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Improvement of the Performance and Stability of Dual Stator Induction Machine Using LQR Controller

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Abstract

Induction machines have been reliable in its operations and this increase its usage in the industries.

Demand for better performance in its area of application calls for research to address some of its shortcomings like speed variation with applied load, poor trajectory tracking capabilities, low frequency vibrations. The main objective of the study was to improve the performance and stability of Dual Stator Induction Machine (DSIM) using Linear Quadratic Regulator (LQR) controller. The implementation of the DSIM control strategy involved investigation of its performance improvement using LQR compared to PID control method. The evaluation considered a 5N load condition with performance metric such as step response analysis (overshoot, rise time and settling time), bode plot analysis and sigma plot analysis. To analyse the complex space vector model of the DSIM, a complete set of simulations were carried out using MATLAB/Simulink 2021b modelling software. From the analysis, it was found out that, the LQR controller had a good torque stability, low torque overshoot and moderate current ripple. The time domain metric shows that; PID had an overshoot, rise time and settling time of 4.6%, 0.213s and 0.598s respectively; LQR had an overshoot, rise time and settling time of 0.152%, 0.288s and 0.47s respectively. The frequency response analysis shows that PID controlled DSIM peak gain is -6.02dB and LQR controlled DSIM had a gain and phase margins of 48.8dB (at frequency of 0.0104rad/s) and 19.8^0(at frequency of 0.97rad/s) respectively. In sigma plot analysis, PID controller had a higher negative singular value while LQR has a lesser negative singular value. The findings for current, torque and speed response shows that the efficiency of LQR is better than that of PID controller. Time domain analysis shows that LQR is superior to PID controller in terms of overshoot, rise time and settling time. In sigma plot analysis, PID controller tends to perform well at low frequencies, but lacks high frequency robustness which is improved in LQR. Increased peak indicate power robustness and sensitivity to disturbance. Flatter shape of LQR indicate uniform performance and robustness than PID especially at high frequencies.

Keywords: Induction Machine, Dual Stator, Stability, Performance

1.0 INTRODUCTION

1.1 Background of study

A Dual Stator Induction Motor or Machine (DSIM) is an induction machine which has two separate three-phase stator windings, sharing the same machine core and the common squirrel cage rotor winding. Power is supplied to the two windings by two separate variable frequency inverter drives to provide two independently controllably torque components. In the machine, alternating current is applied to the stator and alternating currents are induced in the rotor by transformer action *(Mataray and Kakkar. 2011)[1].* At low speed, the power supplied to one of the windings can produce torque which opposes the torque from the power applied to the other winding, so that very low speed and standstill operation can be achieved while the frequency of the power supplied by the inverters is always greater than the minimum frequency. At higher operating speeds, power is supplied to the two windings so that the torque from the windings adds. The dual stator machine can be built with minimal modifications to standard winding configurations.

With reference to the layout of the stator windings in the motor core, the dual stator induction motors can be categorized into two basic types. The first type consists of a set up in which two separate three-phase stator windings are located sequentially along the stator core. In this type of the category, there is no magnetic coupling between the stator windings, but each of stator windings is magnetically coupled with the rotor cage winding. The two stator windings can be supplied from the same or separate AC voltage sources of the same frequency. The second type of dual stator set up consists the motor with two stator windings that are spatially shifted and are situated in the same stator core *(Pieńkowski, 2012[2]).*

1.2 Statement of Problem

The problems existing in the induction machine are as follows:

i. The speed of the motor varies with the applied load which consequently affects the general performance of the induction machine, causing low or poor trajectory tracking capability.
ii. From the review, it was found that the dual stator winding induction machine output still records some low frequency vibrations which means that the machine suffers from inadequate compensation capabilities.
iii. The induction machine is very sensitive to disturbances especially the set of disturbances formed as a result of the variation in the load. Thus, the machine suffers from low disturbance rejection capabilities.

1.3 Aims and Objectives

The aim of the study is to improve the performance and stability of the dual stator winding induction machine using linear quadratic regulator (LQR) controller.

The objectives of the study are as follows:

i. To address the speed variation problem of the induction machine using robust control technique.
ii. To optimize the machine output performance in order to cancel the low frequency oscillation and thereby improve its stability.
iii. To analyze the dual stator induction machine output performance using different controllers such as PID and LQR.
iv. To compare the output performance of the DSIM under different controllers (PID and LQR) in order to ascertain the controller with the best improvement characteristics.

2.0 LITERATURE REVIEW

2.1 Theoretical Framework

An induction machine can be used as a motor when it converts electrical energy to mechanical energy or a generator when it coverts mechanical energy to electrical energy. The dual stator induction motor being a rotary machine operate on the same working principle as it linear counterpart - the linear motor. In linear motor magnetic flux from a mover (rotor) is locked or synchronized with that of a stationary track (stator) converting electromagnetic energy into translational motion *(Uju et.al, 2018)[3].*

A squirrel cage induction motor will be composed of the squirrel cage windings. Aluminum bars would be molded on the slots and they will be short-circuited at the end rings. In order to reduce noise, the bars would be slanted in a small rotor. In the squirrel cage type, there won't be any slip rings but it could have conductors like copper, and also it will be galvanically isolated. So the rotor inside this would look like a squirrel cage. The rotor is a cylindrical steel lamination with a conductive material embedded in its surface. So when an AC current passes through the stator windings then a rotating electromagnetic field will be created *(Ashlin, 2021)[4].*

Squirrel induction motor working is based on the principle of electromagnetism. When the stator winding is supplied with a three-phase AC, it produces a rotating magnetic field (RMF) which has a speed called synchronous speed. This RMF causes voltage induced in the rotor bars. So, that short-circuit current flows through that. Due to these rotor currents, a self-magnetic field is generated which interacts with the stator field. Now, as per the principle, the rotor field starts opposing its cause. When the RMF catches the rotor moment, the rotor current drops to zero. Then there would be no relative moment between the rotor and RMF *(Elprocus, 2022)[5].*

2.2 Conceptual Framework

The multiphase induction machine has gained a lot of interests in research and the industries due to its improved power and general performance which include other characteristics that edge it out over the usual induction machine type. The most common type of this multiphase machine is the dual stator induction machine (DSIM), which has its configuration and design in such a way that two sets of three-phase windings, spatially phase shifted by 30 electrical degrees, share a common stator magnetic core *(Ben-Slimene et al, 2012)[6]* as illustrated in figure 2.1.

