

**MIDDLE EAST TECHNICAL UNIVERSITY**

ELECTRICAL AND ELECTRONICS ENGINEERING DEPARTMENT

EE 462-EE 464 COMMON PROJECT

Design of a SM-PMSM Variable Frequency Drive with MATLAB/Simulink

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# 1.Introduction

# 2. Part A: Pre-design Stage

## 1.

We can calculate the base speed of the PMSM from the calculation of voltage on MTPA. The base speed equation in d-q coordinates is written as follows:

In addition, Sinusoidal-PWM modulation is applied to the system. This means that the output voltage is half of the DC voltage.

Also, inductances in the d and q axes are equal to each other in SM-PMSM.

Another situation is that in case of MTPA there is only current on the q axis. The current value on the d axis is zero.

Moreover, flux linkage is given as shown below:

So:

The base speed we found above is electrical. A pole pair is required to find the mechanical base speed. The pole pair is found as follows:

The mechanical base speed is found by the equation given below:

There is a gearbox in the system, with a ratio of 8.5. With the help of the following formula, the mechanical shaft speed which is referred to as the vehicle speed is found.

In the project definition, vehicle speed is expected in km/h. Therefore, we must first multiply the velocity we found in rad/s by the radius. Then we have to multiply by 3600/1000.

## 2.

The maximum speed of the motor is given in the project description.

In order to find the maximum electrical frequency applied, we first need to find the mechanical frequency. So we need to find the maximum speed in rad/s.

Now that we have found the maximum speed in rad/s, we can calculate its frequency as shown below:

As is known, the electrical frequency is greater than the mechanical frequency. The ratio between them depends on the pole pair. The electrical frequency is found as shown below:

The frequency modulation ratio should be chosen as an odd value that is not too high to reduce harmonic effects. In electric vehicles, this ratio is usually chosen between 8 and 12.

As a result, choosing this ratio as 11 would be a good choice.

# 3. Part B: Sinusoidal PWM

In this part, we are expected to implement a motor drive using sinusoidal PWM (Sine-PWM), and implement a cascaded speed and current controller using parameters

## 1.

In this section , firstly , we need to calculate the equivalent inertia and the load seen at the electric machine shaft. Also, there is a single speed gear box connected between electric motor and wheels with 8.5 gear ratio.

The equivalent inertia is found as follows :

We know the inertia on the wheel. But this inertia is on the load side. Therefore, we need to transfer this to the electric machine side with the gear ratio. We can do this as follows:

Now we need to calculate the inertia of the vehicle. Since the result we found will be on the load side, we need to transfer it to the electric machine side with the gear ratio.

Since all inertia values are found and transferred to the electric machine side, the equivalent inertia is as follows:

The load characteristics of the vehicle are given in the project description. Here is given as shown below.

However, we need to calculate the load torque seen at the electric machine shaft. So, to obtain load torque expression, we should multiply the expression of the load force by radius.

Figure 1shows the speed, torque and dq current waveforms during the transition from 35km/h to 40km/h speed. The motor torque is the summation of load torque and the torque resulted from the equivalent inertia. The motor torque reaches the nominal torque of the machine during the transition. The limitation is determined with saturation block used for the iq, quadrature axis current. The reason for reaching nominal torque of the machine is usage of step change of speed. If the reference speed were given with ramp function, the motor torque during the transition could be adjusted. The functionality of controller is sufficient. As seen in the Figure 1, the reference speed and the speed of the car matches after the transition period. Moreover, the reference of id current is given as zero since the motor operates in the base speed region. Hence, MTPA is applied. On the other hand, as shown in the figure below, the transition time is about 0.35 second.

The operating mode of the motor does not change before, after and during the transition. The machine operates in motoring mode.

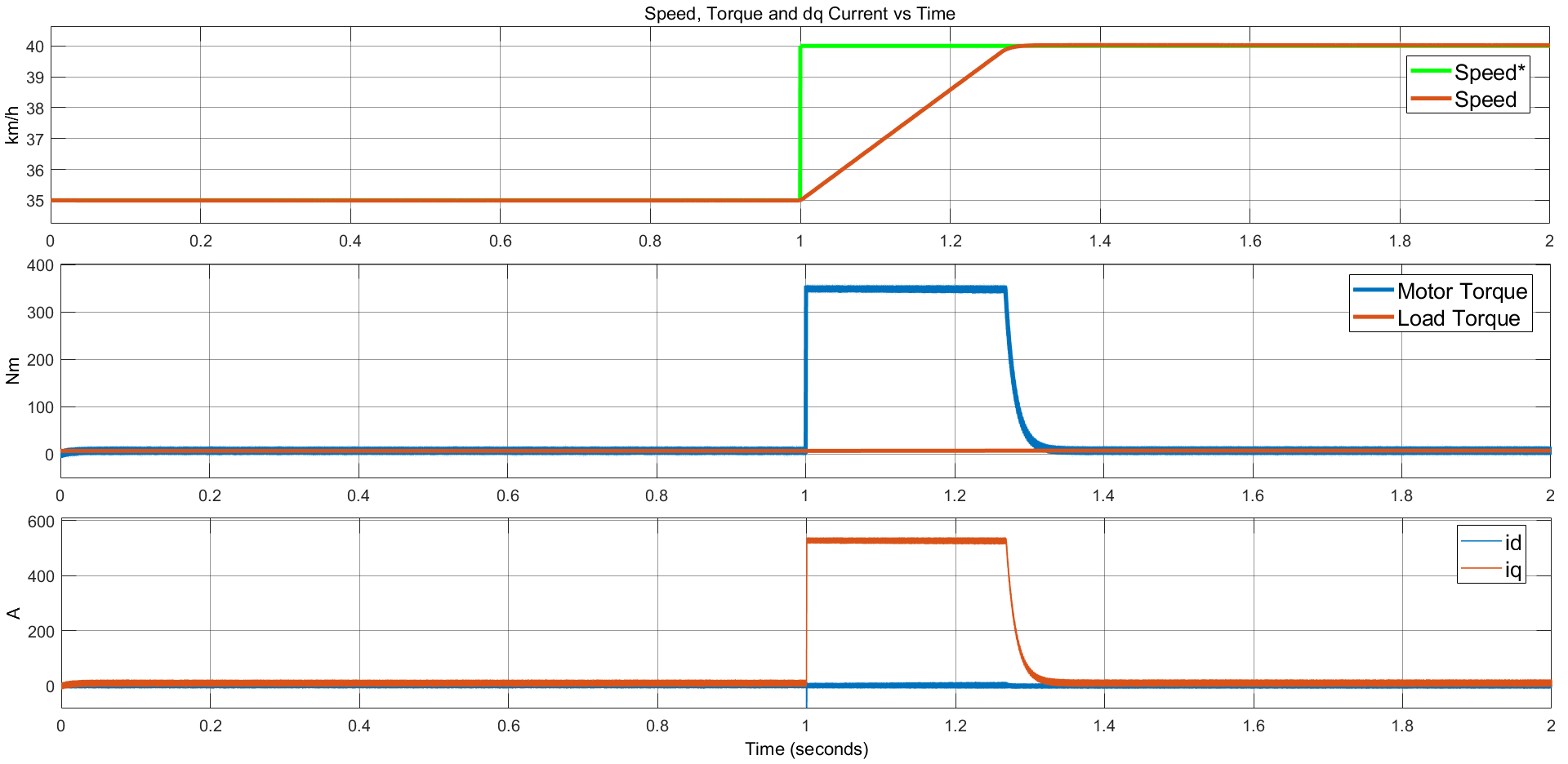
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Figure 1 Speed, torque and dq currents waveforms for step change from 35km/h to 40km/h. KP\_speed =20, KI\_Speed = 0.8.

