Tesla's Sudden Acceleration Log Data – What It Shows

by

Ronald A. Belt
Plymouth, MN 55447
1 May 2018

Abstract: Accelerator pedal sensor data from the log file of a Tesla S sudden acceleration incident is provided, and a Tesla circuit diagram is used to explain how the data is obtained from the two accelerator pedal position sensors. Examination of the data shows that the accelerator pedal sensor output increased to cause the sudden acceleration. But the increase in the accelerator pedal sensor output could not have been caused by the driver. Instead, the increase in the accelerator pedal sensor output appears to have been caused by a fault in the motor speed sensor, with which it shares a common+ 5V power and ground. This increase in pedal sensor output occurs without the driver pressing on the accelerator pedal. An explanation of how this increase can occur is provided, yielding a testable theory of sudden acceleration in Tesla vehicles. The theory applies to all Tesla S and Tesla X vehicles as a result of commonality in the design of their traction motor/inverter assemblies.

I. Introduction

Reports of sudden acceleration incidents involving Tesla S and Tesla X vehicles have become a common occurrence in the news over the past several years. Almost every month there is a new account of a Tesla vehicle crashing through the wall of a home garage, a storefront, a school, or the side of a building adjacent to a parking space. Although most of the incidents involve only minor damage to the structures and no loss of life, they often involve significant damage to the Tesla vehicle. Occasionally, the damage to both vehicle and structure is much more extensive, with reports of vehicles crashing completely through a fence or a wall and into a dance studio, a restaurant, an exercise facility, or a home swimming pool. The news accounts of these incidents usually report that the driver maintained he/she did not cause the accident by stepping on the accelerator pedal. But the same news accounts often add that Tesla has determined from the vehicle log data that the incident was caused by the driver pressing on the accelerator pedal instead of the brake. As a result, reader comments following these news reports are highly critical of the drivers, asserting that they were either careless, too old to drive, or unfamiliar with operating such a high performance vehicle as a Tesla automobile. Occasionally, a skeptical reader may question whether the log data for the incident is incorrect or misinterpreted, but this skeptic is quickly silenced by a tidal wave of readers who, without even seeing the data, claim that the incident was caused by pedal confusion. As a result of this withering feedback, the driver disappears from public view, keeping silent his/her firm opinion that the incident was caused by the vehicle.

It is interesting that within hours of a sudden acceleration incident Tesla usually provides the following statement to all reporters of the incident, even before contacting the driver:

> *"We take the safety of our customers very seriously and we're glad our customer is safe. We investigate the vehicle diagnostic logs in every accident in which a driver claims their car "suddenly" and "unexpectedly" accelerated, and in every case the vehicle's diagnostic logs confirm that the vehicle operated as designed. Accidents involving "pedal misapplication," in which a driver presses the accelerator pedal by mistake, occur in all types of vehicles, not just Teslas. The accelerator pedals in Tesla vehicles have two redundant sensors that clearly show us when the pedal is physically pressed down, such as by the driver's foot."*

Notice that no log data is provided in this statement. If the driver or the authorities later question the statement, then Tesla may respond with a partial description of the log data, saying that "the log data shows the driver pressed on the accelerator pedal, causing the output to read X% of the maximum in the first Y seconds". But only when the driver or authorities threaten Tesla with a law suit, will Tesla provide the complete accelerator/brake log data for the last five seconds leading up to the incident. In this case, the complete log data will be provided only to the requestor, and not to the general public. This makes it impossible for independent researchers to determine whether Tesla's interpretation of the data is correct. Therefore, some people have suspected that Tesla is covering up the cause of these incidents in order to protect its financial interests.

In this paper, the author has obtained the complete accelerator pedal sensor log data for a sudden acceleration incident from a driver who got the log data from Tesla during a telephone conversation. The Tesla engineer gave a detailed description of the log data to the driver, who then provided it to the author. The author then plotted this data to create the figure used in this study. We will now take a look at this log data.

