**UNIVERSITY OF ENGINEERING AND**

**TECHNOLOGY LAHORE**



**Assignment # 3**

**Induction Motor Drive**

**Course Title: Control of Electric Machine Drives**

**Course Code: EE 535**

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**Induction Motor Model**

A simulation model of the indirect vector-controlled 5 HP, 200V, 0 Hz, 3 Phase induction motor (squirrel cage) drive will be presented. The design was based on the stator equations of the induction machine:

The rotor flux linkage was assumed to be constant:

For the vector controller, the flux is aligned with the d-axis hence

Substituting (5-) in the stator equations (1-2):

The flux producing d-axis component of stator current is constant in steady state:

The torque producing component of stator current is the q-axis component in synchronous frame:

Substituting (10), (12) and (13) in (8):

The stator angular speed is related to the rotor angular speed and slip angular speed by:

Substituting (15) in (14) leads to

Hence the simplified motor model is:

The electromagnetic Torque of the induction motor is given by

The motor dynamic equations are:

Representing (19) in terms of the electrical rotor speed:

The final transfer function between the electrical rotor speed and torque producing current component is:

Substituting (21) in (17):

The Simulink Model for the Induction Motor Drive and its simplification is presented in the figures below:

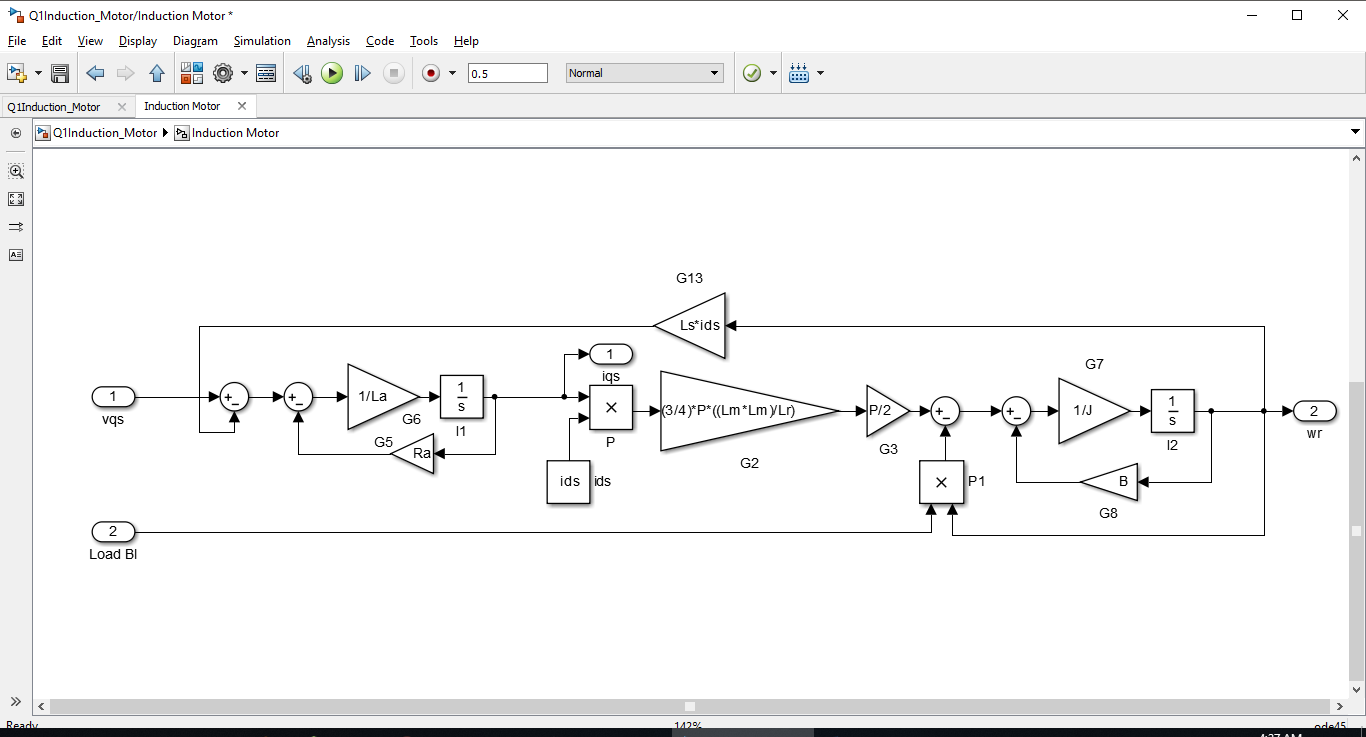


Figure 1: Induction Motor Model (Eq. 16 and 20)