Figure 2also shows the speed, torque and dq current waveforms during the transition from 35km/h to 40km/h speed. However, the Kp and Ki constants of speed controller are 2 and 0.8, respectively. For the sake of comparison for two different values of proportional constant, the change of Kp constant is applied. According to comparison of Figure 1 and Figure 2, the response time of the system slows down, and overshoot is observed for the case in which Kp is 2. As a result, the response time of the system is increased and observed overshoot is eliminated with respect to change of proportional constant, Kp.

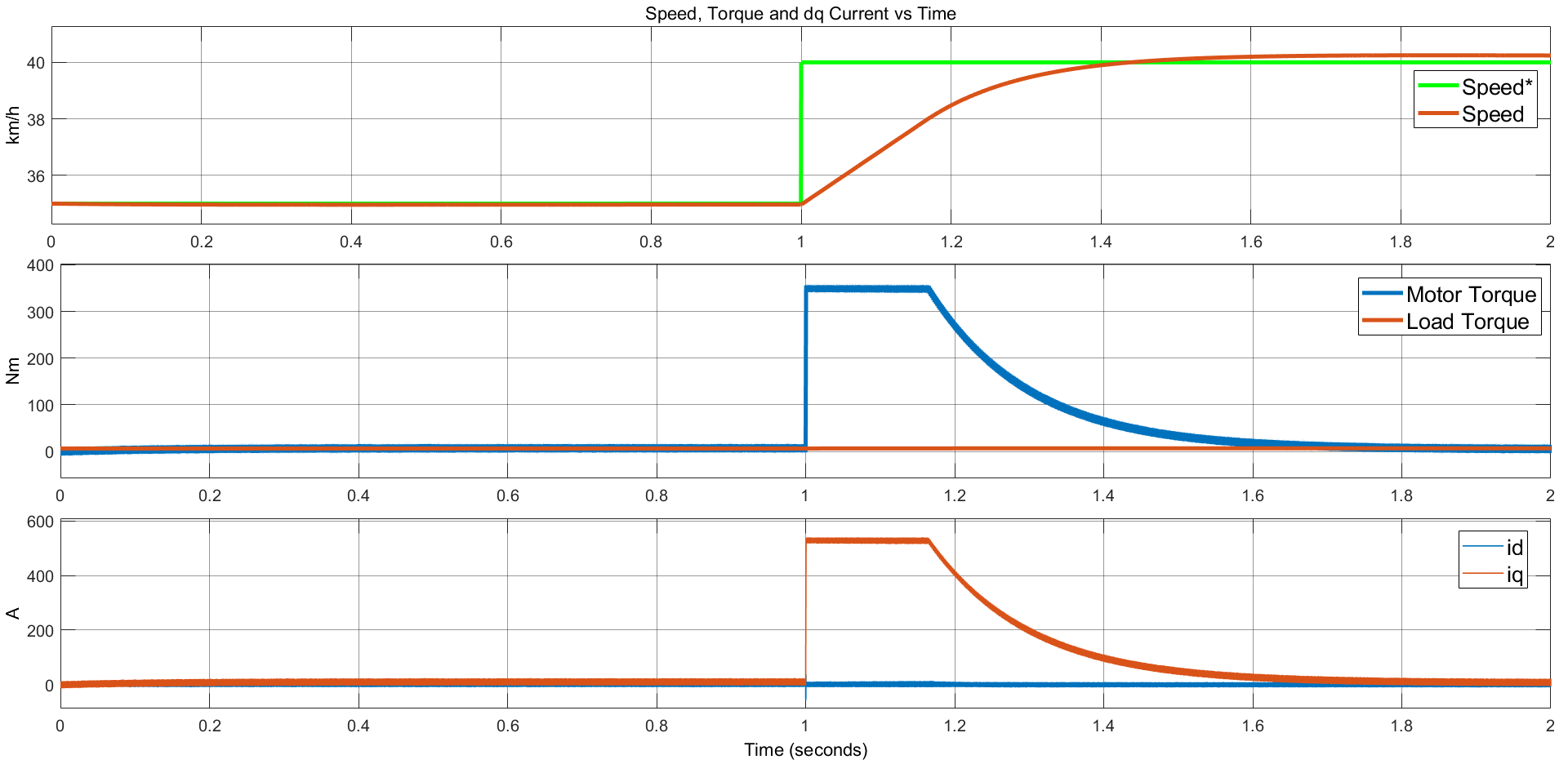
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Figure 2 Speed, torque and dq currents waveforms for step change from 35km/h to 40km/h. KP\_speed =2, KI\_Speed = 0.8.

Figure 3 shows the line-to-line voltage waveforms of the motor. The peak-to-peak voltage value is equal to two times of the Vdc since the voltage measurement is applied between two phases. The peak-to-peak value of the line-to-neutral voltage measurement should be equal to Vdc for the sinusoidal PWM. Since the line-to-line voltage equals to difference of two line-to-neutral voltage, peak-to-peak voltage value of line-to-line measurement is two times of the DC-link voltage. The expected waveforms are shown in Figure 4 and the observed waveforms are matched.