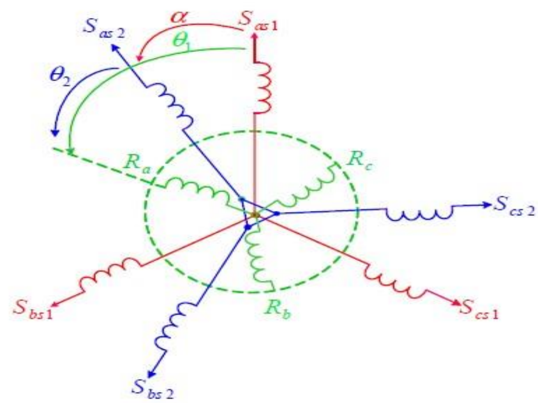

Figure 2.1: Dual Stator IM windings (Marwa et al, 2014)[7]

The analytical d-q model was developed in general reference frame and is suitable for analysis of the machine behavior with an arbitrary angle of displacement.

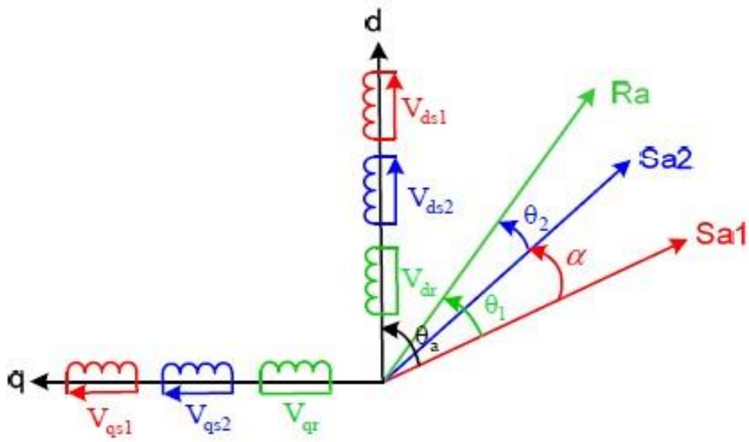

Figure 2.2: DSIM in d-q axis (Marwa et al, 2014)[7]

The voltage equations of the dual stator induction machine using decomposition vector space are as follows. For the stator circuit we can write *(Marwa et al, 2014)[7]:*

$$V_{ds1} = R_s i_{ds1} + \frac{d\lambda_{ds1}}{dt} - w_a \lambda_{qs1} \qquad (2.1)$$

$$V_{qs1} = R_s i_{qs1} + \frac{d\lambda_{qs1}}{dt} + w_a \lambda_{ds1} \qquad (2.2)$$

$$V_{ds2} = R_s i_{ds2} + \frac{d\lambda_{ds2}}{dt} - w_a \lambda_{qs2} \qquad (2.3)$$

$$V_{qs2} = R_s i_{qs2} + \frac{d\lambda_{qs2}}{dt} + w_a \lambda_{ds2} \quad (2.4)$$

The rotor circuit mathematical expression is given as follows *(Marwa et al, 2014)[7]:*

$$0 = R_r i_{dr} + \frac{d\lambda_{dr}}{dt} - (w_a - w)\lambda_{qr} \quad (2.5)$$
$$0 = R_r i_{qr} + \frac{d\lambda_{qr}}{dt} + (w_a - w)\lambda_{dr} \quad (2.6)$$

Where w_a is the speed of the reference frame.

The analytical d- model has been developed in a general reference frame and can be used to analyze the behavior of induction machine in any reference frame.

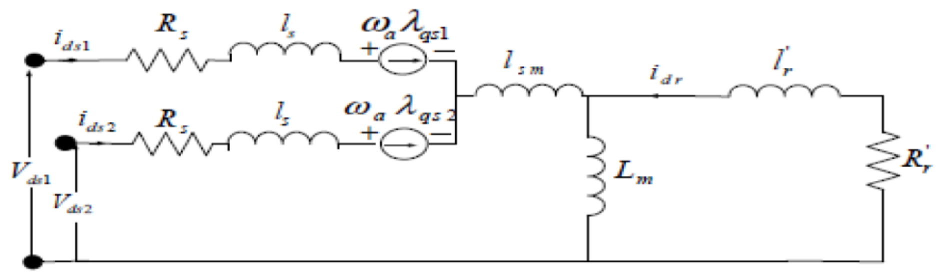

Figure 2.3: The d-axis equivalent circuit of a Dual Stator IM in arbitrary reference frame (Marwa et al, 2014)[7]

The equations from 2.1 to 2.14 propose the equivalent circuit as shown in figure 2.3. The common mutual leakage inductance expresses the point that the two sets of stator windings occupy the same slots and are, thus, they are mutually coupled by a component of leakage flux *(Singh et al, 2003)[8].*

The electromagnetic torque and dynamic equations can be expressed as:

$$C_{em} = n_p \frac{M}{L_r}\left((i_{qs1} + i_{qs2})\lambda_{dr} - (i_{ds1} + i_{ds2})\lambda_{qr}\right) \quad (2.7)$$
$$J\frac{dw}{dt} + K_f w = n_p(C_{em} - C_r) \quad (2.8)$$

Representing the model in state space model, the state equation of the form expressed in equation was used:

$X = AX + BU$ (2.10)
$X = [\lambda_{ds1}\ \lambda_{qs1}\ \lambda_{ds2}\ \lambda_{qs2}\ \lambda_{dr}\ \lambda_{qr}]$ is the state vector
$U = [V_{ds1}\ V_{qs1}\ V_{ds2}\ V_{qs2}\ ]$ is the input vector

2.3 Proportional-Integral-Derivative

A PID (Proportional-Integral-Derivative) controller is a widely used control loop feedback mechanism in industrial control systems. It combines three control actions; proportional, integral, and derivatives to provide a robust and effective means of controlling dynamic systems. The PID controller is particularly valued for its simplicity, effectiveness, and ease of implementation.