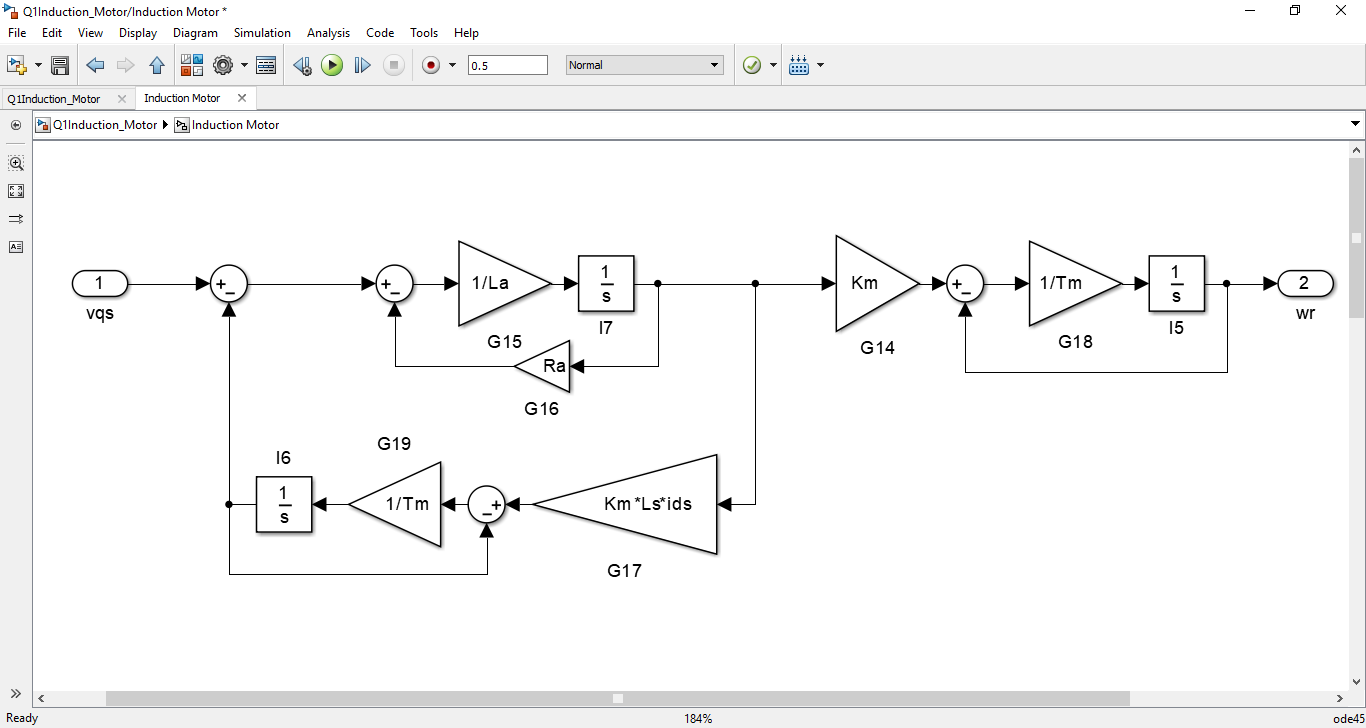


Figure 2: Induction Motor Model (Eq. 17 and 21)