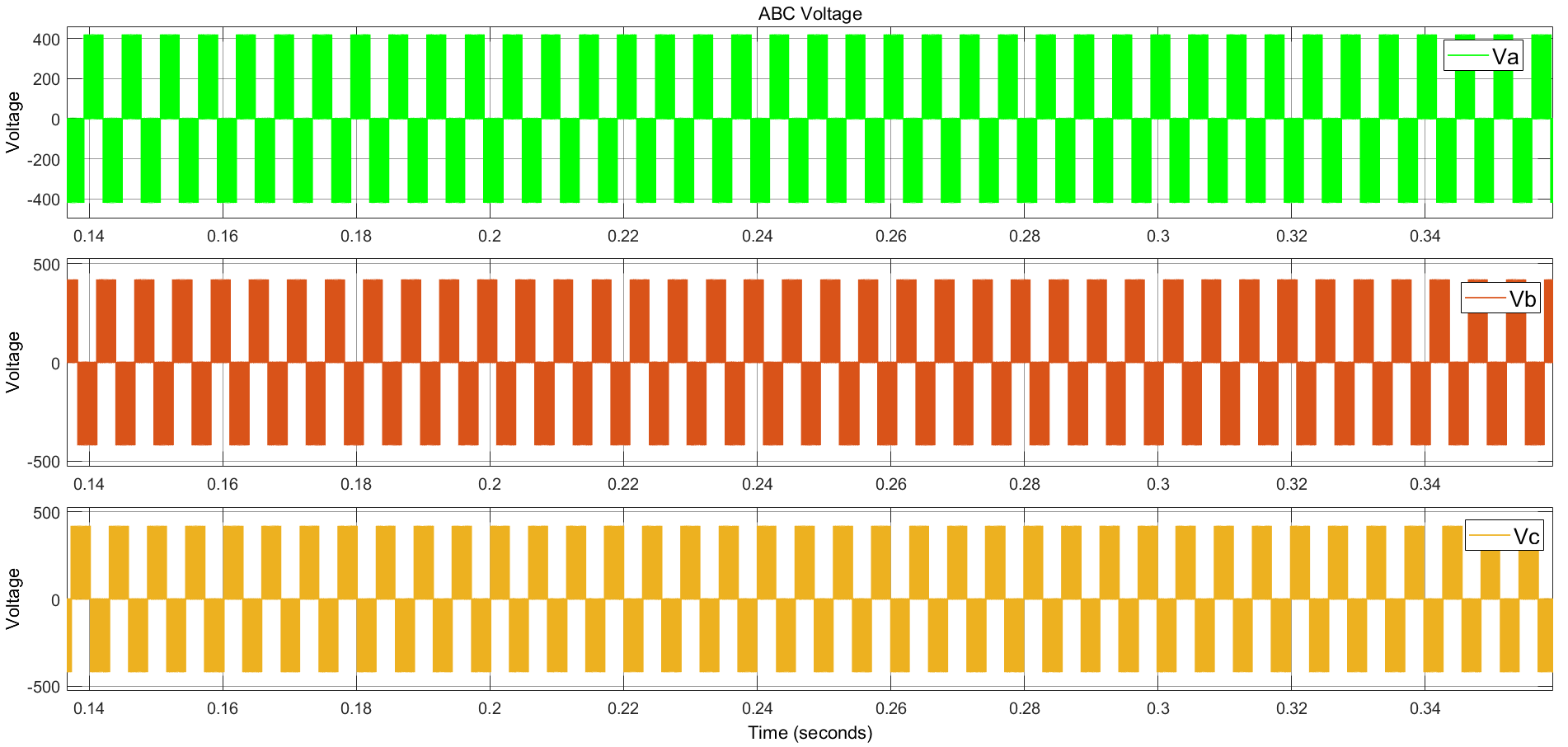


Figure 3 Line-to-line voltage waveforms for step change from 35km/h to 40km/h. KP\_speed =20, KI\_Speed = 0.8.

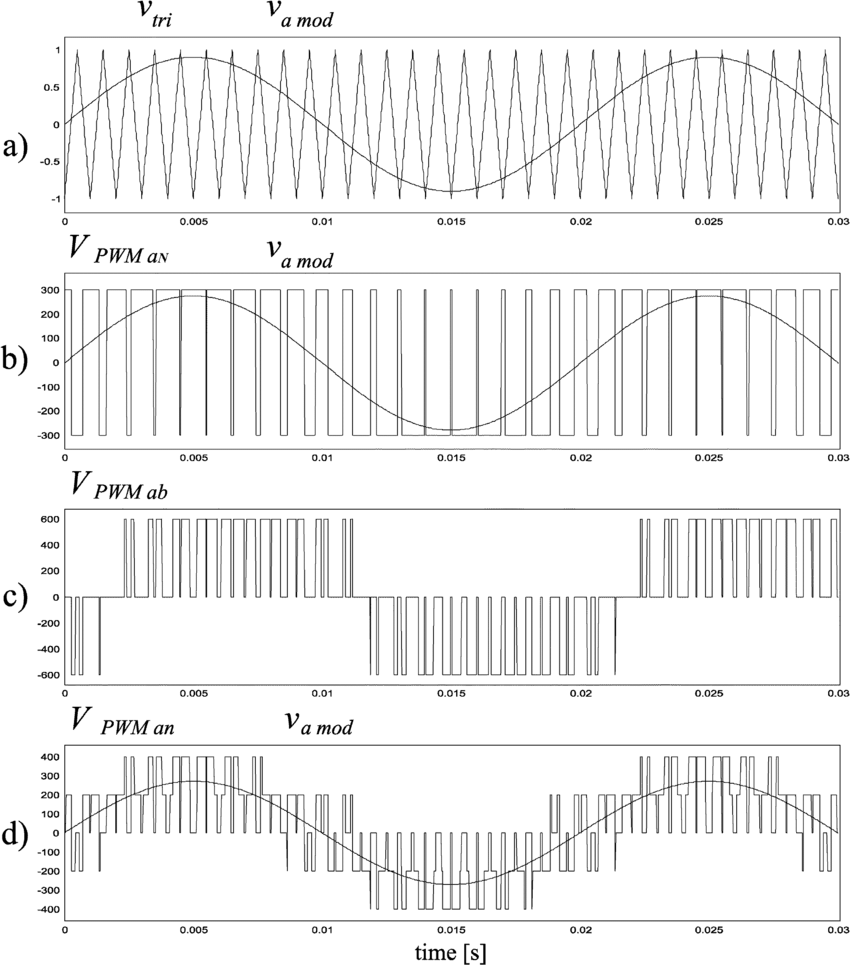


Figure 4 Example line-to-line and line-to-neutral voltage waveforms for sinusoidal PWM

Figure 5 shows the phase currents of the motor during the transition from 35km/h to 40 km/h. The increase in the current at time which equals to 1 second results from the inertia since the step change of speed is applied at that time. The maximum value of the phase current is equal to maximum value of quadrature current due to the amplitude invariant transformation. The waveforms are sinusoidal in Figure 5.