The proportional term produces an output that is proportional to the current error value, which is the difference between the desired set point and the actual process variable. The proportional gain kp determines the reaction to the current error. A higher k_p results in a larger output for a given error, leading to a faster response. However, using only proportional control can lead to a steady-state error, as it does not account for past errors.

The integral term accumulates the past errors over time, providing a corrective action based on the history of the error. The integral ki determines how much influence the accumulated error has on the output. This term helps eliminate steady-state error by adjusting the control output based on the total accumulated error.

The derivative term predicts future error based on its rate of change, providing a damping effect that helps reduce overshoot and improve system stability. The derivative gain kd determines the influence of the rate of change of the error on the output. This term helps to react to changes in the error quickly.

The PID controller is a fundamental tool in control engineering, providing a simple yet effective means of managing dynamic systems. Its ability to combine proportional, integral, and derivative actions allows for improved stability.

The PID control law is expressed as:

$$u(t) = k_p e(t) + k_d + k_i \int e(t)dt + k_d \frac{de(t)}{dt} \qquad (2.11)$$

where $e(t) = \omega_{ref} - \omega_r$

The classical numerical PI regulator is well suited to regulating the motor torque to the desired values as it is able to reach constant reference. The transfer function takes the form *(Benyoussef, 2022)[9]:*

$$G(s) = \frac{k_p(s)+k_i}{js^2+(f+k_p)s+k_i} \qquad (2.12)$$

where $p(s) = s^2 + \left(\frac{f+k_p}{j}\right)s + \frac{k_i}{j} = 0$ (2.13)

2.4 Linear-Quadratic-Gaussian

Linear-Quadratic-Gaussian (LQG) control is a modern state-space technique for designing optimal dynamic regulators and servo controllers with integral action (also known as set point trackers). This technique allows you to trade off regulation/tracker performance and control effort, and to take into account process disturbances and measurement noise.
The compensator (k) in an LQR controller is a gain matrix that optimally balances state feedback to minimize a coat function, typically involving state errors and control efforts. In the context of a DSIM, this matrix is designed to ensure stability and performance by effectively managing the system's dynamic response. The compensator (k) provides feedback based on the current state of the system, allowing for real-time adjustments to the control inputs. This feedback is crucial for maintaining the desired performance of the DSIM.

The LQR framework aims to minimize a quadratic cost function, which typically includes terms for state deviations and control efforts. The compensator (k) is derived from solving the algebraic Riccati equation, ensuring that the control actions are optimally in terms of this function.

In a DSIM, the compensator (k) helps manage the dynamic response by adjusting the control inputs based on the state of the motor. This is particularly important for achieving desired speed and torque characteristics while minimizing overshot and settling time. It plays a critical role in optimizing performance, ensuring stability, and managing the dynamic response of the motor.

After implementing the compensator (k), it is essential to evaluate the performance of the DSIM under various operating conditions to ensure that the desired control objectives are met.

The matrices Q and R used in the LQR formulation must be carefully selected to reflect the relative importance of the state errors versus control efforts. This tuning directly influences the values in the compensator (k).

Given a linear time-invariant system, the state space equation is written in general form as:

$$X^* = Ax + Bu$$

$y = cx + Du$

where A=state matrix of sides $n \times n$, B is the control or input matrix of order $n \times m$, C is the output matrix of order p×n, and D is feedthrough matrix of order p×m, respectively. n is the number of state variables and m is the number of input variables.

The cost function is to minimize:

$J = \int (x^T Qx + u^T Ru)dt \quad from\ 0\ to\ \infty$

Where Q is a positive-definite (or positive-semi definite) Hermitian or real symmetric matrix,

R is a positive-definite Hermitian or real symmetric matrix. Note that the second term on the right-hand side of Equation accounts for the expenditure of the energy of the control signals. The matrices Q and R determine the relative importance of the error and the expenditure of this energy.

1.1.1 Linear Quadratic Regulator

The LQR k(s) is designed using Algebraic Riccati Equation (ARE) ensuring optimal disturbance rejection. It takes the form *(Ben and Khlifi, 2022)[10]:*

$A^T P + PA - PBR^{-1}B^T P + Q = 0$
Where:
A is the state matrix,
B is the input matrix,
Q is the state weighting matrix
R is the control weighting matrix,
P is the solution matrix
The optimal feedback control law is;
$u = -kx$

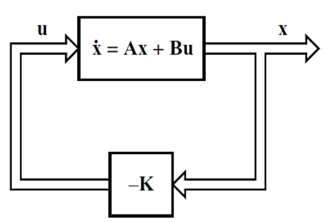

Figure 2.4; Feedback control diagram

Therefore, if the unknown elements of the matrix K are determined so as to minimize the performance index, then u(t)= $-kx$ (t) is optimal for any initial state x(0).

The gain matrix k is computed as:

$K = R^{-1}B^T P$

The control cost weighting matrix R determines the penalty on control effort. A larger R means the controller will use smaller control inputs (smoother but possibly slower response). R>0 to ensure the problem is well-posed. P represent the cost-to-go matrix in the optimal control problem. It is used to solve the Riccati equation and defines the optimal cost function. B defines how control affects the system dynamics.

