the capacitor. The energy continues to dissipate unless a balancing between magnetic reactance and capacitive reactance is reached and at this point the self-excitation ceases.

E.C. Ejiogu, and Y. Tanno, "Transient and Saturation Modelling of the Capacitor-Excitation and Magnetic Braking of the Induction Motor", Proceedings of IEEE International Symposium on Industrial Electronics (ISIE'93), Budapest, Hungary, 1993, pp. 316-320.

In this paper, effect of saturation is shown which increases the value of terminal capacitance where self-excitation is obtained, which generally occurs at low speed when a suitable capacitance is used. The implemented scheme used here is said to provide a fail-safe capabilities and quicker braking achievement. Few further considerations like usage of non-polarized capacitances for braking having adequate rating are done.

Puri IK. Estimation of Optimum Braking Time for Capacitor-Excited Induction Motor. The International Journal of Electrical Engineering & Education. 1978;15(3), pp225-235.

In this paper, an approximate analysis for the estimation of braking time of the induction machine is done. Experimental results are compared with the approximated calculations for braking timing and the self-excitation ceasing limits for multiple values of terminal capacitance is used. The braking time obtained in each case is plotted and the performance been compared with other methods. From the, data plotted an optimum value for the terminal capacitance and control resistance in series with capacitance is also observed.

P. Mynarek and M. Kowol, "Thermal analysis of three-phase induction motor using circuit models," Electrodynamic and Mechatronic Systems, 2011, pp119-122.

In this paper, a thermal study has been presented on a three-phase induction motor with the help of coupled circuit models. The modelling and examination was done in Piecewise Linear Electrical Circuit (PLECS) simulation and results were verified with the physical motor.

Badran, Omar & Sarhan, Hussein & Alomour, B.. (2012). "Thermal performance analysis of induction motor." International Journal of Heat and Technology. 2012, 30. pp75-88.

In this paper, lumped parameters of the motor have been used to apply a mathematical model to determine the temperature distribution of the machine. Thermal stability has also been checked for the insulation level of the copper windings at different operating conditions. The validation is done by comparing the calculated temperature values with the physical temperature obtained from the experimental setup.

CHAPTER 3
CONVENTIONAL CAPACITOR BRAKING

3.1 Introduction

This section of the Thesis discusses the conventional capacitor braking scheme for a three-phase induction machine. The scheme is simulated in the Simulink environment and areas of improvement are traced out from the results obtained. In a conventional capacitor braking system, the capacitor bank is connected across the stator terminals of the induction motor after disconnecting the motor from the power supply. [1-3] For the simulation purpose, a 3 phase 3HP, 4 poles, 415V, 50Hz, squirrel cage motor is analyzed. Different factors affecting the braking operation are examined. Capacitor excitation braking performance on an induction motor depends on the self-excitation. The machine undergoes self-excitation given that a residual magnetism exists, which produces a counter torque to brake down the machine. [10-12] Three-phase breakers are used to control the switching time of the breaker to connect the motor from the power supply to the capacitor bank.[13-14] The ceasing speed limits for different values of terminal capacitance is also observed and a mathematical estimation for the capacitor values is also done. Additionally, the same is implemented in the neural network to calculate the value of terminal capacitance.

Machine parameters;

Table 2. Machine Parameters

Parameter	Value
R_s	0.5 ohm
R_r'	0.7402 ohm
L_{ls} & L_{1r}'	0.003045 H
J	0.05 Kg-m^2
T	10 Nm
Terminal Capacitance	1500 µF
Breaking Time	1 sec
L_m	0.1241 H

(Value of C to be varied and ceasing speed limit is observed in each case).

3.2 Simulink Implementation

The conventional capacitor scheme is implemented in the simulink environment by simply using three phase breakers power supply is switched off and the whole system is connected to capacitor bank at 1.0 seconds. The machine parameters are shown in the Table 2 and Fig. 7.

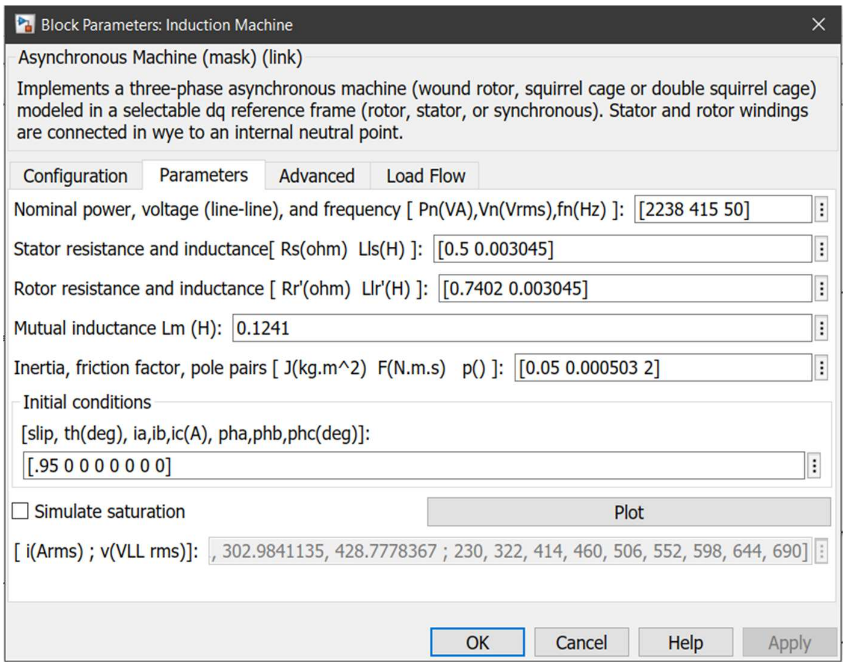


Fig. 7. Machine Parameters in Simulink Block

The major question here is how to choose the value of terminal capacitance for different value of ceasing speed limits of self-excitation.[15] This part is covered in the next portion of the Thesis. A neural netwrok has been developed to calculate the values of terminal capacitance for different values of ceasing limits. Also, a mthematical estimatiton based on balancing between terminal capacitance and mutual inductance is done.

TheSimulink scheme is implemented as shown in the Fig. 8.

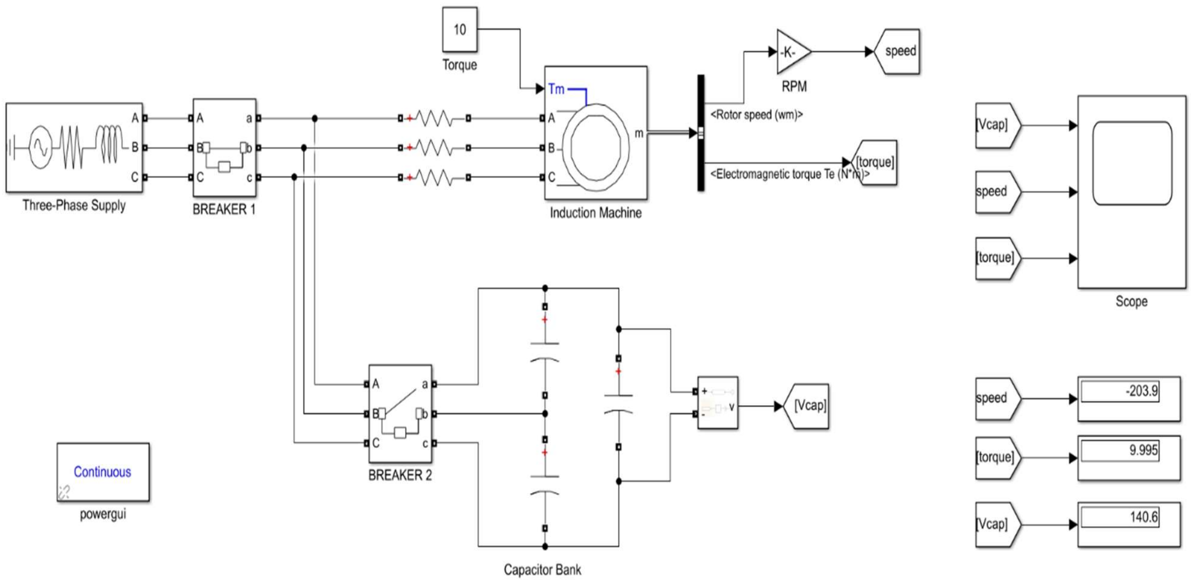


Fig. 8. Simulink Implementation of braking Scheme

3.3 Neural Network-Based Calculation of Terminal Capacitance for Different Ceasing Limits of Speed

Artificial neural network scheme is like a mathematical computation model that work likewise to the working of a human nervous scheme. There are multiple types of artificial neural schemes. These types of networks/schemes can be applied based on the mathematical function or operation and a set of constraints essential to determine the targeted output. A neural network is fundamentally a combination of network of mathematical functioning models and equations which can take one or more argument as input dataset and after undergoing via a network of equations produces out one or more output variable dataset.

Every Neural Network is combination of a several layers interlinked together namely: a node layer, this layer contains the input data set fed to the neural network, second layers are hidden layer, one may have one or more hidden layers according to the complexity of mathematical computation and finally an output layer that gives the result of the neural network. Each node also called as a neuron is connected to one another neurons and thus they have an interlinked connection through weight and a threshold value. If the output data produced by any of individual neuron crosses the defined threshold value, then, that specific node or neuron gets activated and starts sending the data to the immediate next layer of the neural network. Else, no data is passed through that particular layer to the next layer of the neural network.

The reliability of a Neural network depends on good training data for learning and enhancing their accuracy to produce results over time. For higher reliability of the network, a wide range of input data set is provided for the training purpose. Once the learning algorithm is tuned for accuracy of the targeted output, they become a very powerful tool in engineering and artificial intelligence. Thus, allowing the Engineers to organize and group-up tons of data at a high reliability and accuracy. [27]

3.3.1 Different Layers in Neural Network

The different layers involved in a neural-network are defined below:

Input data layer:

The Input data layer in neural network consists of those artificial neurons also termed as units, that are supposed to receive input data from the user sitting in outside world looking to develop a neural scheme. This is point at which the real learning of neural network occurs, or acknowledgement happens else it will be processed.

Output data layer:

The output data layers consist of the neurons or units that responds to the data that is fed into the system and also gives us a cross check whether it has learnt any task to provide the targeted output data set or not.

Hidden layer:

As the name suggests the hidden layers are buried in between the input data layers and the output data layer. The only task of a hidden layer is to transform the input data into something useful that the output layer/unit can be used.

3.3.2 Working of ANN

Artificial Neural Networks are very much similar to a human brain and that of super complex networking of human brain and inspired from their biological inspiration. The network is realised as weighted directed graphs from an input node, to the targeted output data node, through hidden layers having transfer functions and activation functions, where the neuron output are be compared to the node and the connection between two neurons as weighted edges as shown in Fig. 9. The processing section of a nerve cell accepts many signals (together from supplementary neurons and as input signals from the outside world).

Signals are occasionally improved at the receiving synapse and the weighted inputs are also totalled at the processing element. If it surpasses the set threshold, it is energies as input to other neurons (or as output to the exterior world) and this procedure reiterates.

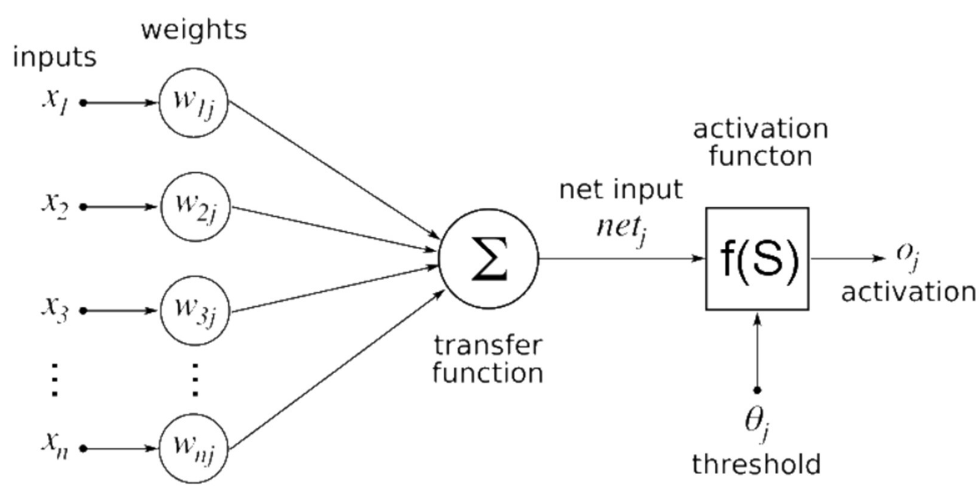


Fig. 9. Basic Scheme of Neural Network

Typically, the weights characterize the interconnection strength amongst the neurons. The initiation function is a transfer function which is applied to get the anticipated output for the problem for which a neural scheme is designed. Let's say, the targeted output is null or unity in the situation of a binary classifier. A sigmoid function may perhaps be utilised as an activation function.