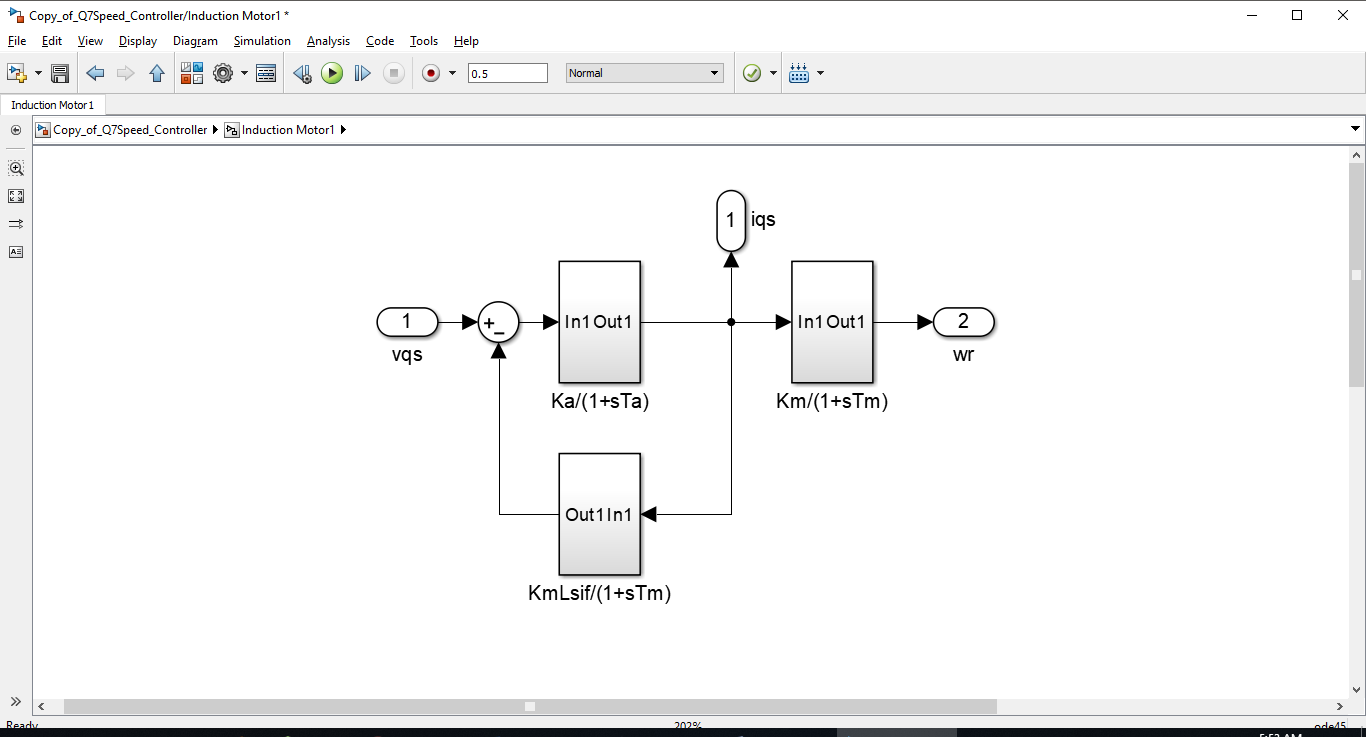


Figure 3: Induction Motor Model (Eq. 21 and 22)

1. **Per unit Current and per unit Speed**



Figure 4: Per unit current and speed

is a V step input applied at t = 0.1 s.

Substituting in :

Hence

The response represents two decaying exponentials and a step starting at t = 0.1s. Hence the simulation results are correct and thus a peak is seen in iqs when vqs is applied.

1. **Steady State per unit Current and per unit Speed**



Figure 5: Steady state current and speed

Steady State Values

In steady state,

The calculations are close to the steady state simulation results in Figure 5.

1. **Limiting Rising Rate of Voltage**



Figure 6: Per unit current and speed

Effect of Rate Limiter

is a V / 0.1 s ramp starting at t = 0.1 s and ending at t = 0.2 s.

Hence,

Hence

Which represents a pulse starting at t = 0.1 s and ending at t = 0.2 s, and a ramp starting at t = 0.1 s and ending at t = 0.2 s. The current also has four decaying exponentials starting at t = 0.1s or t=0.2s. It can be verified using this equation that iqs(t) = 0 A (0 p.u.) at t = 0.1 s. This matches with the simulation result.

Since,

Hence, consists of a ramp function starting at t = 0.1 s and ending at t = 0.2 s and a step function starting at t = 0.1 s and ending at t = 0.2 s. It also has four decaying exponentials starting at t = 0.1 s or t=0.2 s. These results also match with the simulation results.