II. Log Data for a Sudden Acceleration Incident

Figure 1 shows the accelerator pedal sensor data logged during a Tesla S sudden unintended acceleration incident. The driver maintained that her foot was not on the accelerator pedal at any time during the incident. Above each peak and valley are the amounts that the accelerator pedal is being pressed in percent of maximum travel, where maximum travel means pedal floored. The durations of the pressing are shown in seconds. Beneath the peaks the vehicle speed is shown in red in miles per hour. At t = 3.5 seconds when the crash occurred, the power to the drive motor was turned off as the vehicle was going at 15 miles per hour. It can be inferred from the data that the inverter logic and sensors continue to operate as before the crash. Amplitude data was not provided for the two peaks after the crash. After the crash the vehicle was stationary for five seconds before the brake pedal was applied.

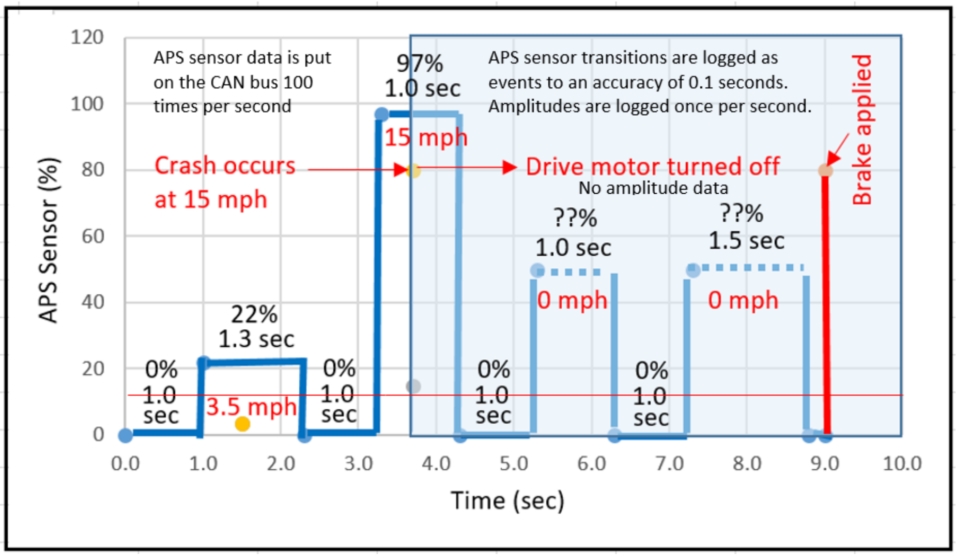

Figure 1. Accelerator pedal sensor data for a sudden unintended acceleration incident

Tesla engineers interpreted the peaks in the data as the driver causing the sudden acceleration incident by pressing on the accelerator pedal. But this does not explain the zero-amplitude periods of one second duration between the periods of higher amplitude. These zero-amplitude periods were explained by Tesla engineers as the driver alternately pressing on the accelerator pedal and releasing the accelerator pedal; i.e., "stabbing" at the accelerator pedal. Note that the time periods of the peaks and valleys are accurate to 0.1 second. There is no way that a human driver can produce four time periods of exactly one second duration accurate to 0.1 second by alternately pressing and releasing the accelerator pedal. Therefore, the author began to look for an alternative way to explain these periods of zero amplitude by some malfunction of the electronic circuitry. One suspicion was that the four time periods of zero amplitude are caused by some integrated circuit component going into reset.

Since the 0.1 second accuracy of these accelerator sensor transitions is important to interpreting the data as not being caused by a human driver, we will take a look at how these transitions and amplitudes are measured. This is done with the help of the wiring diagram for a Model S motor drive inverter obtained from Tesla as shown in Figure 2. Figure 2 shows that two accelerator pedal position (APP) sensors are used by the inverter. The outputs of both sensors go to analog CPU inputs where they are sampled by an A/D converter at a rate of 100 samples per second. The amplitudes of the two sensors are then compared and, if they differ by more than a specified tolerance, the vehicle drive power is disabled and a diagnostic trouble code (DTC) is set. If the amplitudes of the two sensors agree, then the common amplitude is used by the inverter's control system to adjust the torque of the drive motor. This high speed amplitude data is then down-sampled or averaged at a rate of one sample per second for logging by the vehicle's data logging system. The analog output from one of the APP sensors is also converted into a fast rise-time digital signal and inserted into a digital CPU input, where it punches a time clock that provides the time of the transition. The transition times are measured to an accuracy of 0.1 second. The transition data is used only as a check on the amplitude data to declare the amplitude data as valid while the accelerator pedal is being pressed down. It is not used by the control system of the motor drive inverter.