These terms together determine the optimal feedback control law that minimizes the quadratic cost function J.

From the reviewed literature, the following points were identified to be the research gaps in the dual stator induction machine performance improvement:

i. The robustness of the dual stator induction machine was not guaranteed due to lack of proper analysis of the system behavior in frequency domain and lack tracking error analysis determination. These make it difficult to know exactly the ability of the system to withstand disturbances and perform optimally in the presence of significant uncertainties.
ii. The tracking performance characteristic of a controlled system determines the ability of the system to achieve optimal performance by tracking the reference input to the system with reduced error. However, the tracking performance of the dual stator induction machine was not analyzed
iii. The stability of the system is required in the system design and it is used to determine the ability of the system to maintain equilibrium. However, the stability of the dual stator induction machine was not analyzed.
iv. From the results of the reviewed works, there are still ripples existing in the output of the controlled DSIM which shows that the performance of the system needs more improvement.
v. The system sensitivity and disturbance rejection capability are not analyzed in frequency domain. Thus, there is need to carry out a thorough analysis of the system sensitivity to disturbance in frequency domain in order to ascertain the real ability of the controller and the robustness characteristics of the system.

3.0 METHODOLOGY

3.1 Controller Design

The PID control law is expressed as:

$$u(t) = k_p e(t) + k_d + k_i \int e(t)dt + k_d \frac{de(t)}{dt} \quad (3.1)$$

Where $e(t) = \omega_{ref} - \omega_r$

The classical numerical PI regulator is well suited to regulating the motor torque to the desired values as it is able to reach constant reference. The transfer function takes the form *(Benyoussef, 2022)[9]:*

$$G(s) = \frac{k_p(s)+k_i}{js^2+(f+k_p)s+k_i} \quad (3.2)$$

Where $p(s) = s^2 + \left(\frac{f+k_p}{j}\right)s + \frac{k_i}{j} = 0$ (3.3)

The LQR k(s) is designed using Riccati equations ensuring optimal disturbance rejection. It takes the form *(Ben and Khlifi, 2022)[10]:*

$$K = R^{-1}B^T P \quad (3.4)$$

The state space equation for the system is written in general form as:

$$X^* = Ax + Bu \quad (3.5)$$

where A=state matrix of sides $n \times n$, B is the control matrix of order $n \times m$ respectively. n is the number of state variables and m is the number of input variables.

3.2 Implementation

3.2.1MATLAB Environment Set Up

The simulation was conducted by replacing the derived state-space model (A, B, C, D) with the actual DSIM and controller parameters to simulate responses for PID and LQR.

The MATLAB script simulates a unit step input, which represents a disturbance load change. Finally running the simulation to generate all comparative plots for each condition and controller.

A new MATLAB script (DSIM_Control_Comparison) was created using the control system toolbox to generate PID and LQR functions. System parameters (Rs, Ld, Lq, km, J, B, P) were defined at the beginning. The state-space matrices (A, B, C, D) were constructed based on DSIM dynamics and stored as an ss (state-space) object. After constructing the state-space, the controllers were manually selected (kp, ki, kd) for each loop and then combined into a diagonal matrix for feedback looping. The code was structured into clear sections (modeling, controllers, simulation, and plotting). The simulation was finally executed with a time vector t=0:0.01:1, speed of 1500 RPM, and step inputs depending on load conditions. System parameters are specified in Table (3.1). The MATLAB codes are shown in appendix 1.

Table 3.1: Dual Stator Induction Machine (DSIM) Parameters.

Parameter	Value
R_{s1}	0.435Ω
R_{s2}	0.435Ω
L_{s1}	$0.002H$
L_{s2}	$0.002H$
R_r	0.816Ω
L_m	$0.0693H$
L_r	$0.002H$
K_f	$0.001Nm.s/rad$
J	$0.089Kg.m^2$
P	4
F	50Hz