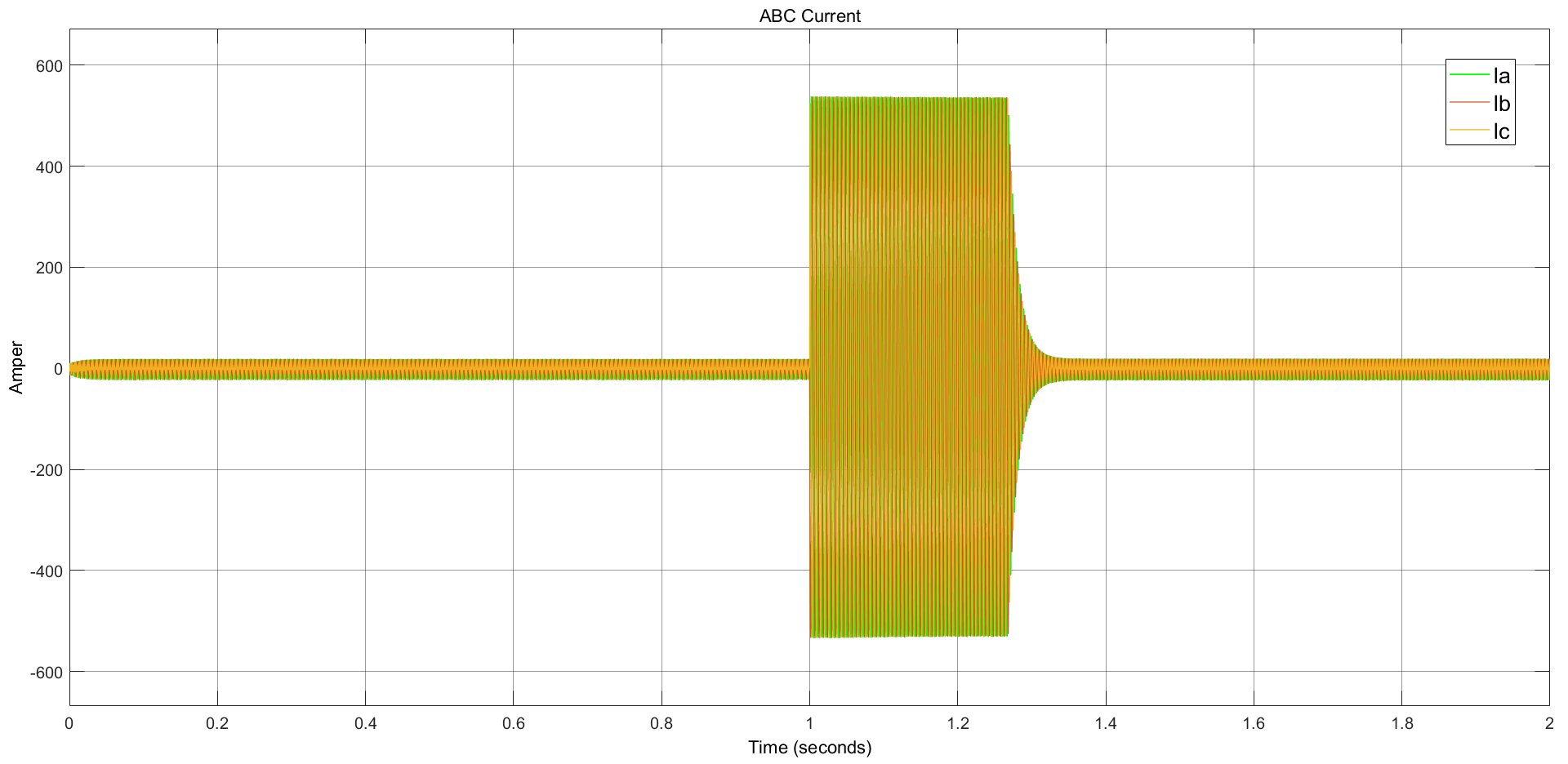


Figure 5 Phase current waveforms for step change from 35km/h to 40km/h. KP\_speed =20, KI\_Speed = 0.8.

## 2.

Figure 6 shows the speed, torque and dq current waveforms during the transition from 40km/h to -8km/h speed. Firstly, the machine works in motoring mode up to the time in which step change of speed is applied and the machine absorbs power in this mode. When the step change of speed is applied the quadrature current diminished from positive value to -530A, nominal current, which implies the machine works in the generating or braking mode. The machine speed is positive, and the torque is negative as implied from the iq current in the 2nd current. In other words, applied voltage is positive and applied current is negative, which implies that the power is dissipated on the brake resistor or supplied to the grid. When the speed of the motor is equal to zero, the sequence of phase voltage changes and machine starts to work in reverse motoring mode. Hence, the power flow is from grid to the motor for reverse motoring mode. The operating modes of the machine for the step change from 40km/h to -8km/h can be seen in Figure 7.

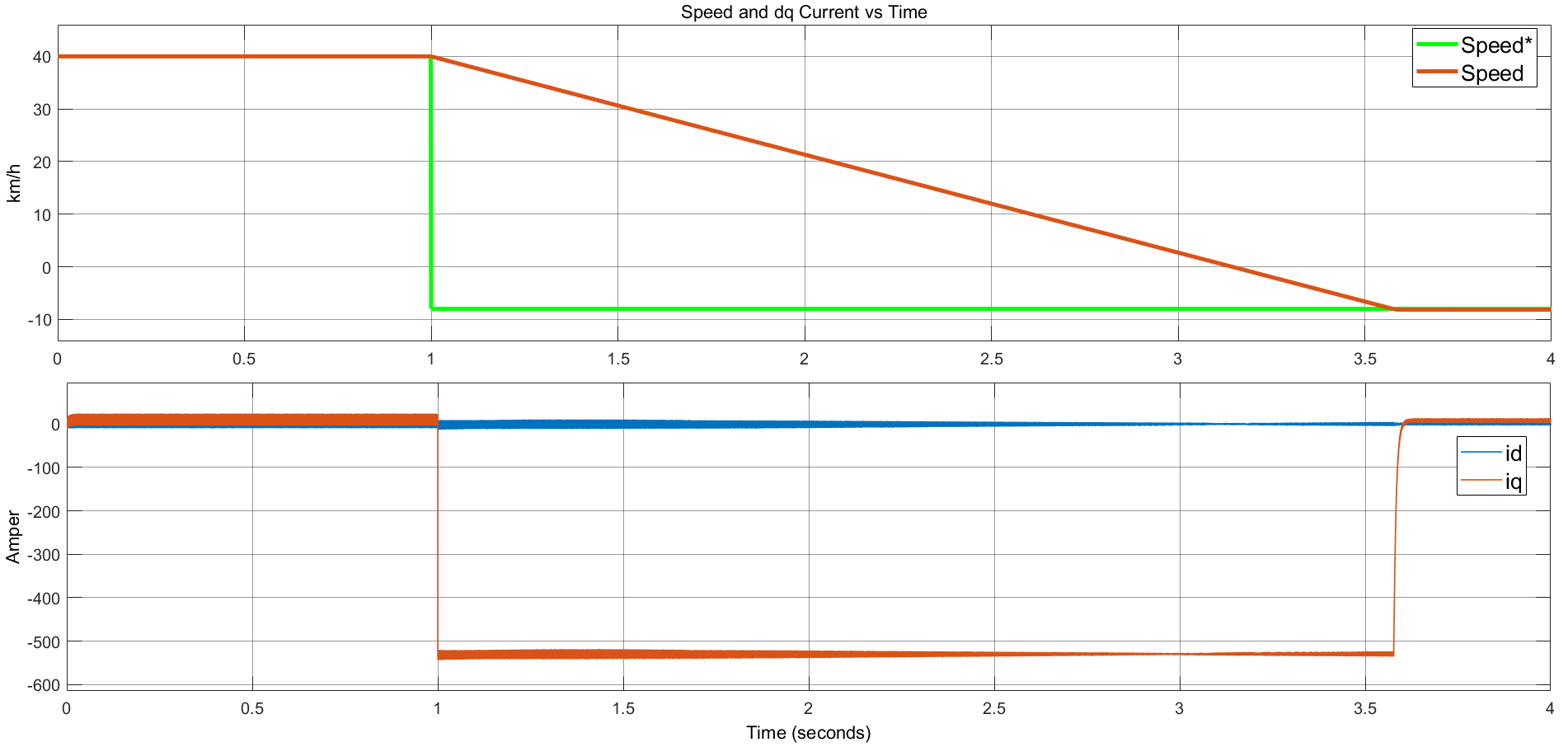


Figure 6 Speed, and dq currents waveforms for step change from 40km/h to -8km/h. KP\_speed =40, KI\_Speed = 0.1.

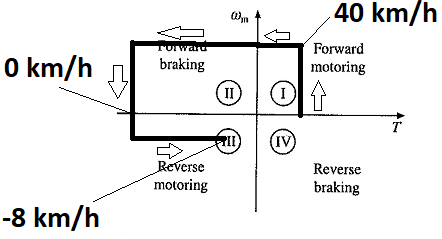


Figure 7 Operating modes of the machine for the step change from 40 km/h to -8 km/h.

Figure 8 also shows the speed and dq current waveforms during the transition from 40km/h to -8km/h speed. However, the Kp and Ki constants of speed controller are 20 and 0.8, respectively. For the sake of comparison for two different values of proportional constant and integrative constant, the change of Kp and Ki constants is applied. According to comparison of and Figure 6 and Figure 8, the response time of the system slows down, and overshoot is observed for the case in which Kp is 20 and Ki is 0.8. The elimination of the overshoot is succeeded with increase in Kp from 20 to 40 and decrease in Ki from 0.8 to 0.1. While increase in the proportional constant makes the system more responsive, decrease in the integrative constant eliminates the error coming from the summation of error between reference speed and measured speed.