There are a several types of activation functions like: linear regression, logistic regression, identity function, bipolar, binary sigmoid, bipolar sigmoid, hyperbolic tangent, sigmoidal hyperbolic and ReLU. Artificial neural systems are precisely designed for a specific function like binary arrangement, multi-class sorting, pattern acknowledgement and so on through an adaptive learning processes. The weightiness of the synaptic networks joints of both neural systems regulate with the learning process.

3.4 Neural Network Implementation

First of all, the neural network is trained for the different sets of values of ceasing speed limits (input variable) and corresponding terminal capacitance (output Variable), the above data set for training is obtained from the Simulink results performed repeatedly over a range of different values of terminal capacitance.

3.4.1 Training Data Set

For the training of neural network, a data set of input value and targeted value is created based on the results obtained from the simulation. As a input data set the ceasing limit for different values after applying different values of terminal capacitance is tabulated. So, ceasing speed limit is the input data and the corresponding value of terminal capacitance is the targeted output which be calculated with the help of neural-network. To obtain a data set the values of terminal capacitance are varied from 100 μF to 3000 μF at a gap of 50 μF and corresponding ceasing limits are obtained. The whole data set can be tabulated in form of sample table as shown in Table 2. The X_m to be kept constant throughout the process.

Table 3. Sample Data Set for Neural Network

CAPACITOR (μF)	**X_c**	**L_m**	**X_m**	**Ceasing Speed**
Target O/P				**Input data**
100	31.84713	0.128	40.192	1336
3000	1.061571	0.128	40.192	322

The data obtained above can be plotted to understand the effect of varying the value of terminal capacitance on the ceasing speed limits as shown in Fig. 10. From the curve obtained form the tabulated data it can be observed that, after a particular value of terminal capacitance the variation in ceasing speed limits is very low. To obtain a general ceasing limit, let's say to 420 RPM an effective range of terminal capacitance ranging from 1200 µF to 2000 µF or 2200 µF can be used effectively. Within this range of terminal capacitances, a mathematical estimation for the ceasing speed limits can also be done. The ceasing limit remains close unless a very high unpractical value of capacitance is used.

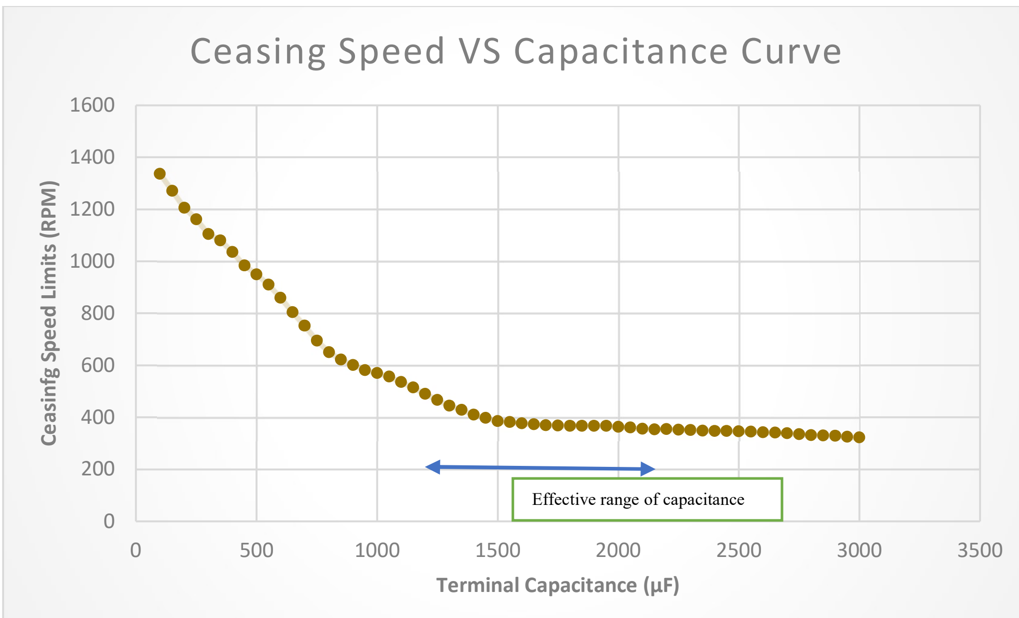


Fig. 10. Ceasing Speed limit VS Terminal Capacitance

The data obtained from the Simulink is tabulated and is used to develop and train the neural network and is implemented in the Simulink model to give the value of terminal capacitance for the user-defined ceasing speed limits.

The neural network is trained until optimum training is achieved; Optimum training is obtained at hiddenlayersize=5. Optimum training is checked for the minimum possible error in target output and error curve obtained after each training, as shown in Fig. 11. At optimum training, the value of R should be close to 1, as shown in Fig. 12.

The Levenberg-Marquardt training algorithm is used here.

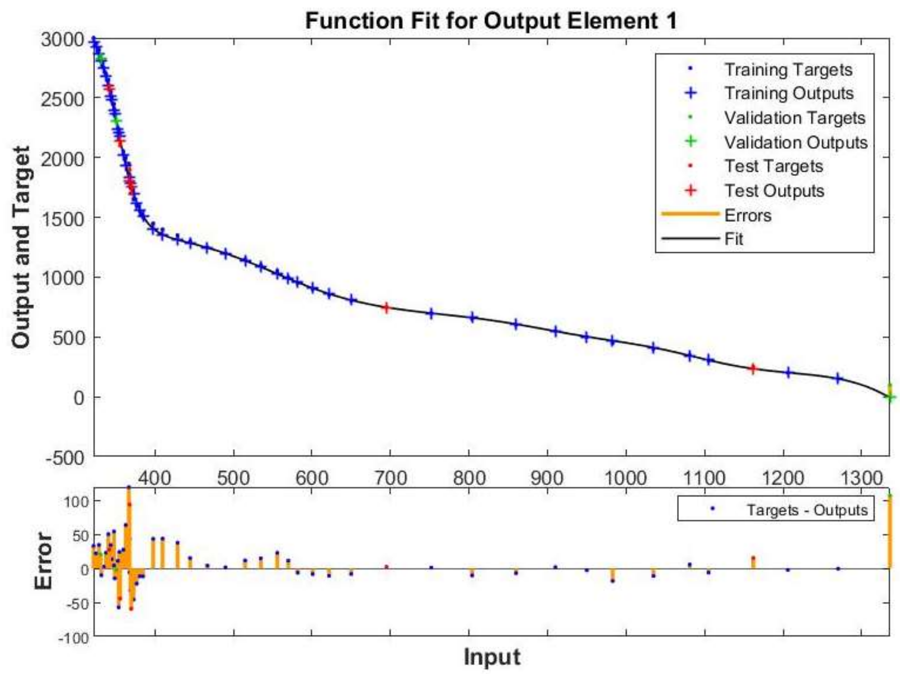


Fig. 11. Function fitting using Neural Network and error plot

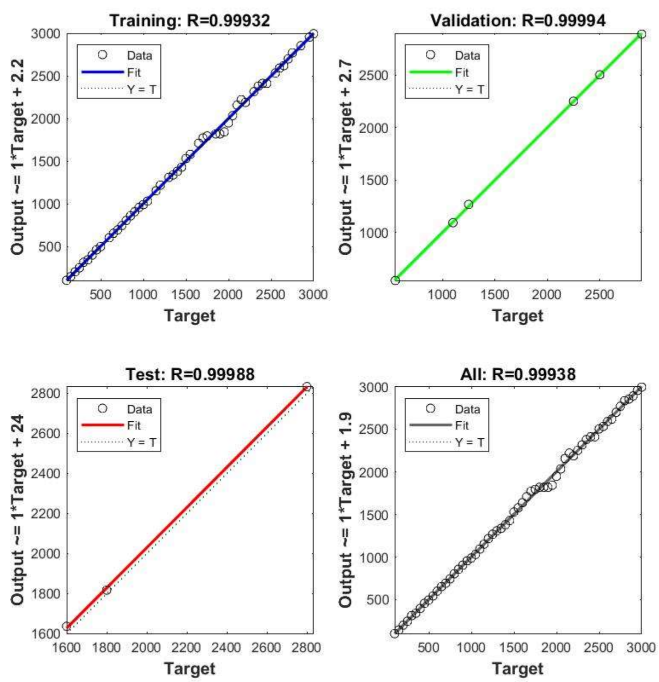


Fig. 12. Regression plot for the Neural Scheme

From the Fig. 11 it can be observed that the plot obtained is similar to the plot obtained from curve fitting from tabulated data obtained is similar. Also, the error plot shows almost zero error at the effective range of capacitor values. This means the training has been effective and accurate results can be obtained from the developed neural scheme.

3.4.2 Architecture of Network

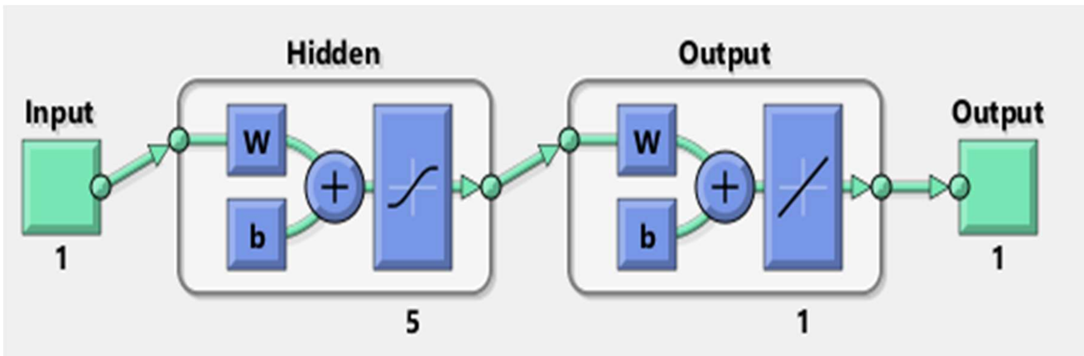


Fig. 13. Architecture of Neural Network

The neural network architecture consists of one input and one output, a hidden layer and a output layer is connected in between the two as shown in Fig. 13. Hidden layer structure consists of having 5-layer size and bias weights. The weights used are shown below:

Biased wights are represented by b1:

b1 = [-8.9777500439061057591; -1.1026574831328086468; -0.46328166820563315698; -2.3625032969027692786; 16.904808651125428298];

Input weights are represented by IW1_1:

IW1_1 = [5.3359866832127629266; 2.0331006757248184513; 4.5157443427398771263; -4.2381717675804999601; 17.969970559046409164];

The output layer consists of a single bias. The corresponding weights are:

b2 = -0.30920751299895993247;

LW2_1 = [-0.35283163674530715337 -0.19760341903110134609 -0.039953574237602471064 0.24275025262530833259 -0.61442354684292732614];

ceasing_limit - input data

capacitor - target data

Choosing a training function is also important i implementing a neural network, for example,

'trainlm' – it is usually fastest function and used more often

'trainbr' – it takes longer but considered as better for more challenging problems.

'trainscg' – it uses lesser memory and is suitable in low memory situations.