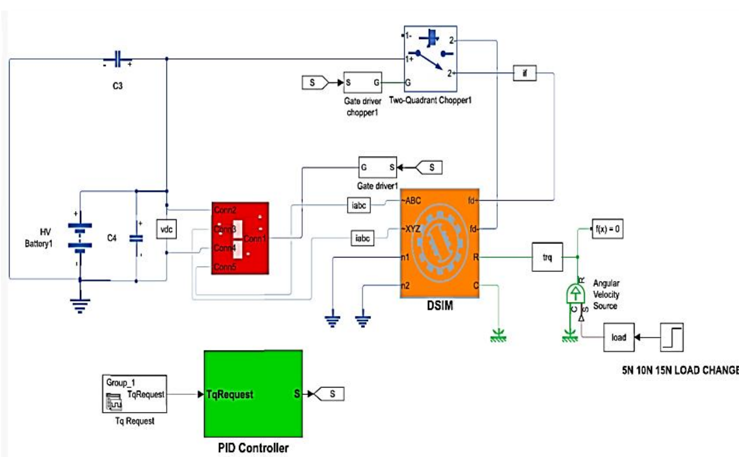

Figure 3.2: Simulink Model of PID Controller-based DSIM

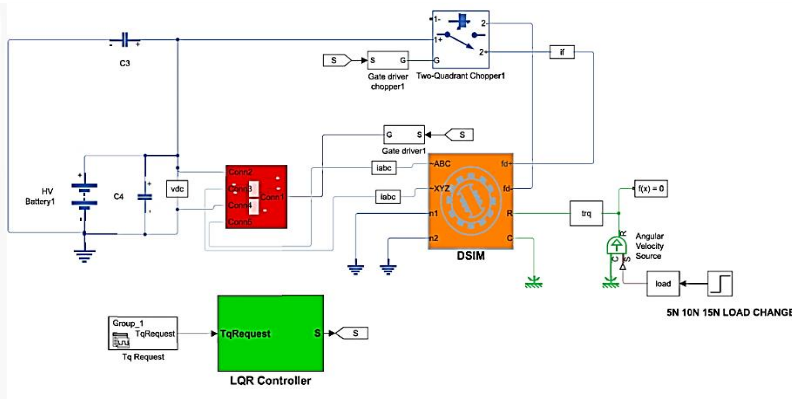

Figure 3.3: Simulink Model of LQR Controller-based DSIM

4.0 RESULTS AND DISCUSSION

4.1 Step Response Results

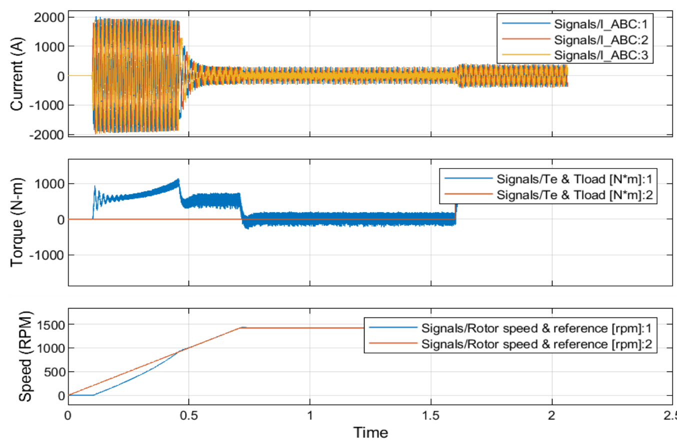

Figure 4.1: Current, Torque, and Speed Response of PID-based DSIM for 5N load

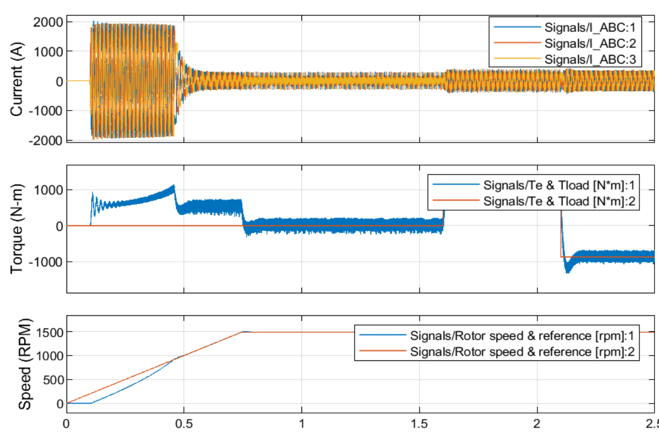

Figure 4.2: Current, Torque, and Speed Response of LQR-based DSIM for 5N load

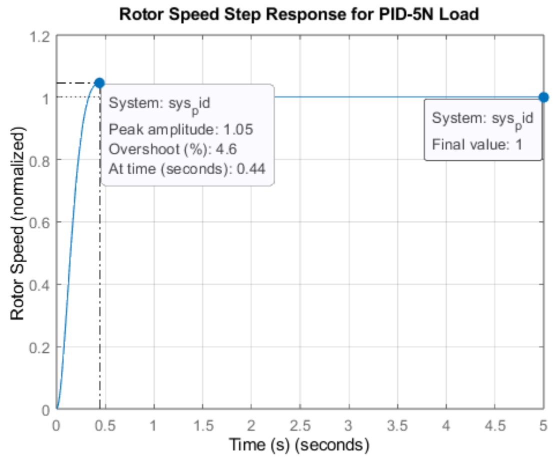

Figure 4.3: Step response of PID-based DSIM showing overshoot (5N Load)

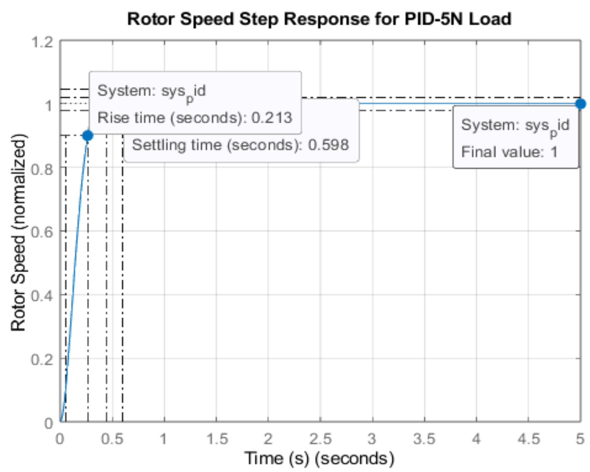

Figure 4.4: Step response of PID-based DSIM showing rise time and settling time (5N load)

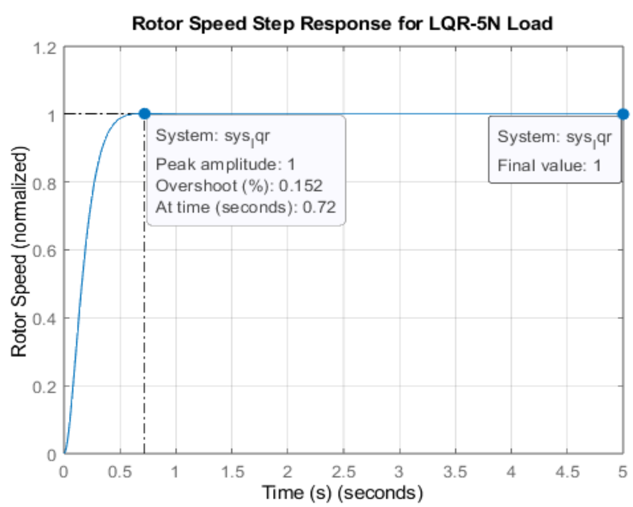

Figure 4.5: Step response of LQR-based DSIM showing overshoot (5N)