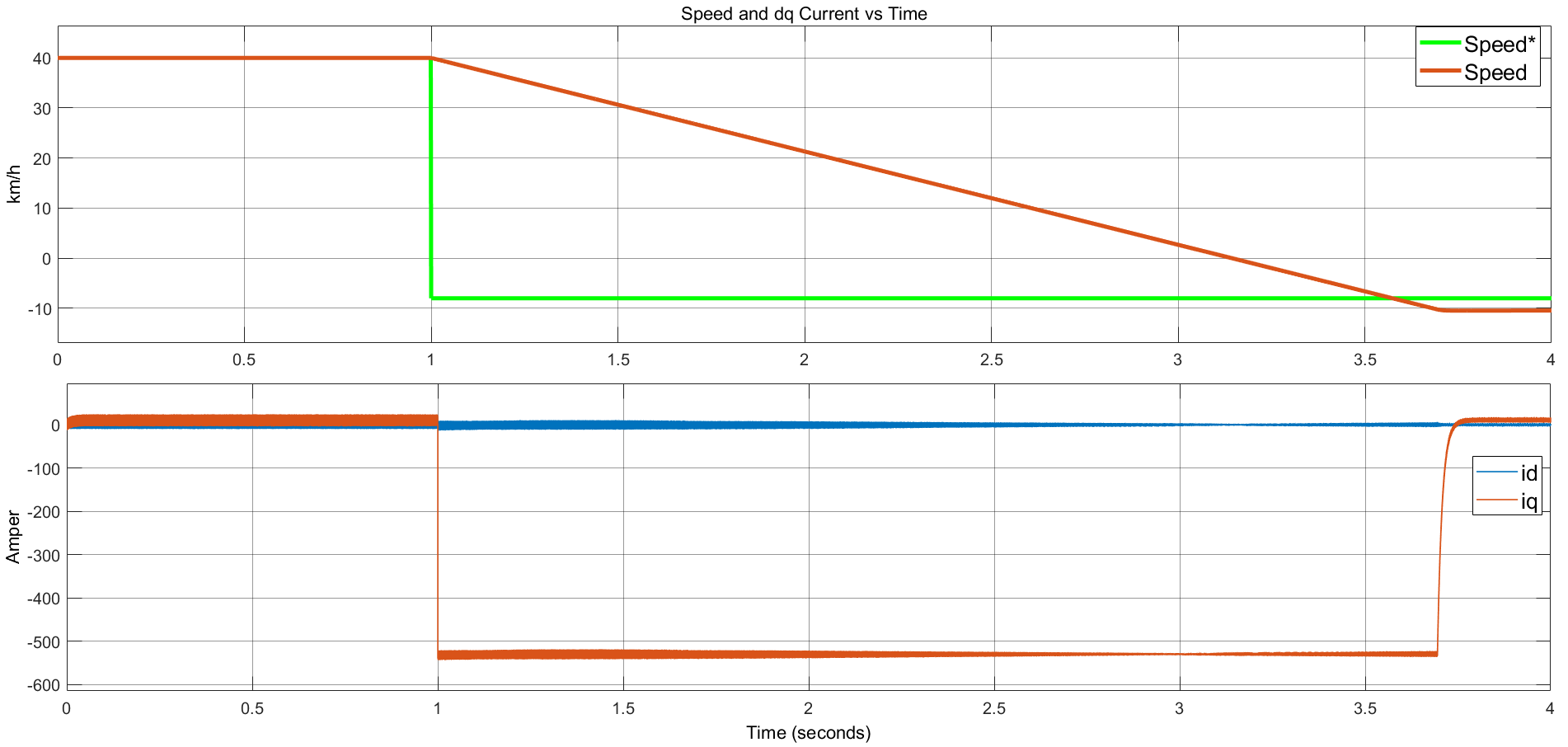


Figure 8 Speed, and dq currents waveforms for step change from 40km/h to -8km/h. KP\_speed =20, KI\_Speed = 0.8.

Figure 9, shows the phase currents of the motor during the transition from 40km/h to -8km/h. The applied step change in speed at t equals to 1 cause that the quadrature current becomes negative nominal current. The negative iq current and positive speed indicates that the braking is applied, which can be also seen by the density of the sinusoidal in Figure 9. As the motor slows down, the period of the phase current increases. When the speed equals to 0, the sequence of phase currents is flipped, and motor rotates in the negative direction. Hence, the machine starts to operate in reverse motoring region. Then, when the motor reaches to -8km/h, the torque due to the inertia becomes zero and the motor torque decreases to the 5.355 Nm.