Here, in implemented network, function used is 'trainlm' as training function and Levenberg-Marquardt backpropagation algorithm for training the neural network.

Thus, a neural network is obtained from the above data set in Simulink to calculate the values of terminal capacitances for different ceasing limits as shown in Fig. 14.

The obtained neural network can be tested to check for targeted output. Vary the ceasing limit of speed for self-excitation and the value of corresponding terminal capacitance can be obtained. This can be verified from the Simulink results or from the mathematical estimation done.

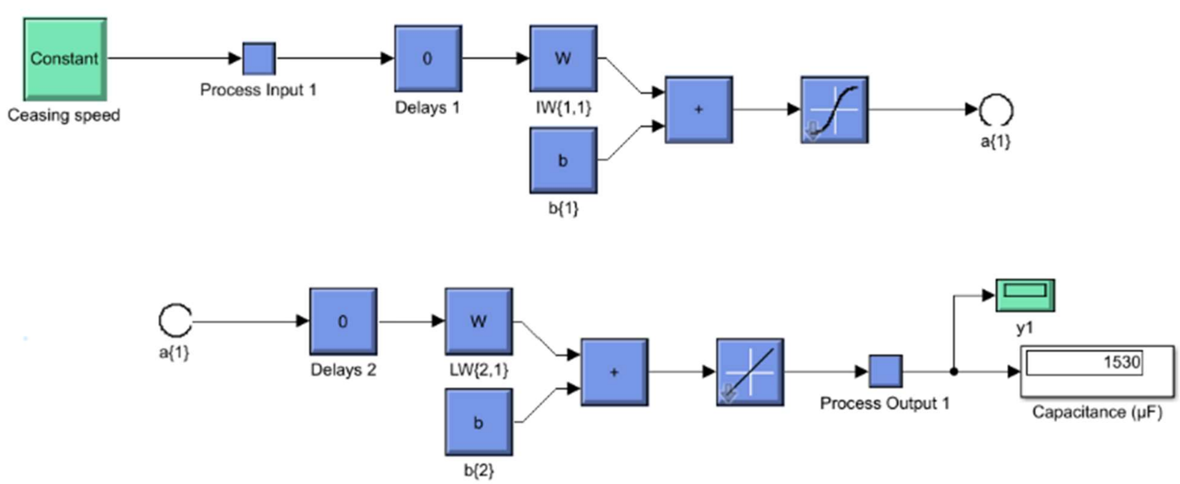


Fig. 14. Neural Network Scheme for the Function

Function definition of both layers

At Layer 1

a1 = tansig_apply(repmat(b1,1,Q) + IW1_1*xp1); (4)

function a = 2 ./ (1 + exp(-2*n)) - 1; (5)

At Layer 2

a2 = repmat(b2,1,Q) + LW2_1*a1; (6)

3.5 Mathematical Estimation for the Value of Terminal Capacitance

An approximate analysis for the calculation of ceasing limits of motor speed is also discussed here. After using the reverse approach, one can estimate the values of terminal capacitance in the effective range by (higher accuracy and validity for an effective range of capacitance).

As the excitation ceasing limits depends on the values of magnetization inductance and the terminal capacitance values. At the point where excitation occurs between L_m and C, it can be said that:

$$X_m = X_C \tag{7}$$

$$2 * pi * f * L = \frac{1}{2*pi*f*C} \tag{8}$$

$$f = \frac{1}{2*pi*\sqrt{L*C}} \tag{9}$$

but, the rotor frequency is given by:

$$f_r = s*f \tag{10}$$

So, replacing f by s*f ;

$$s*f = \frac{1}{2*pi*\sqrt{L*C}} \tag{11}$$

slip is given by:

$$s = \frac{N_S - N_r}{N_S}, \tag{12}$$

above equation can be written as:

$$s = \frac{1}{2*pi*f*\sqrt{L*C}} \quad (13)$$

$$\frac{N_S - N_r}{N_S} = \frac{1}{\sqrt{2*pi*f*L}\ \sqrt{2*pi*f*C}} \quad (14)$$

$$\frac{N_S - N_r}{N_S} = \sqrt{\frac{X_C}{X_m}} \quad (15)$$

So, the point where self-excitation ceases can be given by:

$$N_S - \frac{N_S - N_r}{N_S} = \sqrt{\frac{X_C}{X_m}} \quad (16)$$

The rotor speed at excitation point can be given by:

$$N_r = N_s * \sqrt{\frac{X_C}{X_m}} \quad (17)$$

So, one can define a term fractional speed by:

Fractional speed $(V_f)^2 = Xc/Xm$, (18)

So, $V_c = N_s * V_f$ (19)

After Expanding the above equations:

$$C = \frac{1}{(2*pi*f)^{\wedge}2} * \frac{1}{Lm} * \left(\frac{Ns}{Vc}\right)^2 \quad (20)$$

Ex- For a ceasing limit of 390 RPM, a terminal capacitance of 1500 μF can be used.

3.5.1 MATLAB Calculation

The above calculation was performed by a MATLAB code:

```
%Machine Parameters
POWER=3*746;
P=4;
F=50;
LM=0.128;
% Maximum Torque that can be applied
NS=(120*F)/P;
```

T=9.5488*POWER/NS;

% Speed where Excitation Ceases

NC=390;

M1=1/(((2*pi*F)^2)*LM);

M2=(NS/NC)^2;

%Value of Terminal Capacitance

C=M1*M2

3.6 Simulink Results:

The Simulink result for C=1500 μF is shown here in Fig. 15. It can be seen that the motor excitation ceases near 350 RPM, the mathematical estimation gives the excitation speed as 345. The mathematical estimation is able to give results within 5% error. Thus, the discussed approximation verifies obtained Simulink result. The same can be verified for different values of capacitance range.

The motor is unable to develop a standstill speed in a short time duration in this braking system. This problem has been resolved in the improved capacitor excitation braking, which is discussed later in this Thesis.

(A.) C = 1500 μF, Excitation ceases at = 349.7 RPM

Estimated value = 345; Error = 1.515 %

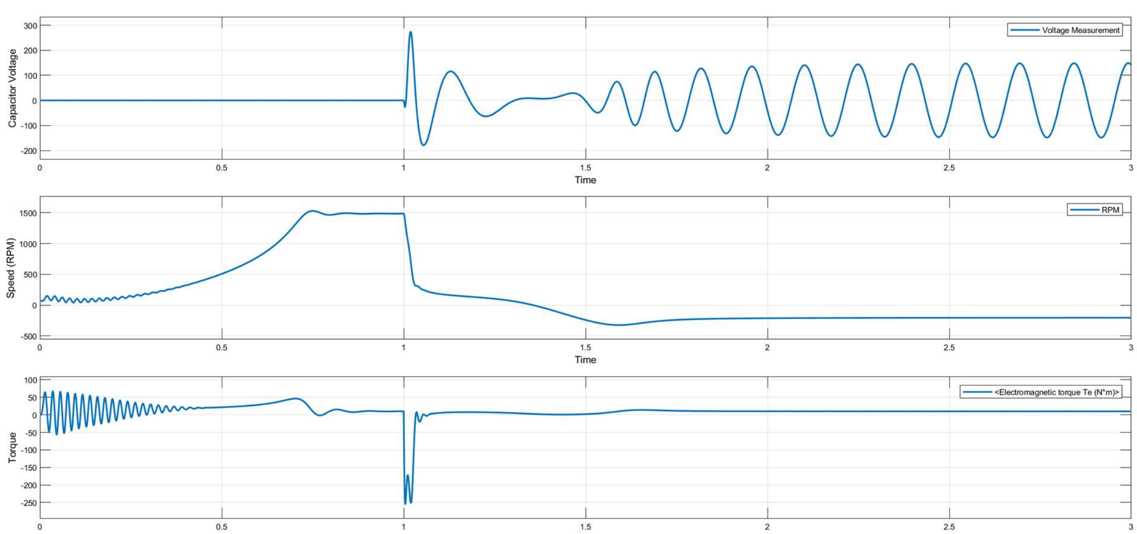


Fig. 15. Output at 1500 μF

(B.) C = 1600 μF, Excitation ceases at = 320.0 RPM

Estimated value = 333; Error = 4.06 %

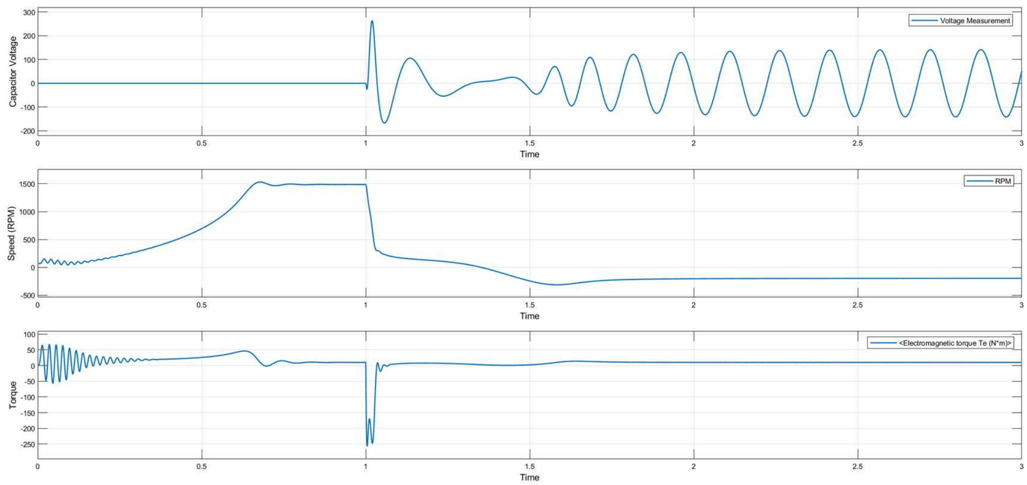


Fig. 16. Output at 1600 μF

(C.) C = 1800 μF, Excitation ceases at = 303.6 RPM

Estimated value = 314; Error = 3.397 %

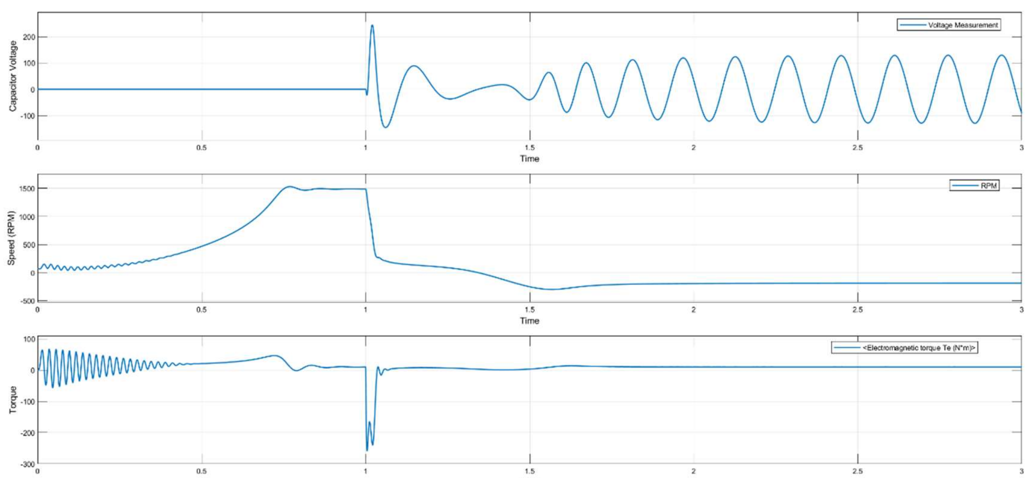


Fig. 17. Output at 1800 μF

CHAPTER 4
IMPROVED CAPACITOR EXCITATION BRAKING

4.1 Introduction

Capacitor Excitation braking has been in the limelight in recent years. A combination of Control Resistance in series with capacitors has been used by multiple scholars to improve the braking capacity of the system. Here, in this scheme, an additional Resistance bank, just like capacitors, is used in parallel instead of series with the stator side of the motor, which improves the braking capacity of the motor. Here, the power flows to the capacitor bank and resistances simultaneously, which aids in quicker and more effective braking of the motor. Most importantly, the braking to a standstill can also be achieved in this combination in short time. Thus, the braking to standstill from this simple scheme of capacitor braking eliminates the requirement of implementation of multistage braking system having combination of two or three types of braking acting back-to-back, making the system complex. Also the braking time can be controlled from adjusting the values of capacitor and resistor bank.