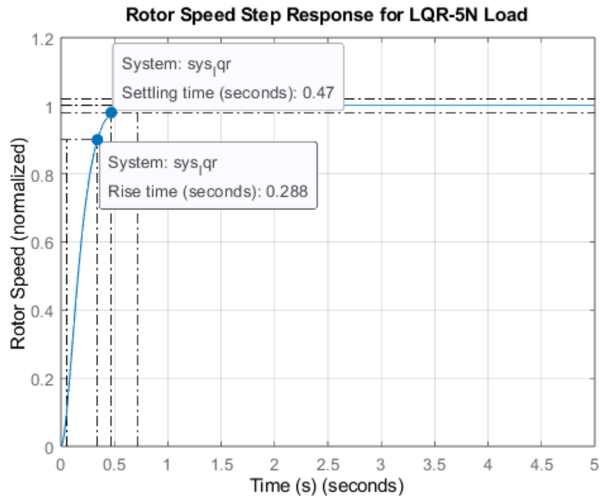

Figure 4.6: Step response of LQR-based DSIM showing rise time and settling time (5N)

4.2 Frequency Response (Bode Plot) Results

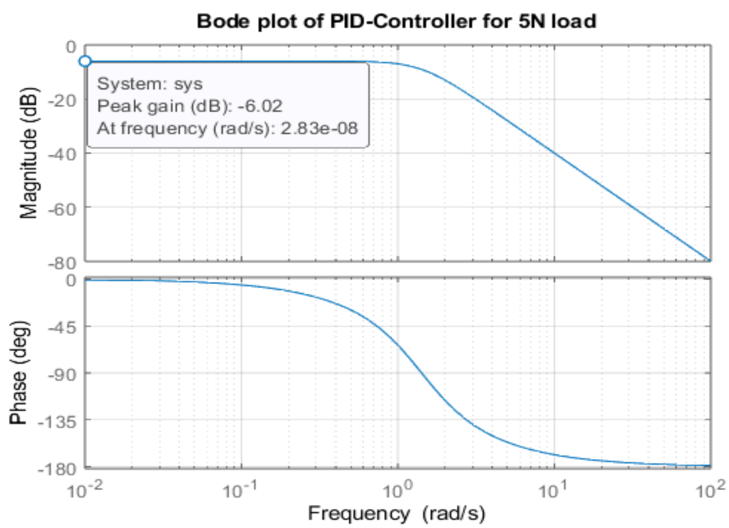

Figure 4.7: Bode plot of the PID-based DSIM showing peak gain (5N)