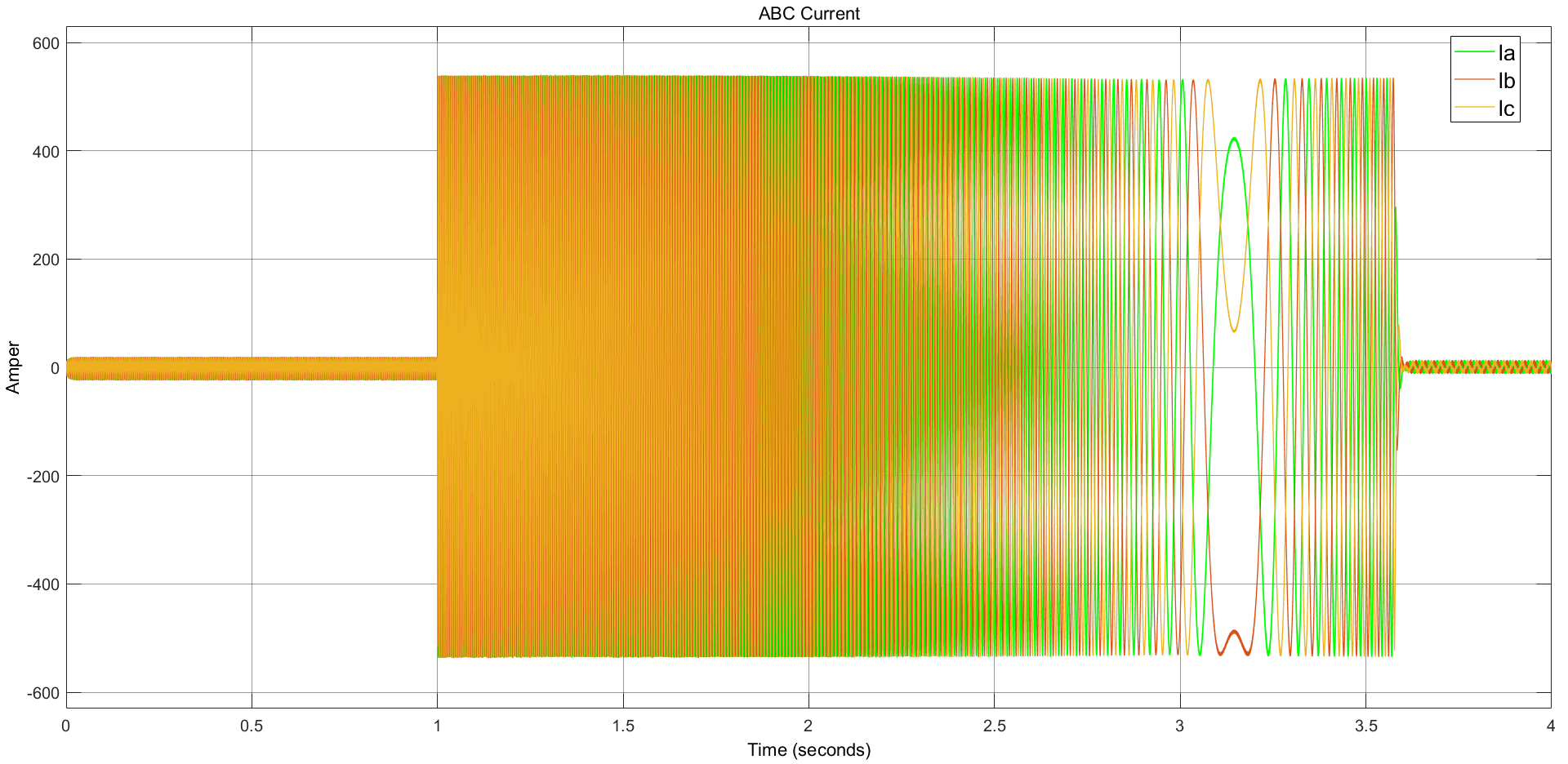


Figure 9 Phase current waveforms for step change from 40km/h to -8km/h. KP\_speed =40, KI\_Speed = 0.1

Figure 10, shows the phase currents of the motor during speed reversal. As known for the rotational MMFs, the direction of rotation can be flipped with change of two-phase sequence, which can be illustrated in Figure 10. The speed reversal occurs approximately between 3.08 and 3.22 seconds. While the phase sequence is green-red-orange before the speed reversal, the sequence of phases changes to green-orange-red.

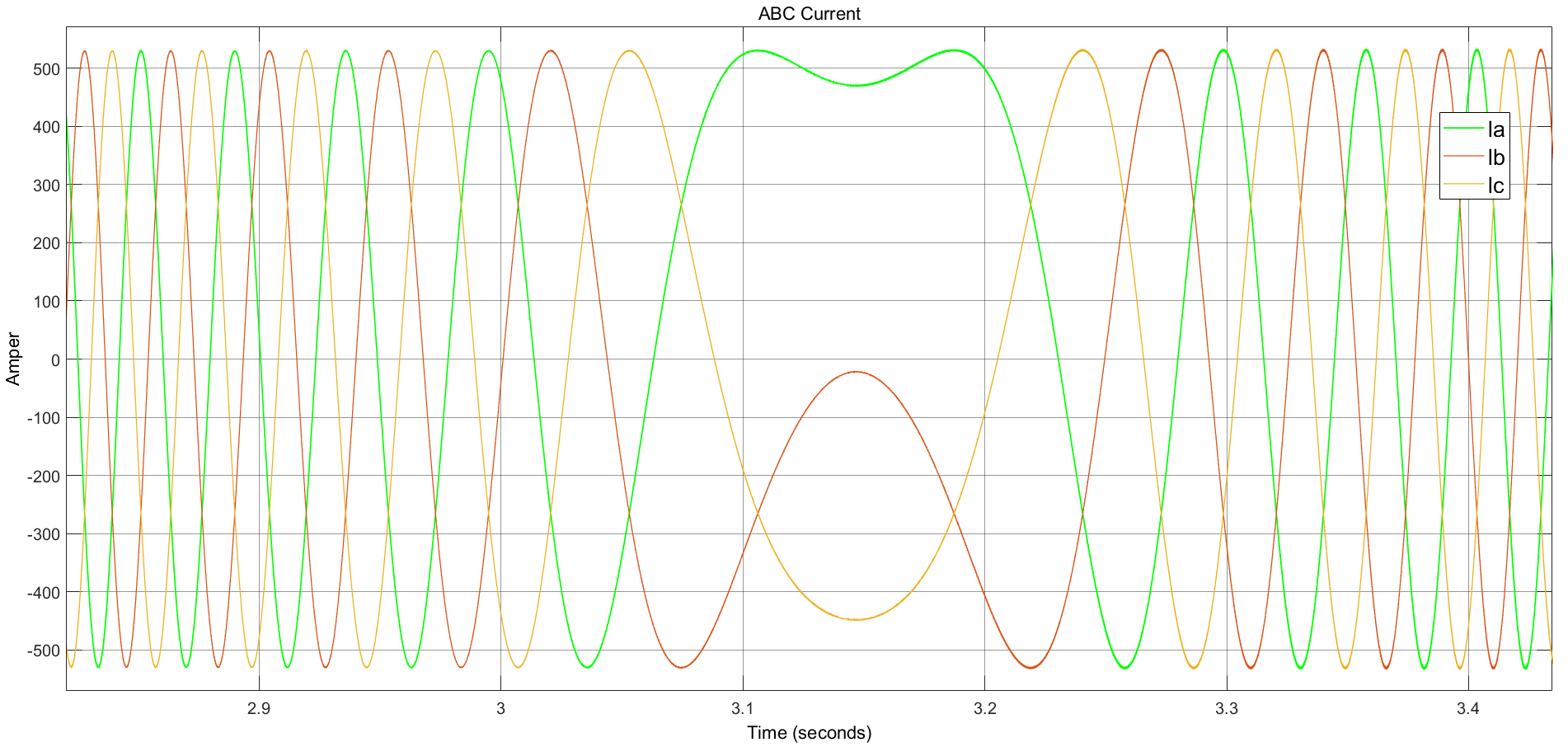


Figure 10 Phase current waveforms during speed reversal for step change from 40km/h to -8km/h. KP\_speed =40, KI\_Speed = 0.1.

## 3.

In this part, first of all, we need to find out in which region our electric motor operates. First of all, we need to find the speed of the vehicle in rad/s and compare it with the base speed. In this way, we can determine in which region it works. If the speed of the vehicle is higher than the base speed, it means that it is operating in the field weakening region. If it is lower than the base speed, it means that it is working in the base speed region. Firstly, we need to convert the speed given in km/h to rad/s.

Now we need to transfer the speed we found to the motor side with the gear ratio.

We previously calculated the base speed. The base speed we found is 342.857 rad/s. We found the speed of the motor as 472.26 rad/s. As it can be understood from here, the speed of the motor is higher than the base speed. Obviously motor is operating in a field weakening region.

Also, we can find by multiplying by the pole pair:

In other words, considering the given conditions, the engine must operate in the field weakening region in order for the vehicle to drive at 60 km/h. It will not be enough to apply only current for the vehicle to drive at this speed. That's why we need to apply current to the system. Since the current is 0 in the base speed region, the vehicle will not be able to reach this speed. As a result, the motor operates in the field weakening region and by applying current along with the current in this region, we ensure that the vehicle drives at the given speed. As a result of this analysis we have done, we need to find and currents. As it is known, the vehicle here is driving at half of the rated torque. So the current will also be halved. current is as shown below.

We can also find the current with the formula given below:

Considering the above analysis results and conditions, we apply 265 A as current and current in the opposite direction to the motor operating in the field weakening region, so that the vehicle can drive at the desired speed.