In this section, the effect of heating is also discussed using simple power loss calculation happening inside the machine. Thus, a combination of the electrical and thermal model is created and is used to analyse the temperature rise of the stator and rotor windings of the motor. For the calculation of constant losses of motor, a no-load test is also performed in the SIMULINK environment.

The excitation limits where braking due to capacitor ceases is also calculated only in the effective range of the capacitor. This section is already discussed earlier in section Analysis of Conventional Capacitor Excitation Braking. A neural network schematic is also employed for the estimation of capacitor values.

4.2 Modelling of Improved Capacitor Braking

Here, first of all for the power calculation of the induction motor throughout the running and braking condition is calculated from the well-known power flow diagram/equations of the motor.

From the power flow diagram, it's obvious that, first of all there is a need of constant losses of the motor. For the calculation of these losses a no-load testing is to be conducted and the constant losses to be separated from it.

4.2.1 No-Load Test

No-load test can be performed on the Induction motor by applying torque = 0 Nm. Input power at the stator side of the motor is calculated for different input voltages. The Result is plotted and Constant friction and windage losses are calculated by extrapolating the graph.

Here, the input voltages were varied from 80V to 415V. The obtained data is plotted as shown in Fig. 18.

Table 4. Sample Table (No-Load Testing)

Applied Voltage (V)	Total Input Power (W)
80 V	34.51 W
415 V	580.7 W

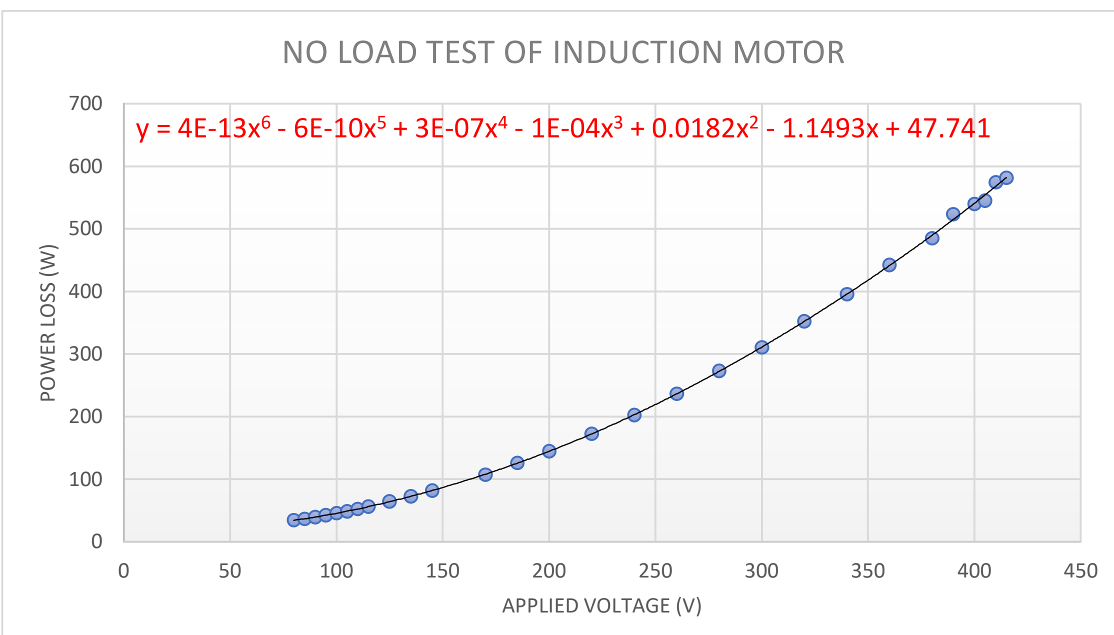


Fig. 18. Power VS Applied Voltage

The equation of order 6 obtained from curve fitting is:

$$P = 4*10^{-13}.V^6 - 6*10^{-10}.V^5 + 3*10^{-07}.V^4 - 1*10^{-04}.V^3 + 0.0182V^2 - 1.1493V + 47.741 \quad (21)$$

The friction and windage losses of the motor are calculated by extrapolating the graph, here after using V=0 in above equation to obtain the constant friction and windage losses.

At V=0:

$$P=47.741 \text{ W} \quad (22)$$

$$\text{So, } P_{Friction\_Windage} = 47.741 \text{ W} \quad (23)$$

The core losses are calculated at rated voltage V=415V

The total input power of the motor can be distributed as:

$$P_{input} = P_{Friction\_Windage} + P_{stator\_Core} + P_{Stator\_Copper\_Loss} \quad (24)$$

In order to find the constant stator core losses, it is now needed to separate the stator copper losses at the rated input voltage from the motor.

4.2.2 Input Power Calculation

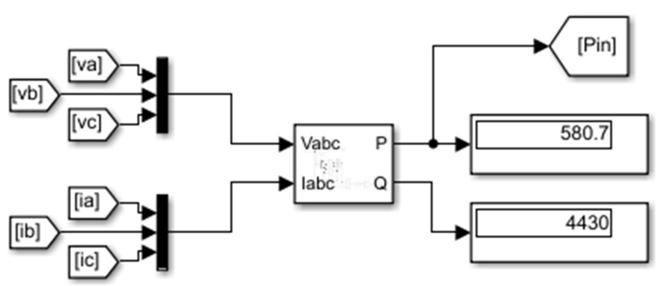


Fig. 19. Input Power Calculation

4.2.3 Stator Copper Loss Calculation

$P_{Stator\_Copper\_Loss} = 3 * (I_{s\_RMS}^{2} * R_s)$ (25)

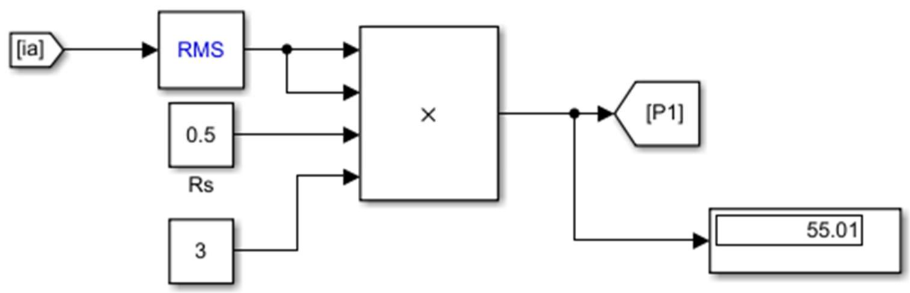


Fig. 20. Stator Copper Loss calculation

4.2.4 Core Loss Extraction

$P_{stator\_Core} = P_{input} - 3 * (I_{s\_RMS}^{2} * R_s) - 47.741$ W (26)

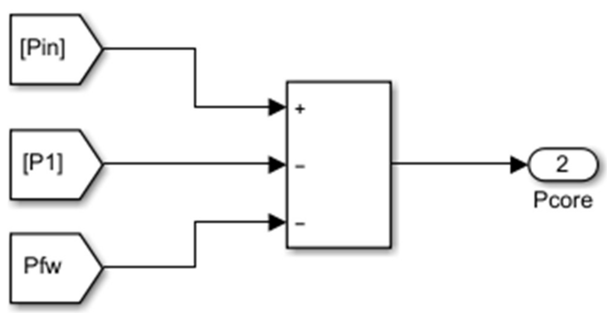


Fig. 21. Core Loss Extraction

$P_{stator\_Core} = P_{input} - 3 * (I_{s\_RMS}^{2} * R_s) - 47.741$ W

Now, having stator copper losses.

$P_{stator\_Core} = 580.70 – 55 – 47.741$

$P_{stator\_Core} = 477.959$ W (27)

So, now having constant losses separated out from the variable losses. These loss values will be used directly in the power calculation for the motor to develop the electrical modelling block Fig. 22 and Fig. 23.

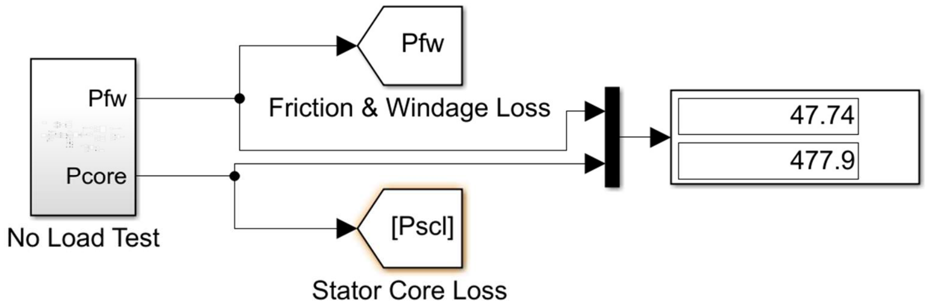


Fig. 22. Final Block for No-Load test

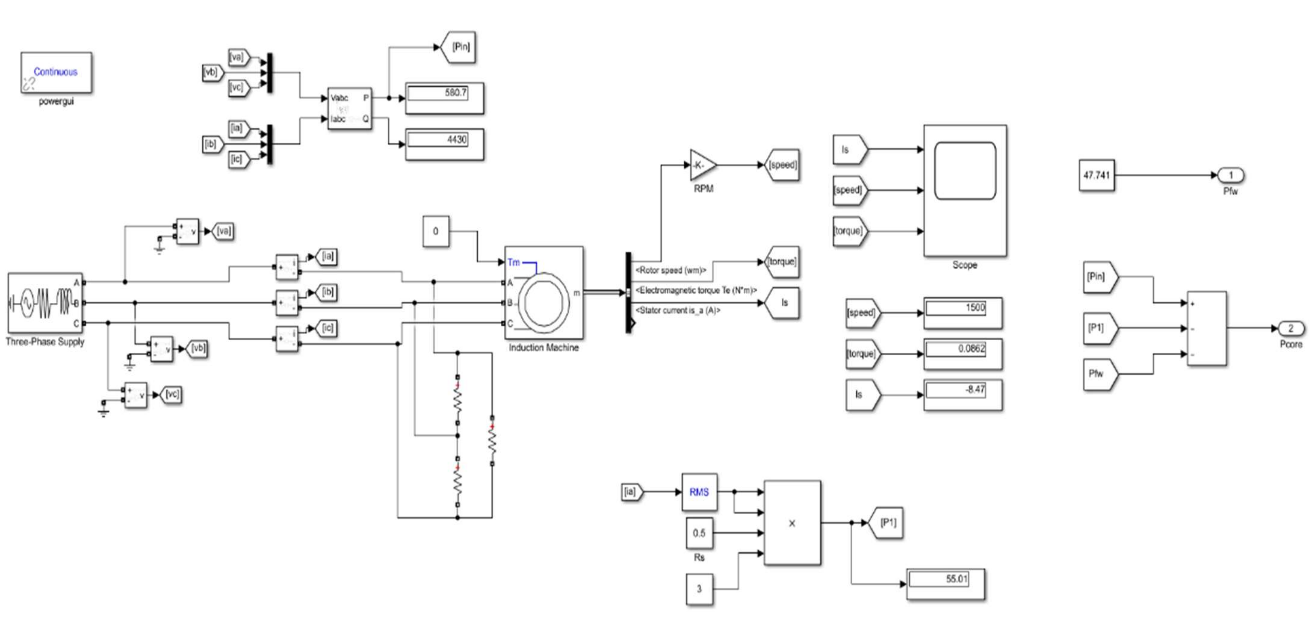


Fig. 23. Detailed View of Sub-System Used for No-Load Testing

4.3 Electrical Model of Improved Capacitor Braking

Given,

P_{stator_Core} = 477.959 W & $P_{Friction\_Windage}$ = 47.741 W

Calculating Input Power :