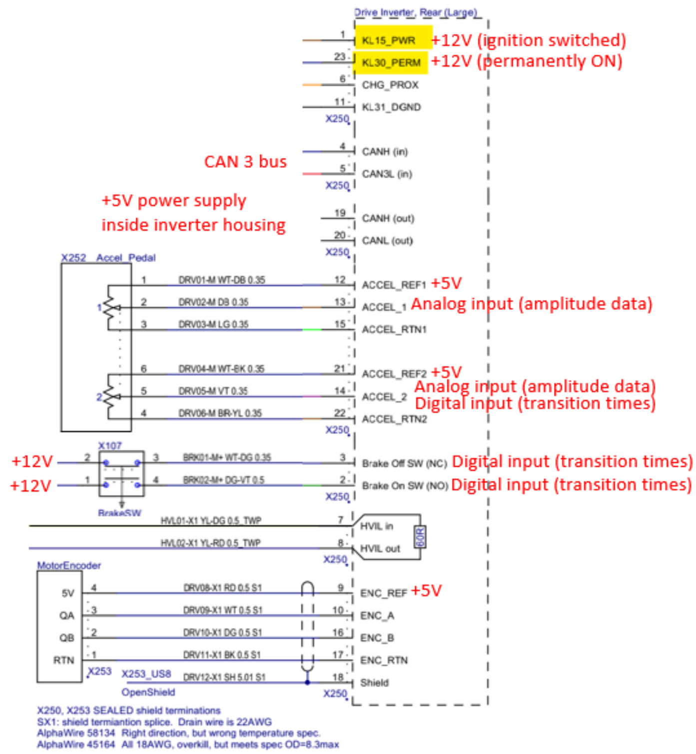

Figure 2. Wiring diagram a Tesla S motor drive inverter.
Author's notations are shown in red.

Figure 2 shows that a motor speed encoder is also used by the inverter, having a +5V supply and GND input and two digital outputs giving the speed. There is also a brake switch having a +12V input and two digital outputs. One of the outputs is normally ON while the brake pedal is released and transitions to OFF when the brake pedal is pressed down. The other output is normally OFF and transitions to ON when the brake pedal is being pressed down. This action provides an exclusive OR function that can be used by the control system as a redundancy check to tell that the brake is being applied.

The wiring diagram of Figure 2 obtained from Tesla does not provide any detail of the functions used within the motor drive inverter. Since Tesla will not provide any further information about these functions, we must find some other way to understand how these components operate.

III. Inside the Motor Drive Inverter Circuitry

From a basic understanding of how the electronic control circuitry is designed in other automobiles, it is possible to draw a block diagram of the major inverter functions as shown in Figure 3. Figure 3 shows that the major inverter functions are a CPU controller, a DSP FOC motor drive controller, IGBT drivers, a CAN bus controller, and one or more +5V regulators. To the inverter block one can then add the external accelerator pedal sensors, motor speed sensor, 12V inverter, and 440 volt drive battery with contactor as shown in Figure 3. In creating Figure 3 it was assumed that the two accelerator pedal sensors and the motor speed sensor share the same +5V regulator and GND. This is standard practice on all modern automobiles even though it compromises the fault tolerance of the dual accelerator pedal sensors. The CPU, DSP, and CAN bus controller were given a separate +5V inverter and GND.