**DC-DC Converter and Unipolar PWM**

1. **Testing the Model**

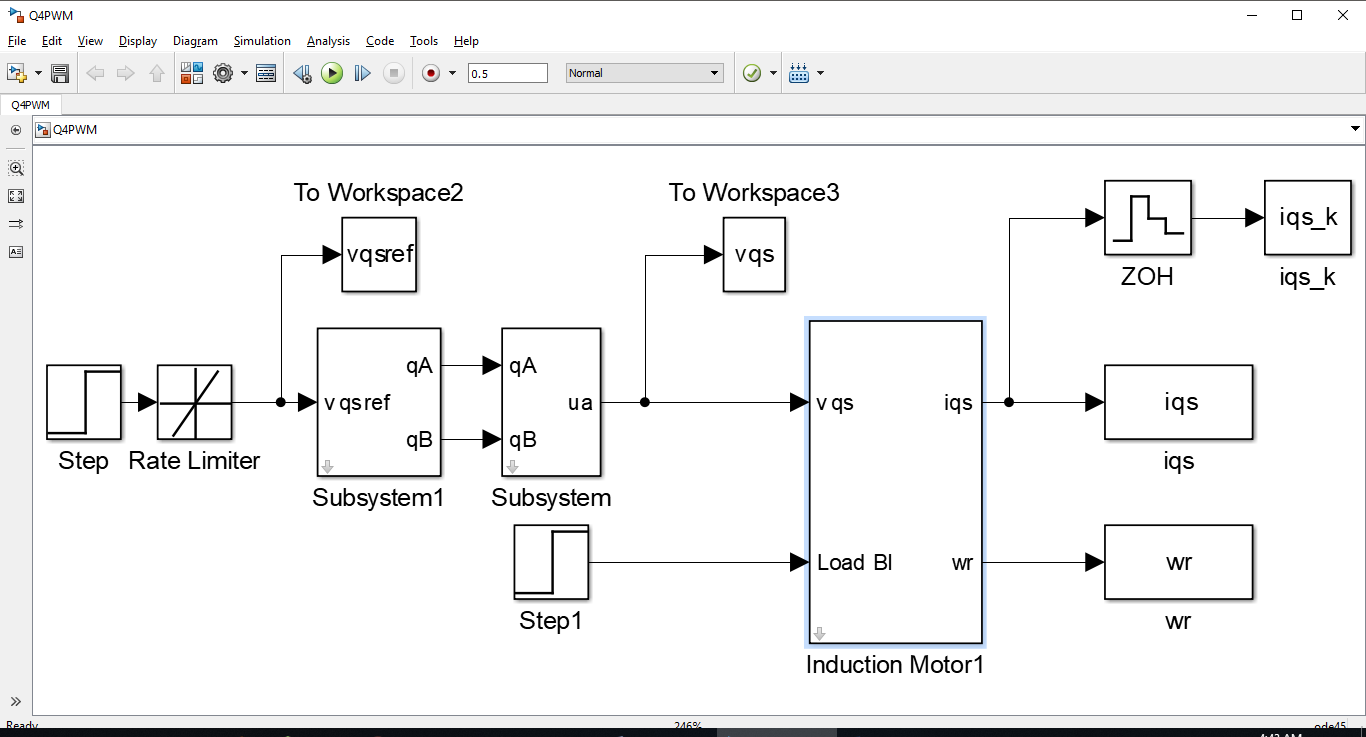


Figure 7: Voltage Control based Model



Figure 8: Per unit current and speed

In this simulation, vqs is supplied using PWM technique. The Average value of is equal to the reference. This is achieved by changing the duty cycles dA and dB. The results of current and speed are almost the same as the last section, where an ideal voltage source was used. The current has much more ripple around the mean value as compared to the last case. This is because the current graph has a much thicker line during transition periods. This is when unipolar PWM is adjusting the duty cycles to reach steady state current. The adjustments cause current to oscillate around the mean value. The Moment of Inertia is quite high hence the speed is unaffected by current oscillations. The speed graph is just like the earlier case.

1. **Plotting Armature Voltage and Current**



Figure 9: Steady state current and speed

The Stator current iqs is a triangular wave because La charges up (current rises) when converter output vqs is high; and La discharges (current deceases) when converter output becomes zero. The vqs on/off sequence is such that the current rises and drops by equal amounts in steady state. Hence the sampled average current iqs\_k seems constant.

**Cascaded Control**

1. **Current Control**

Instead of using the unipolar PWM, the current iT was controlled using current feedback loop. The feedback gain was:

After comparing the feedback with the reference, the error was passed through an Inverter. The Inverter was modeled as a gain with a time lag.