$$P_{input} = 3 * V_{a\_RMS} * I_{a\_RMS} * pf \quad (28)$$

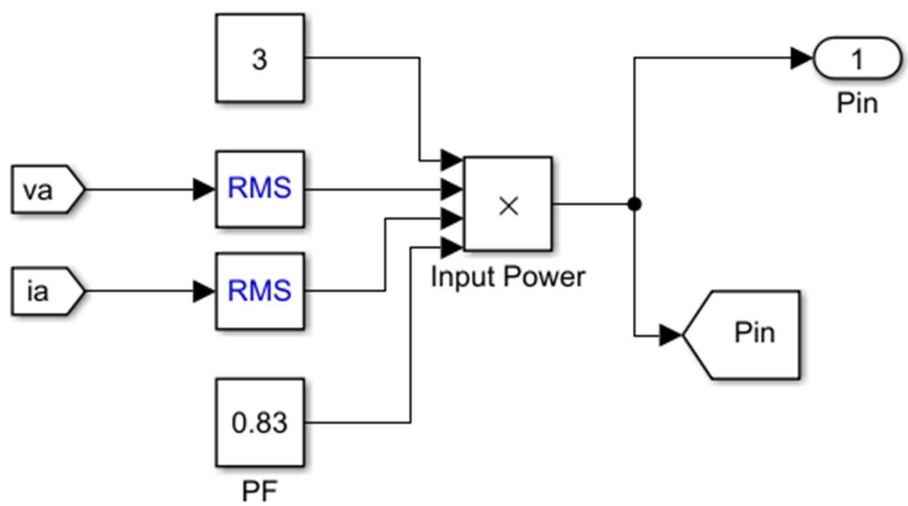


Fig. 24. Input Power Calculation

Input power can be written as (From Power Flow Diagram):

$$P_{input} = P_{Stator\_Copper\_Loss} + P_{Stator\_Core} + P_g \quad (29)$$

$$P_g = P_{input} - P_{Stator\_Copper\_Loss} - P_{Stator\_Core} \quad (30)$$

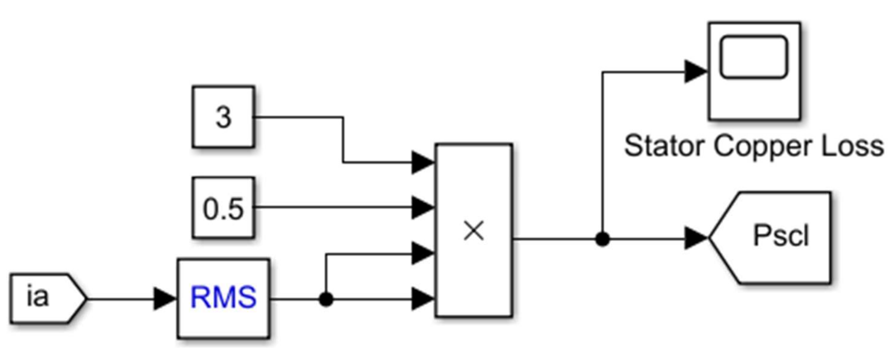


Fig. 25. Stator Copper Loss Extraction

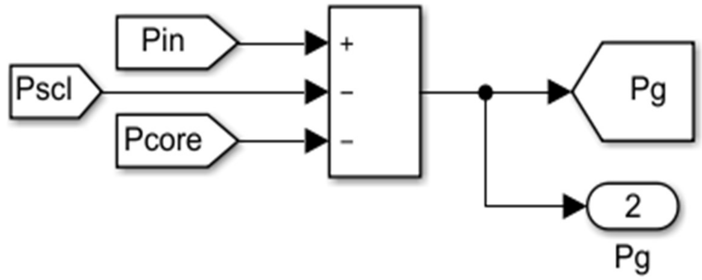


Fig. 26. Air Gap Power Calculation

$$P_m = (1-s) * P_g \quad (31)$$

$$P_{out} = P_m - P_{Friction\_Windage} \quad (32)$$

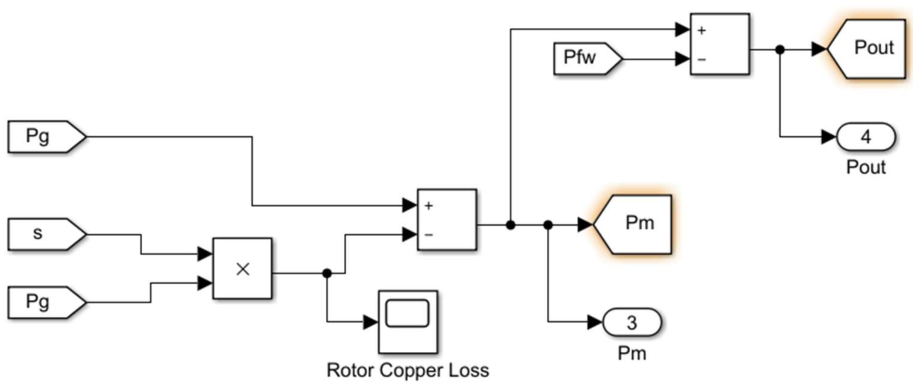


Fig. 27. Calculation of Output Power Available at shaft

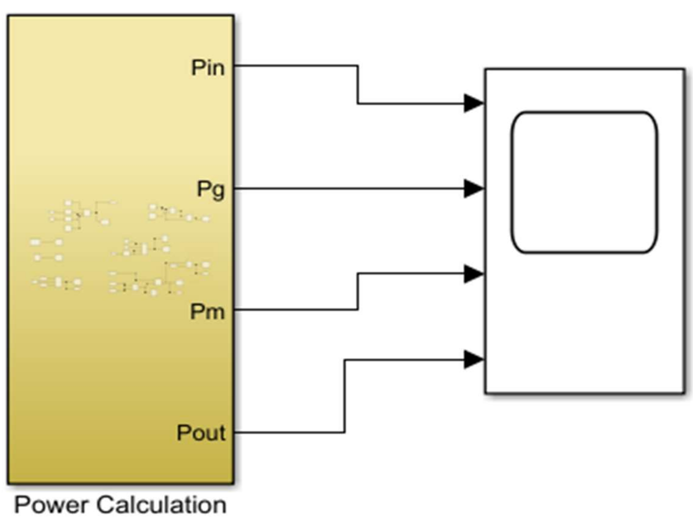


Fig. 28. Sub-System Used in the Simulink Circuit

4.4 Thermal Modelling

For the purpose of the calculation of temperature estimation, assumption is made that rotor and the stator winding of the motor are homogenous thermally. From the thermal balancing, the equations to calculate the rise in temperature are modelled.

4.4.1 For Stator Temperature

For heating of the windings, Stator copper losses are the major contributor to the rise in temperature. The resistance will also vary as the temperature rises.

$$R_{T2} = R_{T1} (1 + \alpha * \Delta T) \quad (33)$$

α – Temperature Coefficient

So, Temperature rise will be due to ($I_s^2 * R_{T2}$) losses.

The heat transferred to the surrounding won't affect the rise in temperature. Consider the equation of convection for the heat transferred to the atmosphere. [17-19]

The rest of the heat is causing the temperature to rise in the windings. It can be calculated after applying the reverse approach to the thermodynamics formula, calculating the heat required to increase the temperature by 1°C. Different substances have different specific heats since they require differing amounts of energy to change temperature by 1 degree Celsius.

So, from thermal balancing one can obtain:

$$R_s (1 + \alpha * \Delta T) * I_s^2 - h.S.\ \Delta T = c.m.\frac{d\Delta T}{dt} \quad (34)$$

where,

c – Heat capacity
m – Mass of windings
ΔT – Change in temperature
S – Surface of heat transfer
h – Heat Transfer Coefficient
α – Temperature Coefficient

α - 0.00386, c - 0.385, h – 385 (35)

m – Density(copper) * Volume of the winding

S- Surface Area to be calculated from motor Dimensions.

Table 5 Machine Dimensions

Parameters	LENGTH	DIAMETER
ROTOR	82 mm	71.5 mm
STATOR	82 mm	131.5 mm

Above equation (20) can be re-arranged to :

$$\int \frac{d}{dt}\,\Delta T = \int \frac{Rs(1+\alpha*\Delta T)I_s*I_s - h*S*\Delta T}{m*c} \qquad (36)$$

4.4.2 Implementation

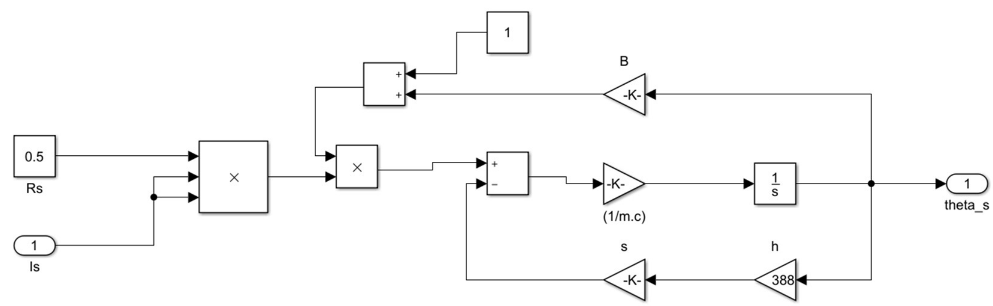


Fig. 29. Stator Temperature Estimation

Similarly, a thermal model for rotor temperature estimation can be prepared. For the thermal model, the stator and rotor losses can be taken from the electrical model discussed above, or the losses can directly be calculated from the stator and rotor currents of the model.

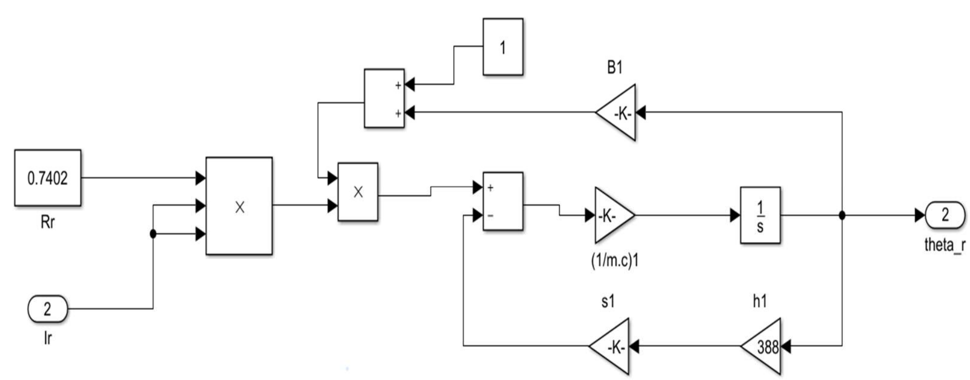


Fig. 30. Rotor Temperature Estimation

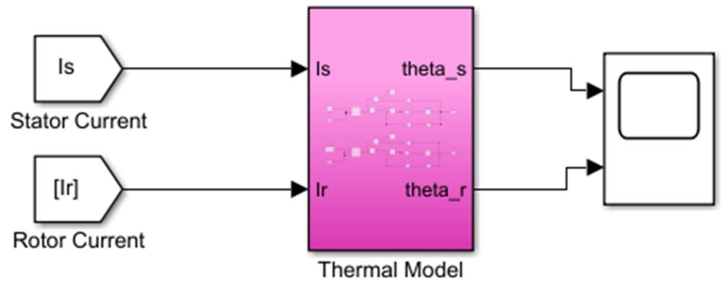


Fig. 31. Sub-system used in the Simulink Circuit

4.5 Block Diagram of Proposed Scheme

All the discussions made above are implemented in Simulink environment. Electrical and thermal modelling are interlinked together to implement the improved braking scheme.