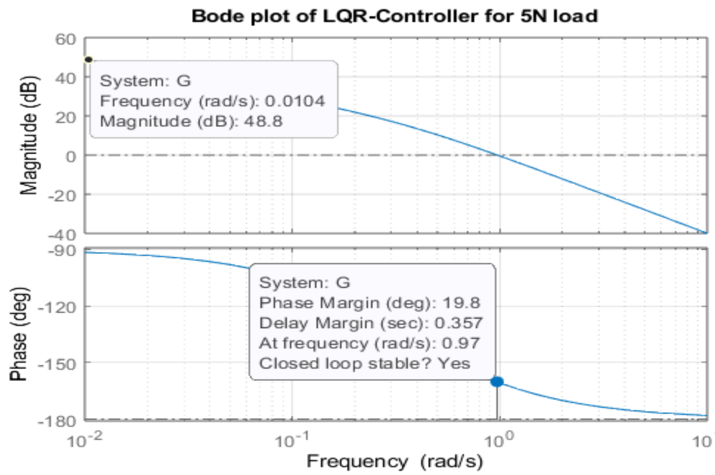

Figure 4.8: Bode plot of the LQR-based DSIM under 5N load

4.4 Sigma Plots Results

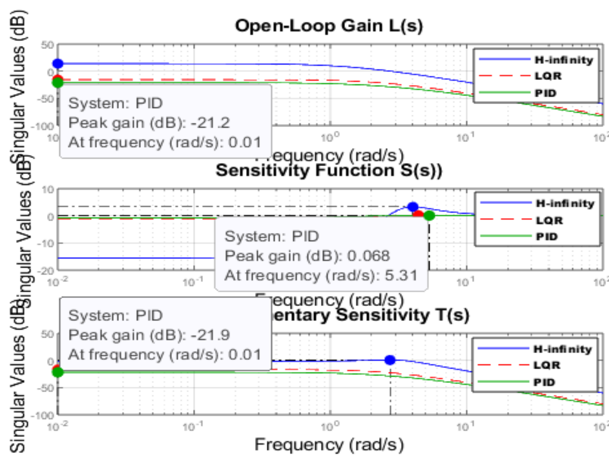

Figure 4.9: Analysis of the combined sigma plot under 5N load

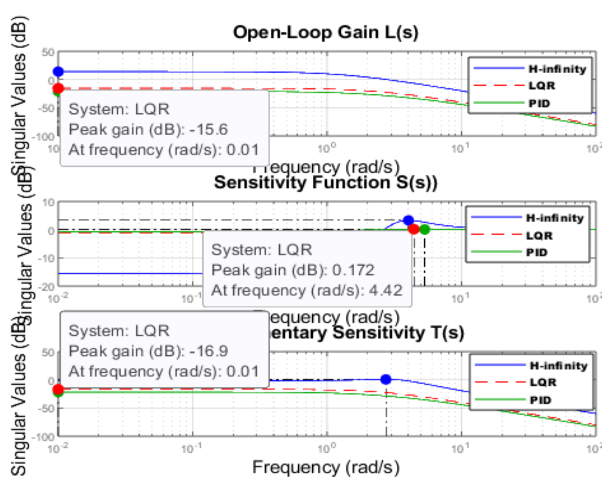

Figure 4.10: Analysis of the combined sigma plot under 5N load

4.5 Discussion of Step Response Results

Figures 4.1 depicts the PID controller based DSIM outcomes concerning torque, speed, rotor, and stator currents under 5N load change. The stator currents reflect how the machine draws power to meet load demands. With PID control, the current response is generally sharp and sometimes excessive. The electromagnetic torque generated by the machine reflects how the controller counters the applied load. In case of PID control, torque tends to lag behind the load changes. As can be seen, there is an abrupt overshoot from 0.1s to 0.5s before it stabilizes. This indicates the controller's reactive nature and limited ability to handle sudden disturbances. As can be seen in figure 4.2, LQR handles load changes better due to state feedback but still shows sensitivity. It offers moderate overshoot with more consistent damping and constant settling behavior than the PID controller. Under LQR control, the current response is improved and better synchronized but there are still some ripples, especially if sensor noise or un-modeled dynamics affect the state estimation, but the overall behavior is more stable than with PID control method. Torque reacts more quickly to the applied loads. The controller manages to anticipate the demand to some extent, so the torque increases more smoothly and settles faster than with PID control strategy
In figure 4.3, the rotor speed step response of PID-based Dual Stator Induction Machines under 5N load disturbance shows an overshoot of 4.6% and in figure 4.5, the step response of the LQR based Dual Stator Induction Machine under 5N load disturbance shows an overshoot of 0.152%.The reduced overshoot in the case of LQR shows that it has better performance characteristics than PID.

In figure 4.4, the rotor speed step response of PID-based Dual Stator Induction Machines under 5N load disturbance shows a rise time of 0.213 second and settling time of 0.598 second while in figure 4.6, the step response of the LQR based Dual Stator Induction Machine under 5N load disturbance shows a rise time of 0.288 second and settling time of 0.47 second. The settling time in the case of LQR is less than in PID showing improvement of LQR over PID.

4.6 Discussion of Frequency Response Results

In figure 4.7, the frequency response (Bode Plot) of PID-based Dual Stator Induction Machine under 5N disturbance shows a peak gain of -6.02dB at a frequency of $2.83e^{-08}$ rad/s. In figure 4.8, the frequency response (Bode plot) of LQR based Dual Stator Induction Machine under 5N load disturbance indicates a magnitude (gain margin) of 48.8dB at a frequency of 0.0104rad/s and a phase margin of 19.8^0 at a frequency of 0.97rad/s. The high gain margin of 48.8dB in LQR as compared to -6.02dB in PID makes LQR the controller with better performance characteristics.

4.7 Discussion of Sigma Plots Results

Figure 4.9, shows the sigma plots of all three controllers (PID, LQR and H-infinity) together for the Dual Stator Induction Machine under 5N. For the open loop gain, L(s), PID indicates a peak gain of -21.2dB at a frequency 0.01rad/s. For the sensitivity function, S(s), PID indicates a peak gain of 0.068dB at 5.31rad/s. For the complimentary sensitivity, T(s), PID indicates peak gain of -21.9dB at frequency of 0.01rad/s. Figure 4.10 shows the sigma plots of all three controllers (PID, LQR and H-infinity) together for the Dual Stator Induction Machine under 10N. For the open loop gain, L(s), LQR indicates a peak gain of -15.6dB at a frequency 0.01rad/s. For the sensitivity function, S(s), LQR indicates a peak gain of 0.172dB at 4.42rad/s. For the complimentary sensitivity, T(s), LQR indicates peak gain of -16.9dB at frequency of 0.01rad/s.

5.0 CONCLUSION

The performance of two control strategies (PID and LQR) were compared for the DSIM under 5N load performance metrics considered include overshoot, rise time and settling time with frequency analysis via Bode and Sigma plots to ascertain robustness and stability margins while PID is simpler to implement than the LQR, the latter offer a better performance than the former.

PID sigma plot shows higher peaks, indicating poor disturbance attenuation, LQR improves in disturbance rejection but still shows peaks under high loads.

In frequency domain, PID shows reduced phase margin and lower gain cross over frequency, indicating reduced stability and increased sensitivity to disturbance. LQR maintains a better phase margin, offering improved robustness.

Recommendation

The current study of H-infinity based DSIM is based on a single load condition of N. Future work should include a study under varying load conditions.

Acknowledgement

5.0 REFERENCES

1. Mataray M. and Kakkar V. (2011), Asynchronous Machine Modeling Using Simulink Fed by PWM Inverter, International Journal of Advances in Engineering & Technology, Vol. 1, Issue 2,pp.206-214
2. Pieńkowski K., (2012), Analysis and control of dual stator winding induction motor, Archives of Electrical Engineering, VOL. 61(3), pp. 421-438 (2012)
3. Uju I.U, Nzeife I.D & Asiwe U.M (2018). Analysis and Application of Linear Motors; an Overview. International Journal of Innovative Engineering Technology and Science. Vol.2, Issue 1.
4. Ashlin A., (2021), what is the Difference between Squirrel Cage and Wound Rotor Induction Motor? https://automationforum.co/what-is-the-difference-between-squirrel-cage-andwound-rotor-induction-motor/
5. Elprocus, (2022), What is a Squirrel Cage Induction Motor and Its Working, https://www.elprocus.com/what-is-a-squirrel-cage-induction-motor-and-its-working/
6. Ben Slimene M, Khlifi MA(2022). Investigation on the Effects of Magnetic Saturation in Six-Phase Induction Machines with and without Cross Saturation of the Main Flux Path. Energies. 2022;15(24).
7. Marwa B.S, Larbi K.M, Mouldi B.F. and Habib R., (2014), Dual Stator Induction Motor Operation from Two PWM Voltage Source Inverters, Unit Signal, Image and Intelligent Control of Industrial Systems (SICISI)
8. Singh G.K., Pant V., Singh Y.P., (2003). Voltage source inverter driven multi-phase induction machine, Computers and Electrical Engineering, Vol. 29, no. 8, pp. 813–834
9. Benyoussef E, Barkat S (2020). Five-level Direct Torque Control with Balancing Strategy of Double Star Induction Machine. Int J Syst Appl Eng Dev. 2020;14(Dci):116–23.
10. Ben Slimene M, Khlifi MA(2022). Investigation on the Effects of Magnetic Saturation in Six-Phase Induction Machines with and without Cross Saturation of the Main Flux Path. Energies. 2022;15(24).