The overall transfer function from to iT was

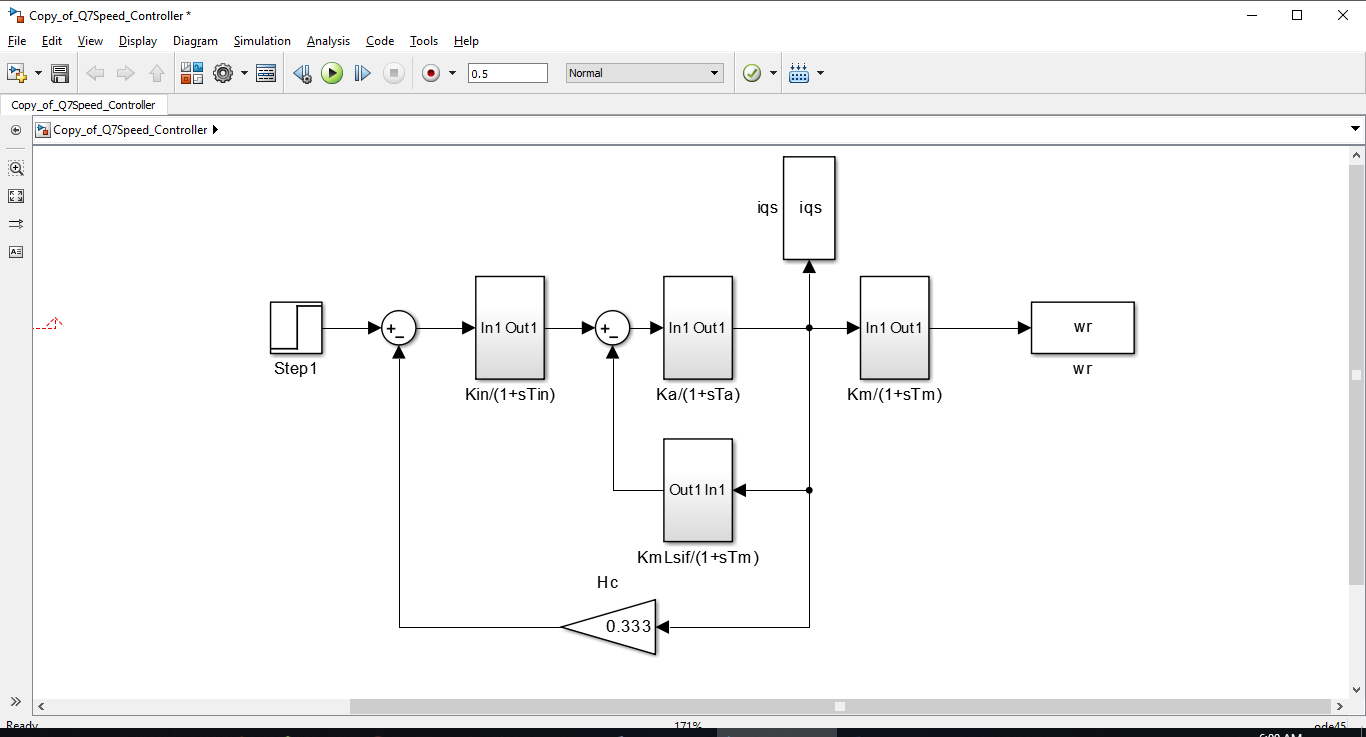


Figure 10: Current Control Loop Model



Figure 11: Current and Speed Response



Figure 12: Current Step Response

From the torque step response (Fig. 9), the rise time (from TM = 0.1Nm to TM = 0.9 Nm) is 0.709 ms.

The Time Constant of Torque is . The rise time is 0.6994 ms. Hence the simulation result is correct and desired bandwidth has been achieved.