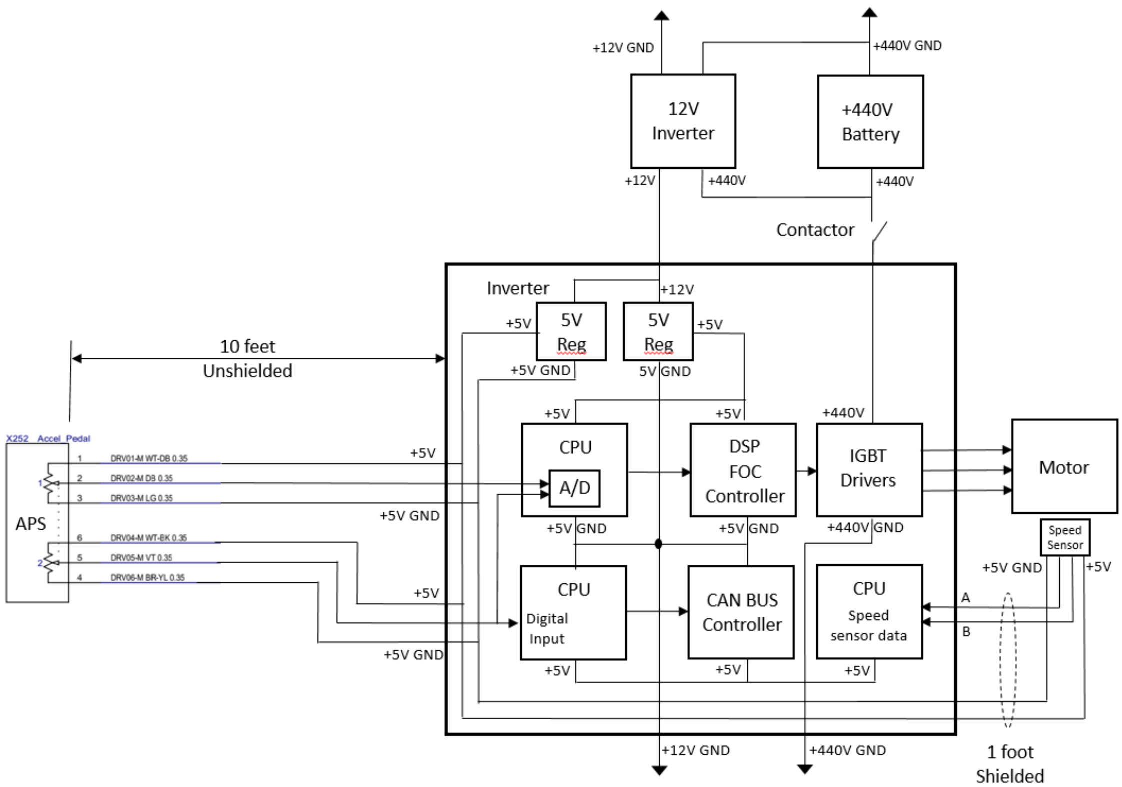

Figure 3. Block diagram of the major functions inside the motor drive inverter

After creating this figure, the author began to consider how one might explain the logged accelerator sensor data. After mulling over the figure, it became apparent that the peaks in the logged accelerator data might be explained by a rise in the APP sensor GND voltage. The valleys, on the other hand, might be explained by the +5V APP sensor voltage regulator going into reset with a 1.0 sec reset time. The fall in the APP sensor signal after the +5V sensor regulator goes into reset can be detected because the CPU remains functional as a result of its separate +5V power supply. A quick check of +5V regulator specifications showed that +5V regulators can have widely varying reset times that are either fixed by design or adjustable by the user via external capacitors. The rise in the APP sensor GND voltage may be explained by an increase in the APP sensor GND current acting on the parasitic resistance in the APP sensor GND line. But the cause of the increase in the APP sensor GND current must still be found.

The first thought was that maybe some stray current from the IGBT drivers was getting into the APP sensor GND line. However, this could not explain why APP sensor transitions in Figure 1 still occur after the 440V power is shut off. Therefore, it was concluded that the 440V drive circuit is not the cause of the APP sensor output transitions and is not the cause of the sudden acceleration.