The above scheme can be understood from the following block diagram Fig. 32

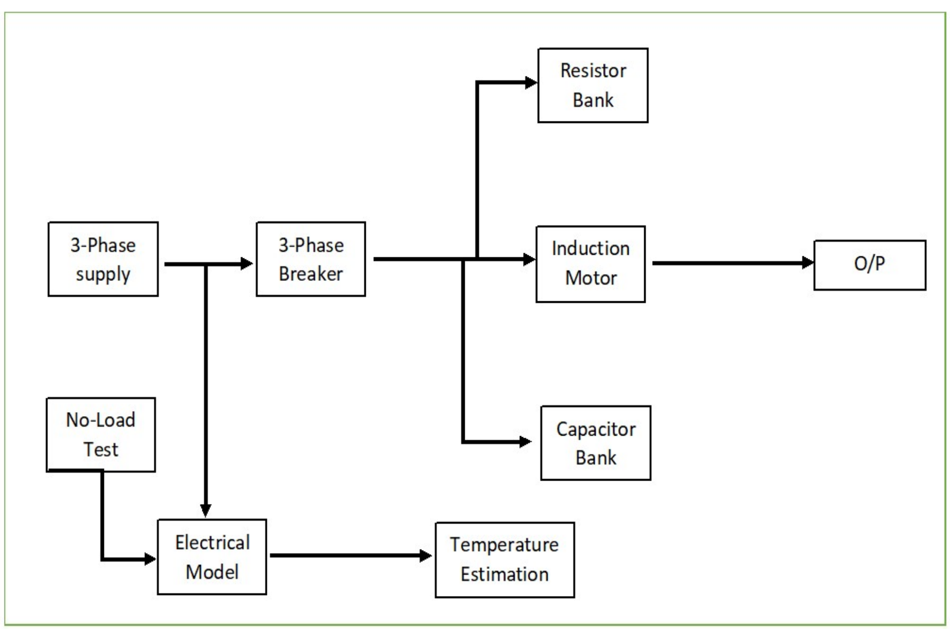


Fig. 32. Block Diagram of the proposed braking scheme

4.6 Proposed Braking Scheme

The Simulink circuit for the implemented braking scheme is shown in Fig. 33

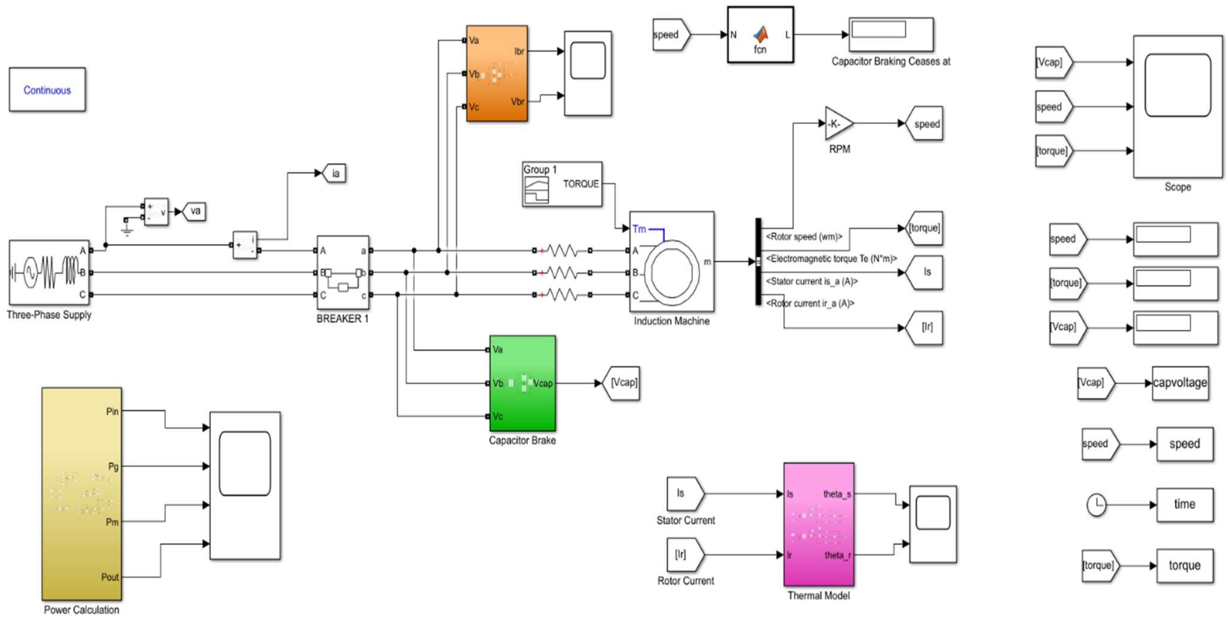


Fig. 33. Simulink Circuit Diagram

Above scheme shows the implementation of the proposed scheme. The Power calculation block is implemented to calculate the power before and after the braking is implemented. The thermal model uses the power losses as calculated from the power block and process the power to estimate the rise in temperature of stator and rotor windings. The MATLAB function is also used to calculate the ceasing speed limits due to the capacitor excitation braking alone (discussed in the earlier section of this paper); after ceasing limits or self-excitation ceases, the rest of the braking is done by the power dissipated in the resistive bank.

Breaker 1 – Supply On/Off Control

Breaker 2 & 3 - To Connect Cap & Resistor Bank

4.7 Simulink Results

The Simulink is run for a period of 2 seconds; the breakers are switched at 0.8 secs, i.e., the supply is switched off at 0.8 sec and the induction motor is connected to the capacitor and the resistor bank at 0.8 sec. From the Simulink output waveform Fig. 34, it can be clearly seen that the motor is able to achieve a standstill speed within

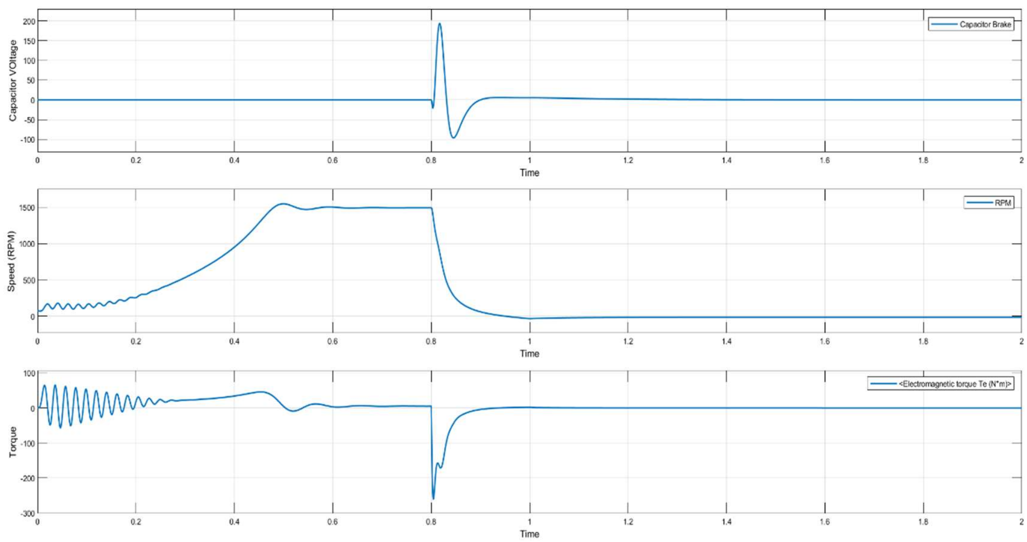


Fig. 34. Simulink Result of the Proposed Braking Scheme

0.13 seconds at the same value of negative electromechanical torque value instead of 0.40 seconds in a conventional braking system. Also, it has now eliminated the need for implementation of any type of combination of multistage braking scheme. The applied scheme is easy and simple to implement. The capacitance value can also be adjusted to obtain different braking times according to the requirement or for obtaining different ceasing speed limits die to self-excitation.

The rise in temperature of the induction machine is shown in Fig. 35, considering the class B insulation, maximum allowable rise in temperature is 80^0C with a service factor of 1.0 and an ambient temperature of 40^0C. Thus, the implemented braking scheme is effective and temperature rise are within the insulation limits.

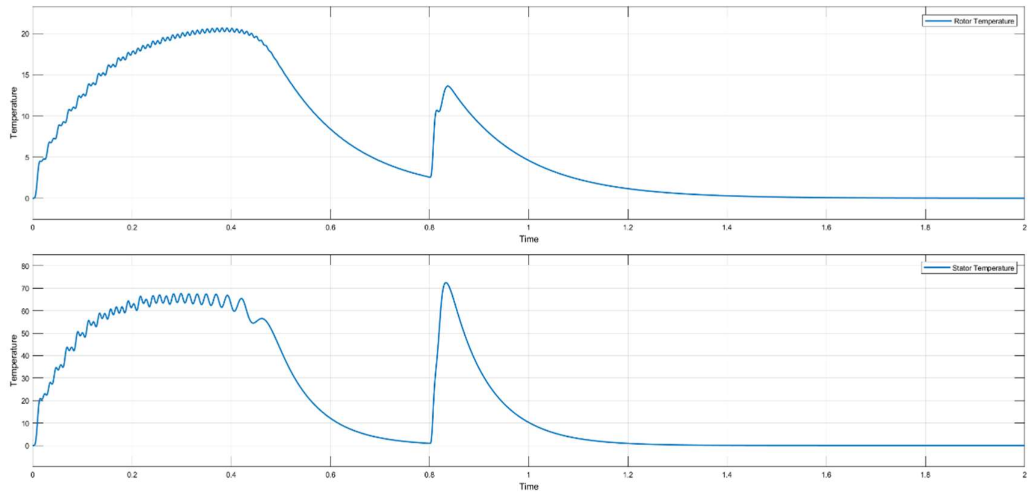


Fig. 35. Rise in Temperature of Rotor and Stator Windings

Output of the Electrical model is shown in Fig. 36, it can be observed that the machine is dissipating the power within the braking time and considerable insulation limits to achieve a quick braking to standstill.

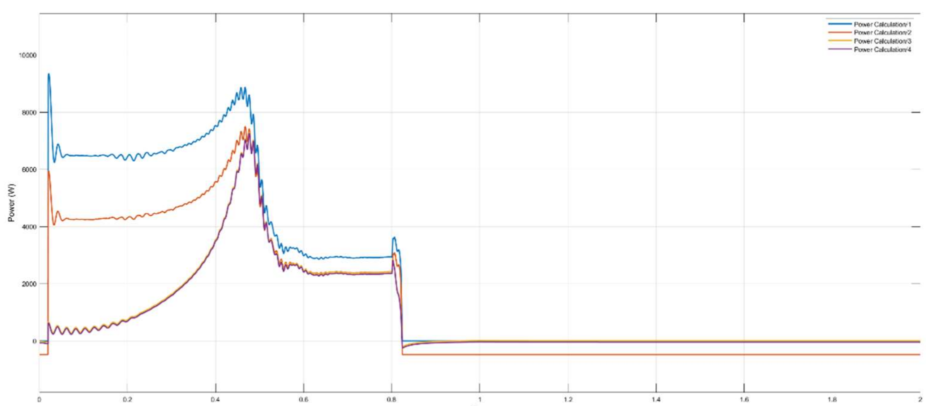


Fig. 36. Output of Electrical Model

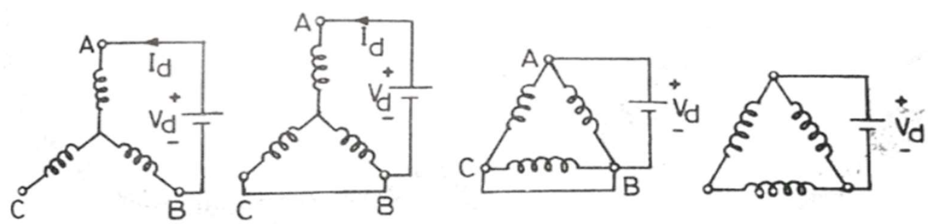
CHAPTER 5

DC AND AC DYNAMIC BRAKING

5.1 Introduction

5.1.1 DC Dynamic Braking

This type of electrical braking is achieved, when the stator side of a dynamic induction motor is detached from AC source and coupled to a DC supply. Two and three lead networks are the two common types of configurations for the star and delta associated stators as shown in Fig. 37.