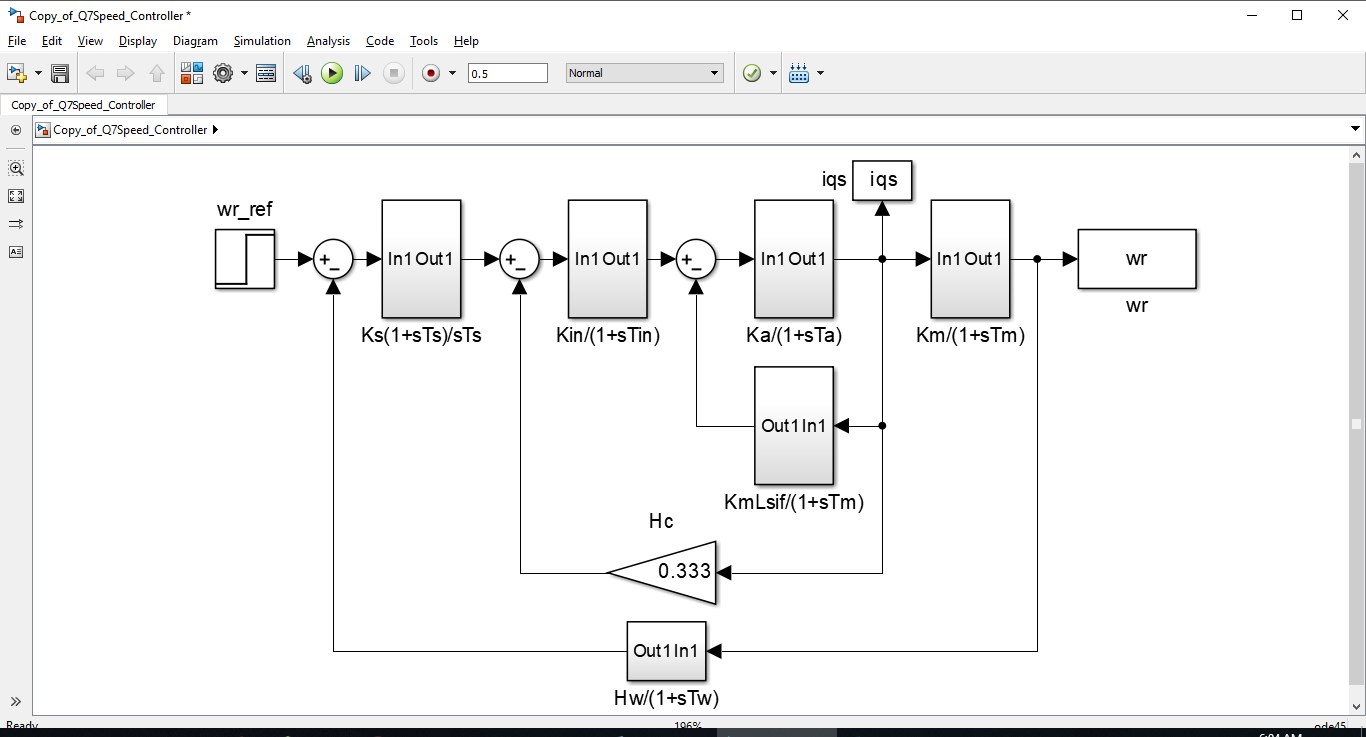
**Cascaded Control**

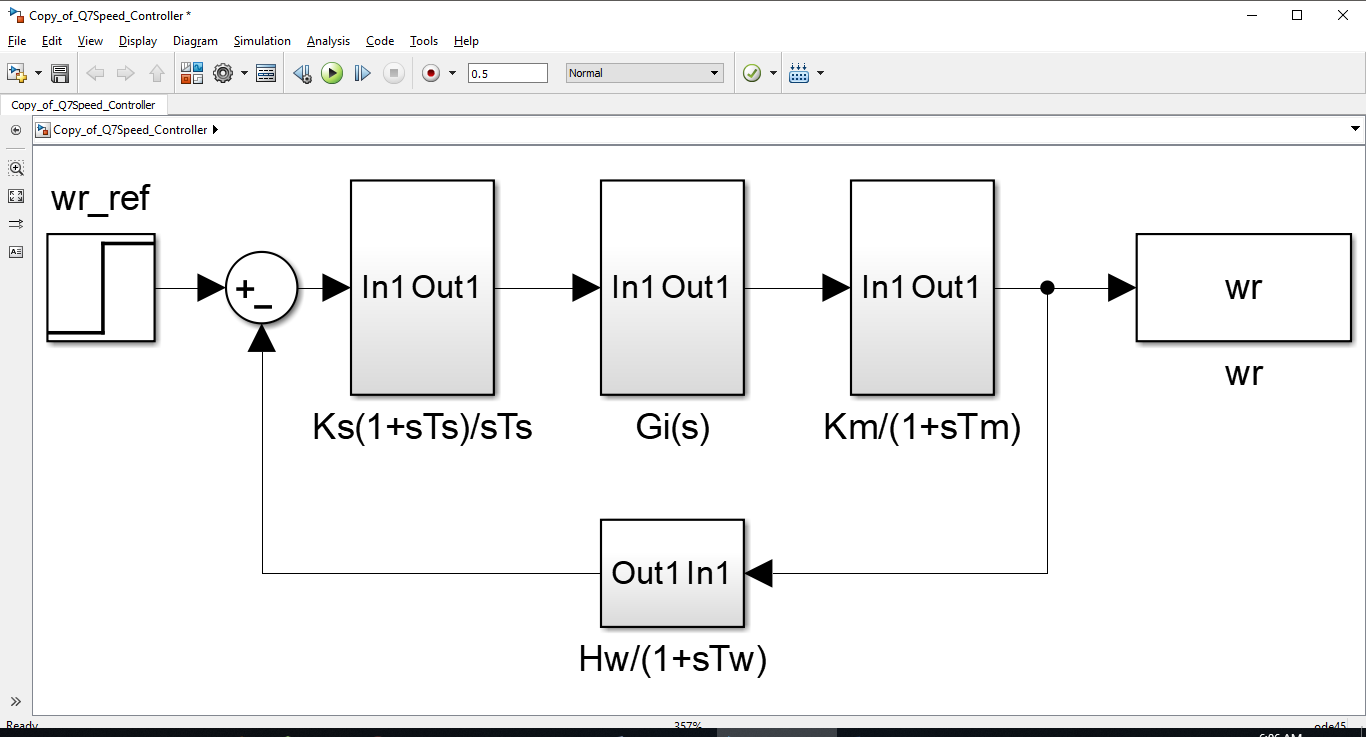
1. **Transfer Function**

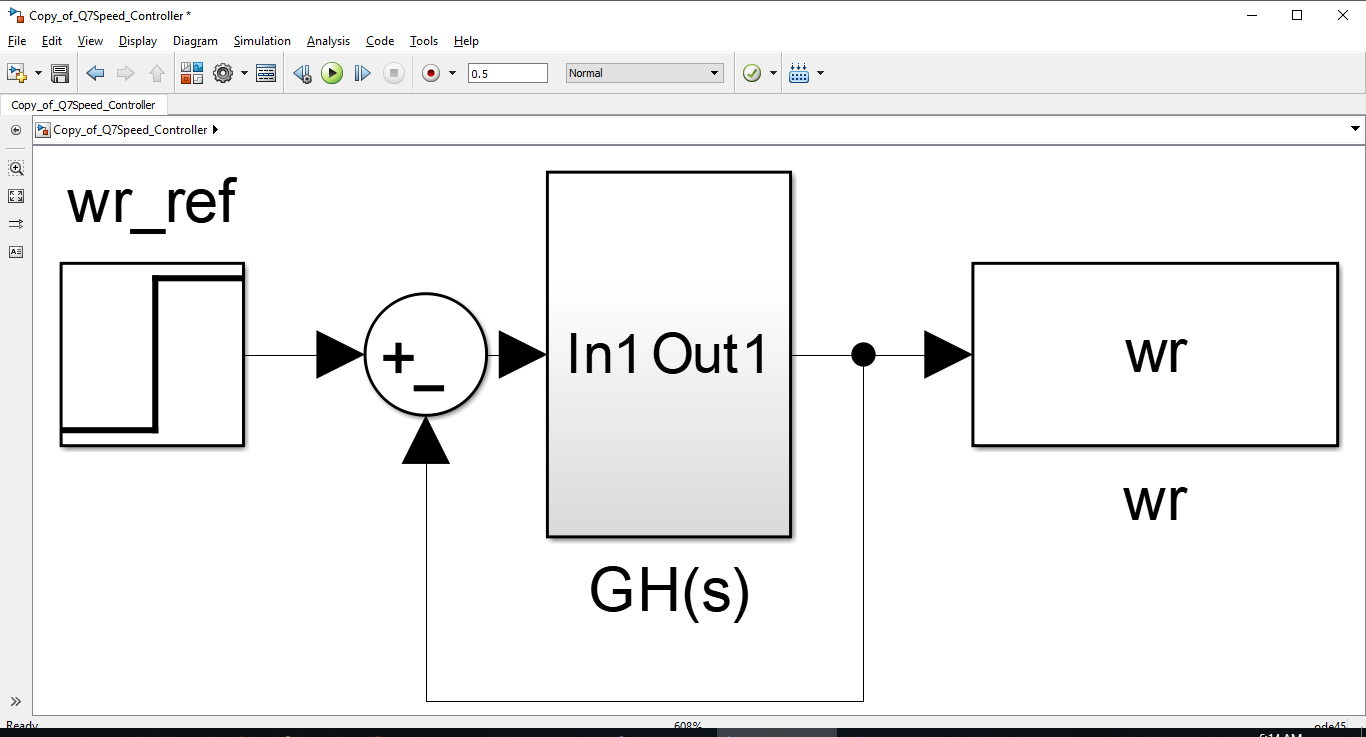
The speed control feedback loop generates the reference for torque producing current component to drive the current control feedback loop. The rotor electrical speed is sensed and passed through a filter

The output of the filter is compared with the reference speed. A PI controller:

generates the current control loop reference.







The Speed Control Transfer function is:

1. **Testing the Model**

GH(s) can be approximated using symmetric function:

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Figure 18: Speed, Current and Torque Response

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Figure 19: Speed Step Response

From the simulation results, the rise time (from ωM = 0.1 to rad/s = 0.9 rad/s) is 6.4 ms.

The theoretical rise time for ωM is:

6.994 ms

Hence the result matches with the simulation. The speed controller has the desired bandwidth.

1. **Tolerances**

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Figure 20: Speed, Current and Torque Response

The 2-DOF PI controller parameters were designed for the original values of Ra and La. The controllers provided desired closed loop bandwidth using perfect pole-zero cancellation.

With temperature changes, Ra increased; and magnetic saturation decreased La. However, the Speed, current and Torque responses are the same as before. This indicates that the controller is very robust against parameter errors. The PI speed and current controllers have been affected very little by the parameter errors. Although imperfect pole-zero cancellation occurs due to the 2-DOF PI controllers, they are still able to generate precise control commands to track speed, current and Torque references.

1. **Removing Anti-windup from Speed Controller**

The integral action in PI controller is an unstable mode if input error to the controller is large or the input error remains nonzero for a long time. This can cause saturation of controller leading to delayed response. The Anti-windup minimizes performance degradation by accounting for the saturation and reducing integrator input. This prevents the error from accumulating.