Figure 10 shows the proposed method for the speed transition from 40km/h to 60km/h without exceeding rated currents. Conceptually, we propose a method how to apply the calculated id\* and how to adjust limitation on the iq\*. The above f(u) block provides the switch with calculated id current based on the phase limit equation. Then, if the calculated id is negative, switch output gives calculated id\*. If not, switch gives zero as a reference. The below switch may be trivial, but it placed to make it understandable. Function of the below switch is determination of whether the speed is above or under the base speed. If above, the output of the above switch is given as id\*. If not, id\* becomes zero. The bottom f(u) block determines the maximum iq\* with respect to calculated nominal current. For instance, if the id\* equals to zero, the limit of iq\* is equal to nominal current, 530A. Moreover, the power is also considered not to exceed power limit. Power of the machine is calculated according to we, electrical speed of rotor and the torque. The MATLAB function block compares both values from the f(u) and gain block represents the inverse model of the torque. Then the smaller limit is provided as iq\_limit.

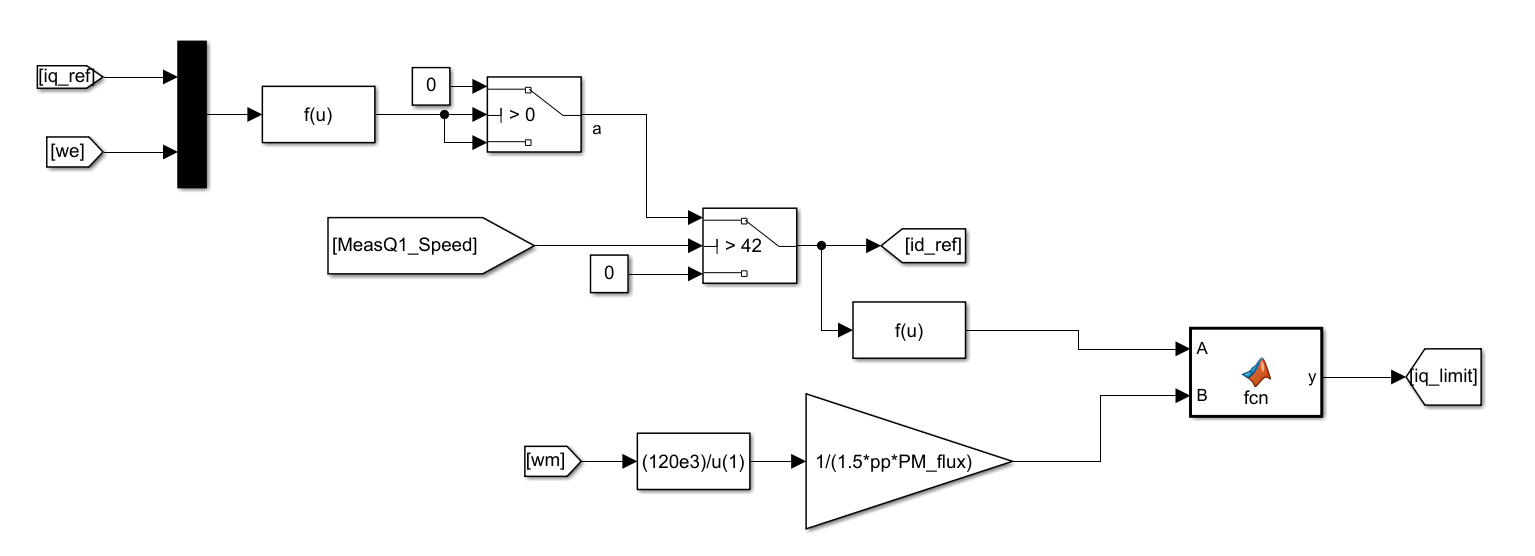


Figure 11 Simulink blocks for closed-loop control of speed transition from 40km/h to 60km/h with field-weakening

Figure 11 shows how the calculated iq\_limit is applied to saturation block.

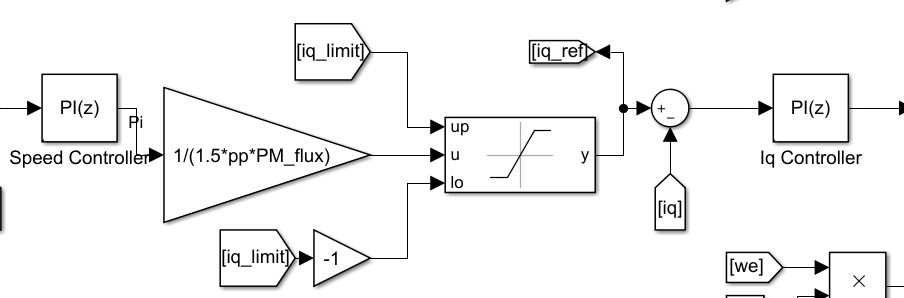


Figure 12 The method for applying iq\_limit to saturation block of iq.

Figure 12 shows the speed and dq current waveforms for the step change of 40km/h to 60km/h at the half of the rated torque, 175Nm. As expected, apply of negative id current is a must not to apply over-modulation. When the step change is applied at time equals to 1, the id\* current is still given as zero since the the rotor speed is smaller than the base speed. On the other hand, iq reached to the nominal current when the step is applied. Then, the iq current starts to decrease when the rotor speed is equal to the base speed for the sake of power conservation of the machine. The point id\* becomes negative is calculated according to the formulation below. Then, the steady-state values of iq and id current reach 265A and -47.23A as calculated above, respectively, which represents the the current values final condition. The initial values of iq and id is simply 265A and 0A. As we see, the id current has no contribution on torque for SM-PMSM.