(b) (b) (c) (d)

(a) and (d) are two-lead connections; (b) and (c) are three lead connections

Fig. 37. DC Dynamic Braking [16]

When the AC power is disconnected and the D.C. power is passed through the terminals of the induction motor, a stationary magnetic field is created due to the D.C. current flowing, and when the motor's rotor rotates in this field, there is a partial armature field induced in the rotor winding, and thus the machine acts as a generator mode and the generated energy is dissipated in the resistance of the rotor circuit and dynamic braking of the induction motor is obtained.[29-30]

5.1.2 AC Dynamic Braking

This type of induction motor braking is achieved when the motor is operating on single-phase power by disconnecting any one of the three phases from the supply, and leaving it open or connected to another phase. When the disconnected phase is left open, it is called a two-conductor connection, and when the disconnected phase is connected to another phase of the machine, it is called a three-load connection. Brake operation can be understood easily. When the motor is running on single-phase power, the motor is energized in the forward and negative order, the net torque generated by the machine is the sum of the torque due to the positive and negative sequence voltages.

At high resistance, the actual torque becomes negative and braking occurs. From the Fig. 38 the two and three load connections can be understood.

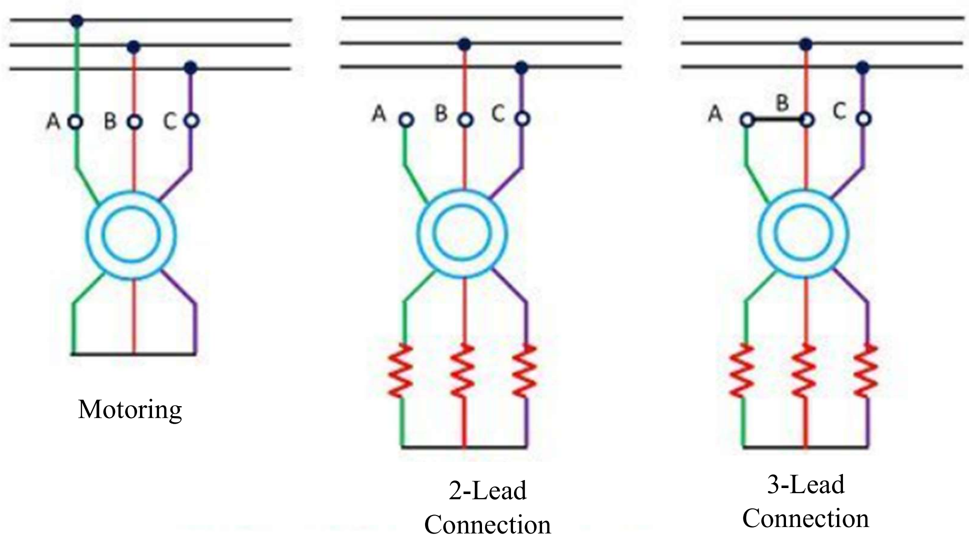


Fig. 38. AC Dynamic Braking [16]

5.2 Mathematical analysis of 2-lead connection (DC braking)

The implementation of this type of braking scheme is quite similar in MATLAB environment, therefore a mathematical analysis of this scheme is hereby important to implement and improve the said braking scheme.

5.2.1 Magnetization characteristics

Magnetisation characteristics of induction motor used is as follows:

I_m = [0.6 0.9 1.2 1.7 2.24 2.9 3.9 4.9 6.0 8 9 9.5];

E_m = [53.8 80 106 142 173 200 227 246 260 280 288 292];

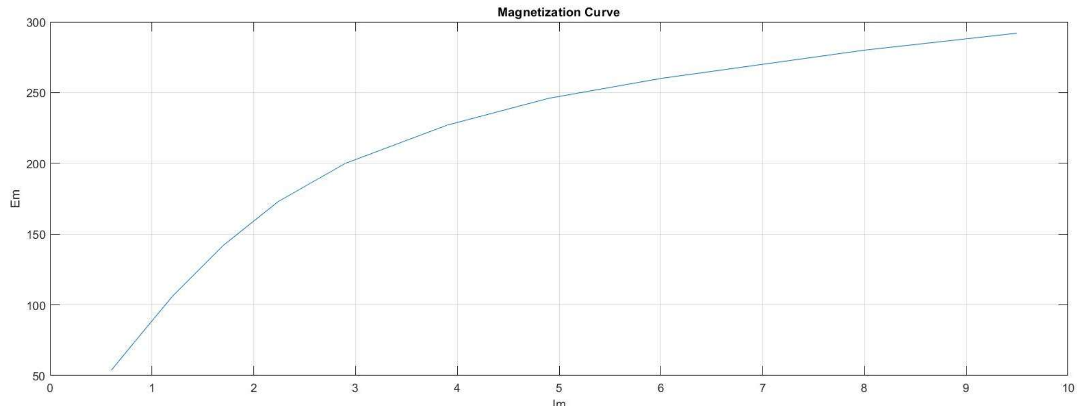


Fig. 39. Magnetization Characteristics of the machine

The magnetization characteristics has been plotted in Fig. 39.

5.2.2 Mathematical model

Expression of stator current for a two-lead braking is as follows:

$$I_s = \sqrt{\frac{2}{3}} * I_d \tag{37}$$

Determine the value of I_m and E_m from the magnetisation characteristics as shown in Fig. 39. After that rotor current can be calculated by the following formula:

$$I_r^2 = \frac{I_s^2 - I_m^2}{1 + \frac{2 * X_r * I_m}{E_m}} \tag{38}$$

The Speed in Radian per seconds is calculated as:

$$\omega_{ms} = \frac{1500 * 2 * pi}{60} \tag{39}$$

Now, slip,S for corresponding value of rotor current is computed by:

$$S = \frac{R_r}{\sqrt{\frac{E_m^2}{I_r^2} - X_r^2}} \tag{40}$$

So, speed (N)= S*1500 (41)

Torque for the corresponding speed is given by:

$$T = \frac{3}{\omega_{ms}} \, I_r^2 \frac{R_r}{S} \tag{42}$$

From the above calculation, Torque for different values of speed can be calculated and the speed torque curve can be plotted as shown in Fig. 40.

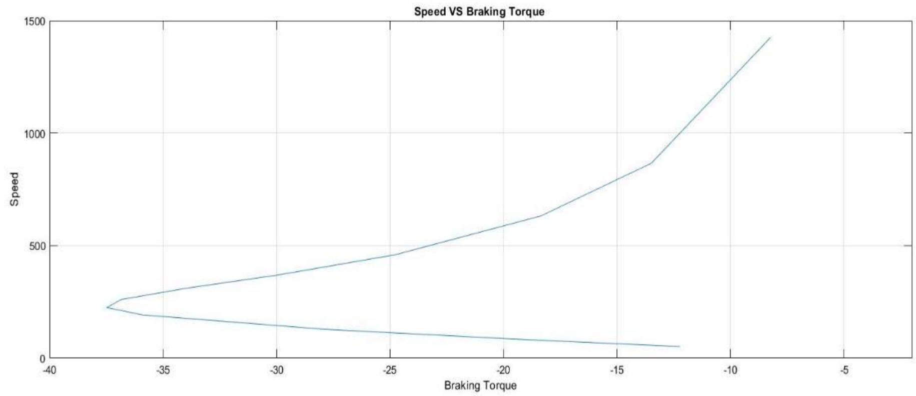


Fig. 40. Speed vs Torque Curve

To calculate the braking time or the time duration in which the motor reaches the standstill for the induction motor, can be calculated by calculating the area of graph between J/T vs Speed plot as shown in Fig. 41. [30-32]

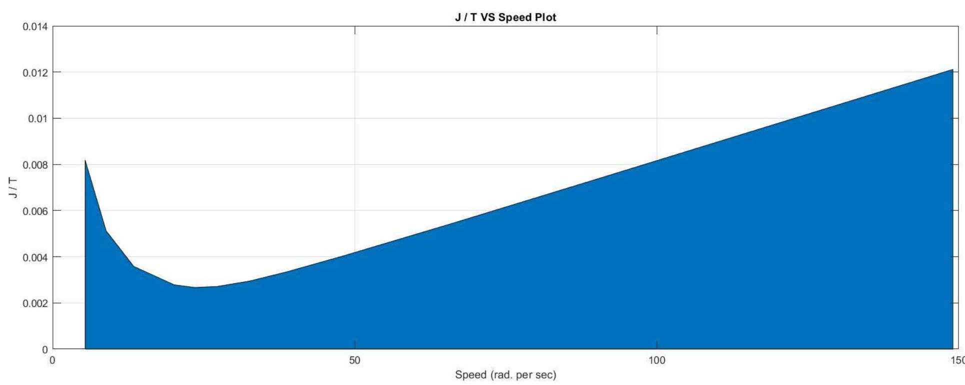


Fig. 41. Area of J/T Vs Speed

Suppose a DC link is present across the motor having a braking resistor R_d , then the braking power and braking resistance can be also be calculated by the following equations:

Line to line voltage; $V_{L\text{-}L} = 415$ V

Relation between DC link and AC is given by :

$$V_{n=1} = \frac{4 * V_{DC}}{\sqrt{2} * pi} \text{ (fundamental component)} \quad (43)$$

From above equation (43), V_{DC} can be calculated.

The braking power, P_d can be calculated by the formula:

$$P_d = T * \omega \qquad (44)$$

Torque,T and speed, ω can be calculated by using equation (39) to (42)

Power vs Speed curve can be plotted as shown in Fig. 42

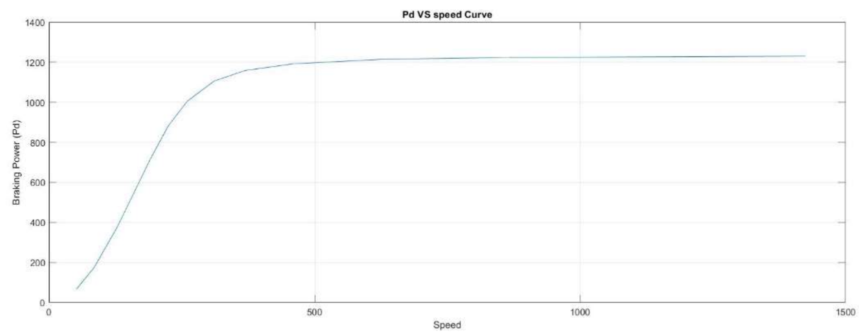


Fig. 42. Braking Power VS Speed Plot

Here, the braking resistor can be calculated by:

$$R_d = \frac{V_{DC}^2}{P_d} \qquad (45)$$

After using the equations from (39) to (44), the values for DC link Voltage, braking power, braking resistor and braking time can be calculated. The above equations are solved and a MATLAB code is implemented to solve and plot the above equations for a varying range of magnetization characteristics and following values are obtained from the above. The values obtained are as:

DC Link voltage is 460.88 Volts, the braking power is calculated to be 1230.10 Watts with a braking resistor of 172.68 ohms. The time duration in which the machine achieves standstill is calculated to be 0.9611 seconds**.**