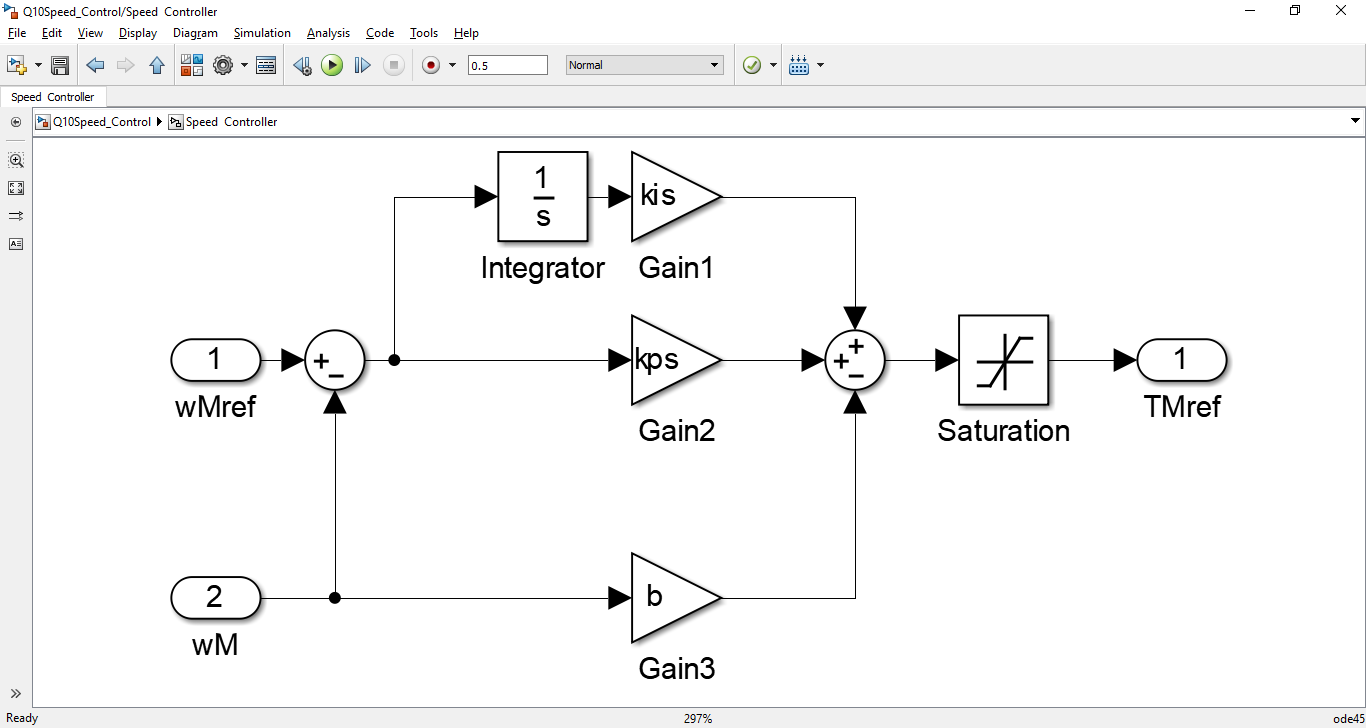


Figure 21: Speed Controller without Anti-windup

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Figure 22: Speed, Current and Torque Response

When the anti-windup is removed, the integrator is not informed about saturating output signal. Hence integrator effect is not fully implemented in the system, because the output gets saturated. The integrator then keeps accumulating the error over a longer period resulting in a delayed response and overshoots in Torque and current references. High oscillations also occur in the speed, current and torque response due to accumulation of error in integrator. The resulting responses are much different from earlier case with anti-windup.

**Conclusion**

The electromechanical equations of permanent magnet DC motor were used to build a Simulink Model. The discrete time solver was able to generate accurate values for per unit current and per unit speed. The results were verified using steady state analysis of the DC Motor. The transient behavior of the DC Motor was verified using the Laplace transform of characteristic equations. Time domain response obtained using inverse Laplace transform matched with the simulation results. Hence the accuracy of the results was confirmed by mathematical results; in the case of voltage step and Load Torque step application. The response was dictated by machine constants like Resistance, Inductance and Moment of Inertia.

The rate limiter caused a voltage ramp to appear at the Motor input. When it was modeled in Laplace domain, the transient response of this input also matched accurately with the simulation results.

Next, the motor was fed from a four-quadrant DC-DC converter, whose DC-bus voltage was 140 V. The Unipolar PWM generated a Square wave voltage whose average value was controlled using its Duty Cycle. Hence the complete range of voltages from 0V to 140V could be supplied to the motor. The results of current and speed were almost the same as the last experiment, where an ideal voltage source was used. Unipolar PWM duty cycle adjustments cause current to oscillate around the mean value. The Moment of Inertia was quite high hence the speed was unaffected by current oscillations.

Two Degree of Freedom PI Current Controller was used to generate voltage reference from given Torque/ Current reference. Its output then drove the PWM. The current controller parameters were adjusted to get desired bandwidth. The Proportional and Integral gains were set to cause pole-zero cancellation.

The speed controller was cascaded with the current controller so block reduction was used in determining the overall transfer function. After the simplification, the outer loop was solved for Proportional and Integral gains. The desired speed response was checked using measurement of rise time.

With temperature changes, Motor parameters changed. However, the Speed, current and Torque responses are the same as before. This indicated that the controllers were very robust against parameter errors. Although pole-zero cancellation was imperfect, the response was still satisfactory.

When the anti-windup was removed, the integrator was not informed about saturating output signal. The integrator then keeps accumulating the error over a longer period resulting in deterioration of controller performance.