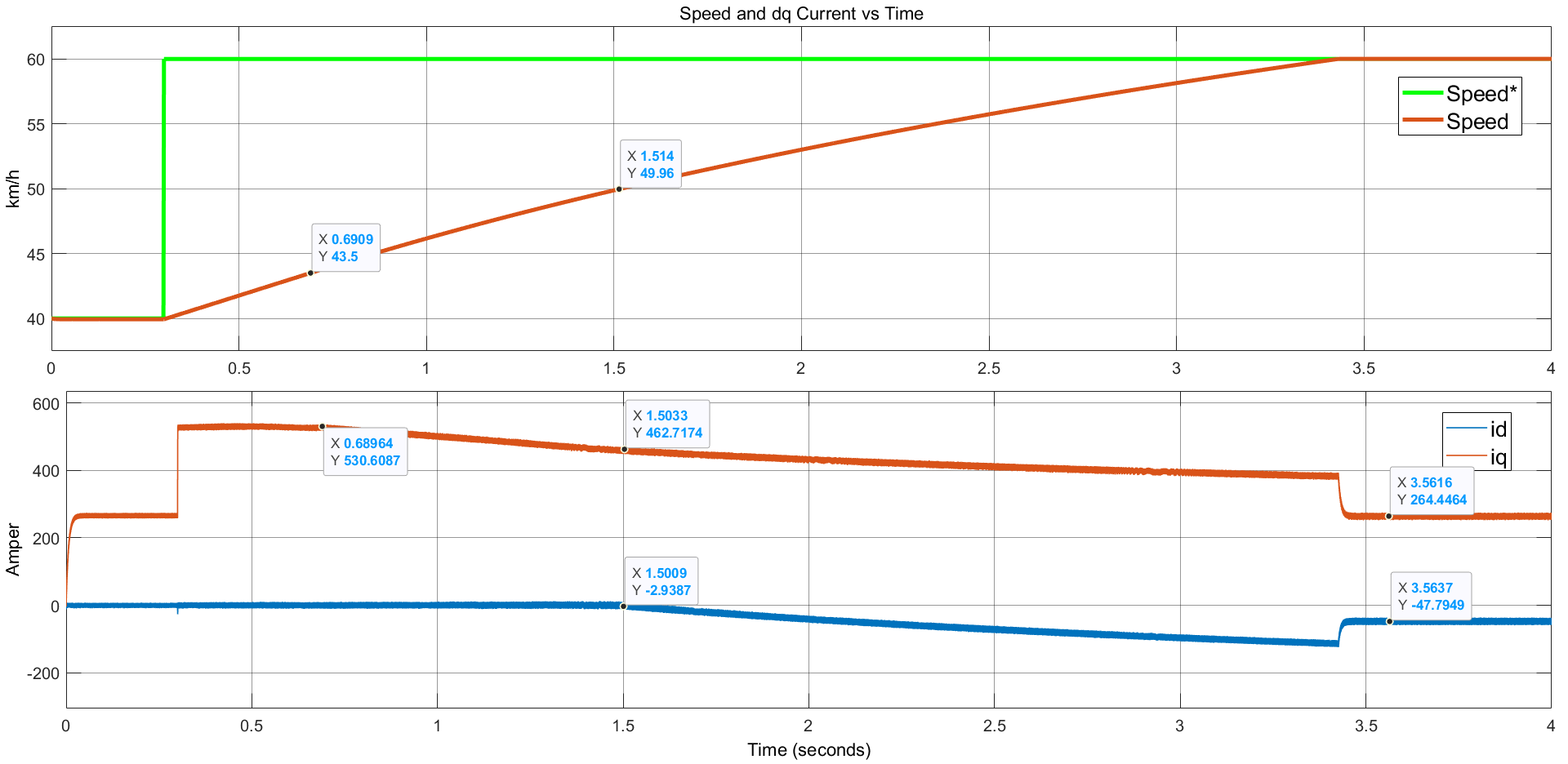


Figure 13 Speed and dq current waveforms for the step change of 40km/h to 60km/h at the half of the rated torque.

The following explanations are solely explained what we have learned with different approach. This approach does not consider the power conservation of the machine. The calculation of id\* is the same as above solution. However, determination of iq\_limit is done with just consideration of phase voltage limit. Therefore, the negative id current start to be applied at 47.469km/h as seen in Figure 14. Also, Figure 14 shows that the required id and iq current for initial and final conditions are the same as the theoretically calculated values.

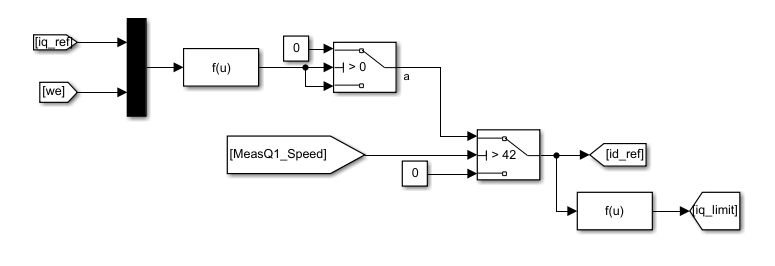


Figure 14 Simulink blocks for closed-loop control of speed transition from 40km/h to 60km/h with field-weakening. Power conservation is not taken account.

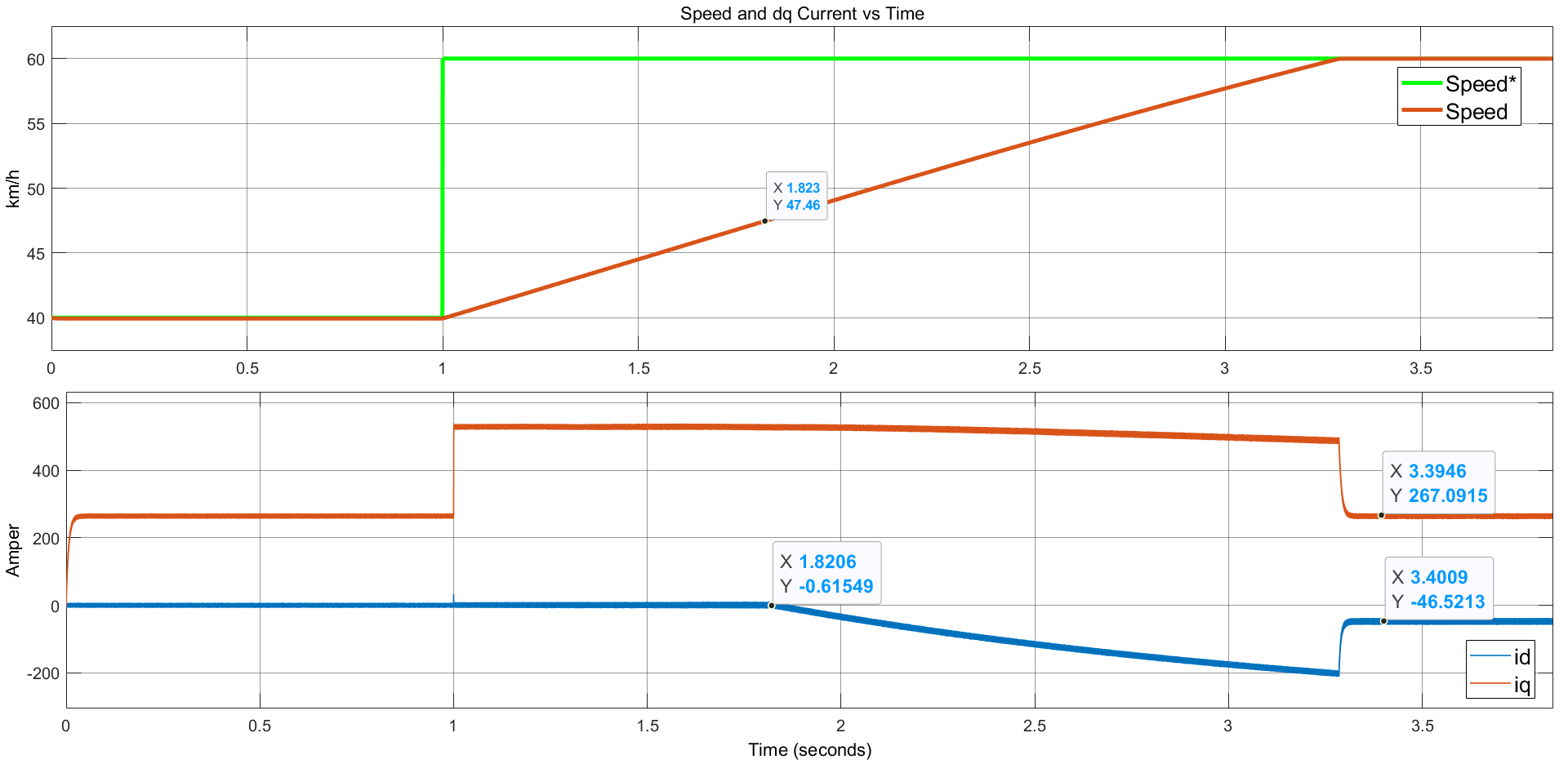


Figure 15 Speed and dq current waveforms for the step change of 40km/h to 60km/h at the half of the rated torque. Power conservation is not taken account.

# 4. Part C: Component Selection

# 5. Part D: About the Project