5.3 Analysis of 2-Lead Connection (AC braking)

Equivalent circuit diagram of the two-lead connection is shown in Fig. 43

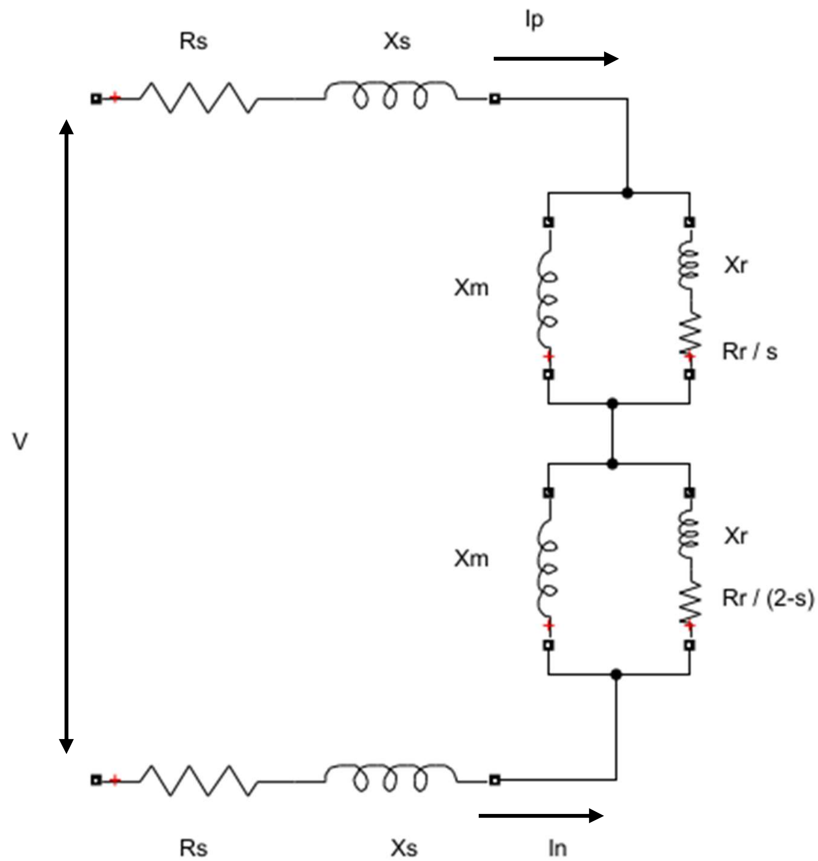


Fig. 43. Equivalent Circuit Diagram

5.3.1 Mathematical Model

From the Equivalent circuit, it can be observed that :

$I_n = - I_p$ (46)

The applied voltage V is given as:

$V = \frac{V_{L-L}}{\sqrt{3}}$ (47)

Equivalent impedance across applied voltage is given by

$Z = 2*(R_s + X_s) + (X_m \parallel (X_r + R_s / s)) + (X_m \parallel (X_r + R_s / (2\text{-}s)))$ (48)

Now, net impedance is know, the value of current can be calculated as:

$$I_p = \frac{V}{Z} \tag{49}$$

Corresponding value of Current I_{rp} can be computed as:

$$I_{rp} = I_p * \frac{j*X_m}{j*(X_m+X_r)+\frac{R_r}{s}} \tag{50}$$

I_{rp} = absolute (I_{rp})

Corresponding Torque will be given by:

$$T_p = \frac{3}{\omega_{ms}}\ I_{rp}^2\ \frac{R_r}{S} \tag{51}$$

Similarly, for I_n torque can be calculated by following the same approach as follows:

$$I_n = - I_p \tag{52}$$

$$I_{rn} = I_p * \frac{j*X_m}{j*(X_m+X_r)+\frac{R_r}{2-s}} \tag{53}$$

Corresponding Torque will be given by:

$$T_n = \frac{3}{\omega_{ms}}\ I_{rn}^2\ \frac{R_r}{2-S} \tag{54}$$

Now, the net torque will be given by:

$$T = T_p + T_n \tag{55}$$

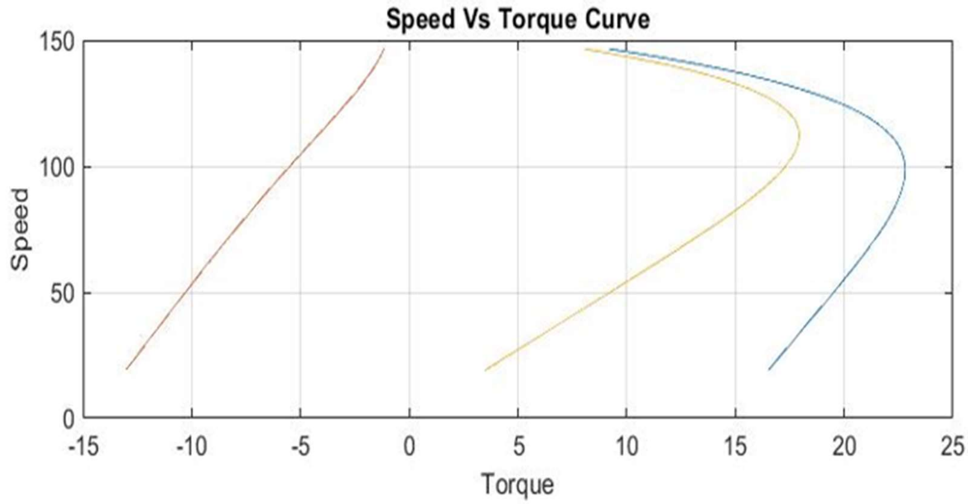


Fig. 44. Speed Vs Torque Curve

The speed torque characteristics can be plotted after calculating torque for different values of speed as shown in Fig. 44

To calculate the braking time or the time duration in which the motor reaches the standstill for the induction motor, can be calculated by calculating the area of graph between Machine inertia/Torque (J/T) VS speed plot as shown in Fig. 45

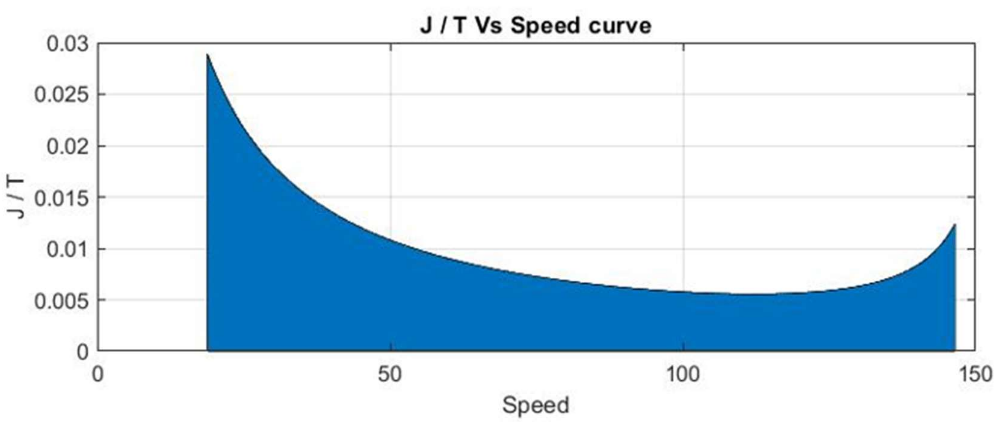


Fig. 45. Area of J/T Vs Speed Curve

Suppose a DC link is present across the motor having a braking resistor R_d , then the braking power and braking resistance can be also be calculated by the following equations:

$V_{L-L} = 415$ V

Relation between DC link and AC is given by :

$V_{n=1} = \frac{4 * V_{DC}}{\sqrt{2} * pi}$ (fundamental component) (56)

From above equation V_{DC} can be calculated.

The braking power P_d can be calculated by the formula:

$P_d = T * \omega$ (57)

Torque,T and speed, ω can be calculated by following the equation (46) to (55)

Braking Power vs speed curve can be plotted as shown in Fig. 46

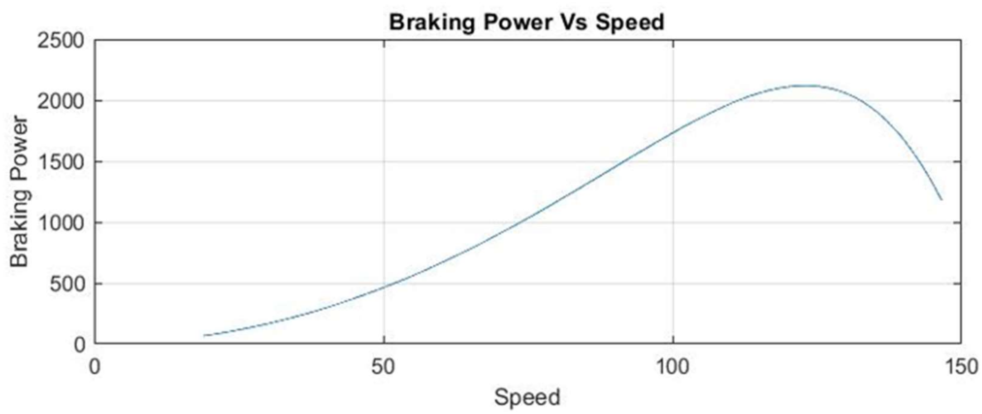


Fig. 46. Braking Power Vs Speed Curve

After using the equations from (46) to (57), the values for DC link Voltage, braking power, braking resistor and braking time can be calculated. The above equations are solved and a MATLAB code is implemented to solve and plot the above equations for a varying range of magnetization characteristics and following values are obtained from the above. The values obtained are as:

DC Link voltage is 460.88 Volts, the braking power is calculated to be 2119.5 Watts with a braking resistor of 100.22 ohms. The time duration in which the machine achieves standstill is calculated to be 11.633 seconds.

CHAPTER 6

CONCLUSIONS AND SCOPE FOR FUTURE WORK

6.1 CONCLUSIONS

From the above studies it can be concluded that:

- In conventional scheme of capacitor excitation braking the motor is not able to achieve a standstill speed in short duration of time span, once the self-excitation occurs at the terminal capacitance the voltage becomes constant across the capacitor terminal and rest of th braking is achieved by the machine frictional forces an inertia. With a medium-sized capacitor at stator terminal, the self-excitation close to 25% of the synchronous speed. The remaining power is dissipated slowly in the internal Circuit of the machine.
- An effective mathematical estimation for the ceasing speed limits due to self-excitation has been implemented and an artificial neural network has been developed to estimate the capacitor values to obtain a particular value of ceasing limit.
- In the proposed scheme of capacitor excitation braking, a quick braking scheme has been implemented in the Simulink environment. The motor is able to achieve a standstill speed in lesser time span in comparison to the conventional scheme, thus eliminating the need of multistage braking schemes. Alongside, a thermal and electrical model has also been developed to observe the power flow and rise in temperature of the machine due to sudden braking. The implemented scheme is more effective at higher speed ranges.
- In the DC and AC dynamic braking of the motor, it can be observed from the speed torque characteristics that they are more effective at lower speed ranges as the higher value of torque is obtained in the lower speed zones. The braking time and braking power has also been calculated for both the schemes.

A comparison of different braking scheme has been shown in the following table.

6.2 Comparison Table

A comparison between different parameters for various types of dynamic braking is analyzed in the following table.

Table 6 Comparison study between different braking schemes

Parameter	**Conventional Scheme**	**Proposed Scheme**	**2- Lead DC Braking**	**2- Lead AC Braking**
Braking time	0.40 sec	0.13 sec	0.96 sec	11.63 sec
Peak Torque	170 N-m	220 N-m	38 N-m	18 N-m
Effective speed range	1500-450	All ranges	<1200	<600
Speed at Max Torque	1450 RPM	1450 RPM	1150 RPM	250 RPM
Braking Power	-	846.40 W	1230.10 W	2119.5 W
Braking Resistor	-	10 ohm	172.68 ohm	100.22 ohm

From the above comparison it can be concluded that the proposed scheme is more effective as compared to other conventional braking schemes and the proposed scheme is much faster than the other schemes. The braking time is reduced to one-third as that of conventional scheme. The proposed scheme is also effective for a higher range of rotor speeds and the peak torque occurs at speeds closer to the synchronous speed of the motor. the other schemes can be implemented in succession but only at the lower ranges of rotor speed.

The rise in temperate windings of the motor is also found to be within the insulation limit considering class B insulation.

6.3 SCOPE FOR FUTURE WORK

- Power converters and energy storage elements can be introduced in the braking scheme so that the power is not wasted as heat.
- Higher order neural networks with a wider training data set can be implemented to reduce the error in estimation of Ceasing limits.
- Regenerative braking can be introduced and proper modelling can be done, and if effective can be implemented with other braking schemes in succession to further reduce the braking time.
- In the thermal analysis for temperature estimation, for higher accuracy parameters like forced cooling and effect of ambient temperature can be considered.

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1. Harsh Agarwal, Ashutosh, Dheeraj Joshi, “Modelling and Analysis of Induction Motor with Adaptive Neural Network-based Improved Capacitor Braking”, International Conference on Machine Learning and Data Engineering, Procedia Computer Science Journal, Elsevier 2022. [communicated]