APPENDIX 1
MATLAB CODES

```
% Dual Stator Induction Machine Control Using LQR
% Author:
% Date:
% Objective: Compare PID and LQR Control

clc;
clear;
% Motor Parameters
Rs = 0.435;
Rr = 0.816;
Ls = 0.002;
Lr = 0.002;
Lm = 0.0693;
J = 0.089;
B = 0.005;
p = 4;
```

```
% Torque constant
Kt = (3/2)*(p/2)*(Lm/Lr);

% System Matrices
A = zeros(7, 7);
Bmat = zeros(7, 4);

% Fill A matrix
A(1,1) = -Rs/Ls;
A(1,5) = -Lm/(Ls*Lr)*Rr;
A(2,2) = -Rs/Ls;
A(2,6) = -Lm/(Ls*Lr)*Rr;
A(3,3) = -Rs/Ls;
A(3,5) = -Lm/(Ls*Lr)*Rr;
A(4,4) = -Rs/Ls;
A(4,6) = -Lm/(Ls*Lr)*Rr;

A(5,1) = -Lm/(Lr*Ls)*Rs;
A(5,3) = -Lm/(Lr*Ls)*Rs;
A(5,5) = -Rr/Lr;
A(6,2) = -Lm/(Lr*Ls)*Rs;
A(6,4) = -Lm/(Lr*Ls)*Rs;
A(6,6) = -Rr/Lr;

A(7,1) = Kt;
A(7,3) = Kt;
A(7,2) = -Kt;
A(7,4) = -Kt;
A(7,5) = -Kt;
A(7,6) = Kt;
A(7,7) = -B/J;

% B matrix (inputs are vds1, vqs1, vds2, vqs2)
Bmat(1,1) = 1/Ls;
Bmat(2,2) = 1/Ls;
Bmat(3,3) = 1/Ls;
Bmat(4,4) = 1/Ls;

% Output: rotor speed
C = [0 0 0 0 0 0 1];
D = zeros(1, 4);

% Create system
sys = ss(A, Bmat, C, D);

% Simulation time
t = linspace(0, 5, 1000);
dt = t(2) - t(1);

 %Display transfer function from each input
tf_sys = tf(sys)

% Function to simulate response with load torque
```

```
simulate_response = @(TL) simulate_with_load(sys, J, t, TL);

% Run simulations
[omega5] = simulate_response(5);
% Plot
figure;
pl0ot(t, omega5, 'r', t,  'g-.', 'LineWidth', 1.5);
xlabel('Time (s)');
ylabel('Rotor Speed (rad/s)');
title('DSIM Rotor Speed Response to Load Torque Disturbances');
legend('5 Nm', ');
grid on;

%% 1. PID Controller Design
C_pid = pidtune(sys_siso, 'PID');
T_pid = feedback(C_pid * sys_siso, 1);

%% 2. LQR Controller Design
Q = C'*C;
R = 0.01;
K_lqr = lqr(A, Bmat(:,1), Q, R);
sys_lqr = ss(A - Bmat(:,1) * K_lqr, Bmat(:,1), C, 0);
T_lqr = feedback(sys_lqr, 1);

systemnames = 'sys_siso Wp Wu';
inputvar = '[dist; control]';
outputvar = '[Wp; Wu; sys_siso]';
input_to_sys_siso = '[control + dist]';
input_to_Wp = '[sys_siso]';
input_to_Wu = '[control]';
P = sysic;

%% 4. Simulate Step Torque Disturbance
t = 0:0.01:5;
dist5 = -5/J * ones(size(t));    % rotor deceleration due to load

% H-infinity system is already configured for disturbance as input
[y_pid5,~] = lsim(T_pid, dist5, t);
[y_lqr5,~] = lsim(T_lqr, dist5, t);
%% 5. Plot for 10 Nm Disturbance
figure;
plot(t, y_pid10, 'g', t, y_lqr10, 'b--', t, y_hinf10, 'r-.', 'LineWidth', 1.5);
title('Rotor Speed Response to 10 Nm Load Torque');
xlabel('Time (s)'); ylabel('Speed (rad/s)');
legend('PID', 'LQR', 'H-infinity'); grid on;

%% 6. Compare Performance
info_pid = stepinfo(y_pid10, t);
info_lqr = stepinfo(y_lqr10, t);
info_hinf = stepinfo(y_hinf10, t);

fprintf('\n--- Step Response Metrics for 10 Nm Disturbance ---\n');
fprintf('PID     | Overshoot: %.2f%% | Settling Time: %.2fs\n', info_pid.Overshoot, info_pid.SettlingTime);
```

```
fprintf('LQR    | Overshoot: %.2f%% | Settling Time: %.2fs\n', info_lqr.Overshoot, info_lqr.SettlingTime);


%Bode and Sigma plot

% T_pid    = closed-loop system with PID controller (SISO)
% T_lqr    = closed-loop system with LQR controller (can be SISO or MIMO)
% Define frequency range
w = logspace(-1, 3, 500);  % from 0.1 to 1000 rad/s

%% Bode Plot
figure;
bode(T_pid, 'g', T_lqr, 'b--', CL_hinf, 'r-.', w);
legend('PID', 'LQR',);
title('Bode Plot Comparison');
grid on;

%% Sigma Plot (for robustness analysis, only for MIMO systems)
figure;
sigma(T_pid, 'g', T_lqr, 'b--', CL_hinf, 'r-.', w);
legend('PID', 'LQR', 'H-infinity');
title('Sigma Plot (Singular Value) Comparison');
grid on;
```