The next thought was that maybe the additional current in the APP sensor GND line was caused by an increase in the current drawn by the motor speed sensor. After all, the motor speed sensor shares the same +5V supply and GND with the two APP sensors. If its GND current increases as a result of an increase in the speed sensor's temperature, then this can explain the rise in APP sensor GND voltage. This becomes even more obvious when one considers that the motor speed sensor is located inside the traction motor housing, whose temperature can increase to very high temperatures during normal vehicle operation. The traction motor temperature gets so high during normal operation, that water cooling must be used to keep the motor bearings from failing prematurely. So, it appears that the leakage current of the motor speed sensor inside the motor housing can potentially explain the increase in APP GND current as a result of the motor temperature rising. A more detailed look can be more helpful.

A detailed circuit diagram of the essential components is shown in Figure 4. Figure 4 shows that when the temperature of the motor speed sensor increases, the increased sensor leakage current I_L through the parasitic R_{GND} causes the ground voltage to rise due to the voltage drop across R_{GND}. This, in turn, causes the APP sensor output signal to rise without the accelerator pedal being pressed. A rise of 100°C in the motor speed sensor temperature can cause a rise of 10^3 times in the sensor leakage current, producing a rise in the APP sensor output voltage of up to 5 volts with a stray resistance of only a 1-10 ohms in the ground line. When the leakage current gets too high, the +5V regulator powering the APP and motor speed sensors is shut off for a fixed amount of time. Voltage regulators can have widely varying reset times that are either fixed by design or adjustable via external capacitors. The voltage drop across R_{GND} will not be noticeable (< 5 mV) when the current through the motor speed sensor is only a few milliamps at room temperature. The circuit of Figure 4 can therefore explain the increase in the APP sensor output without the driver pressing on the accelerator pedal. A closer look at the motor speed sensor will help to understand the source of the temperature-dependent leakage current.

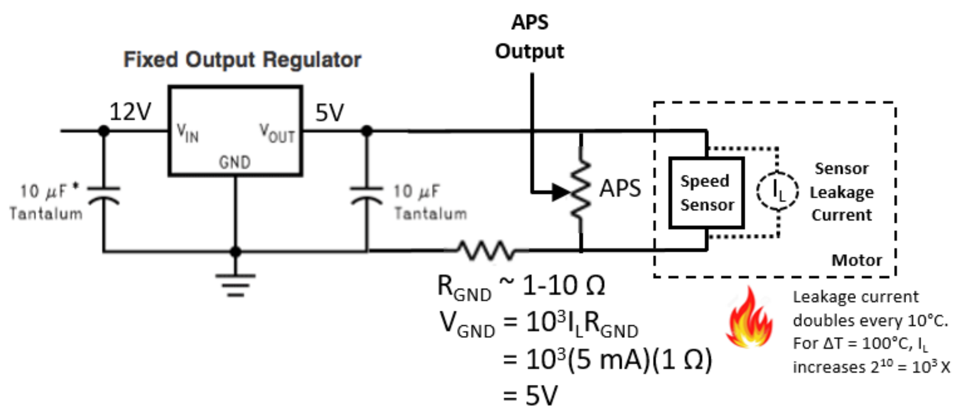

Figure 4. Circuit diagram showing essential components affecting the output of the accelerator pedal sensor (APP)

IV. Motor Speed Sensor Construction and Operation

The motor speed sensor used by Tesla is a Hall motor encoder that has a +5V power and GND and two digital outputs. It is made using two Hall effect switches as shown in Figure 5. Each Hall effect switch is a small printed circuit board containing a Hall effect sensor, some output signal processing circuitry, and a regulator for powering the Hall effect sensor and the signal processing circuitry. The output signal processing circuitry consists of a high gain amplifier for amplifying the small sensor output voltage, a Schmitt trigger circuit for converting the analog Hall signal to a digital output, and an output drive transistor, which can be either a bipolar transistor or an NMOS transistor. The output can be made compatible with any standard I/O interface circuitry, such as TTL, CMOS, or open collector by using external components. The figure shows how an external pull-up resistor can be used to make the digital output compatible with standard TTL circuitry.

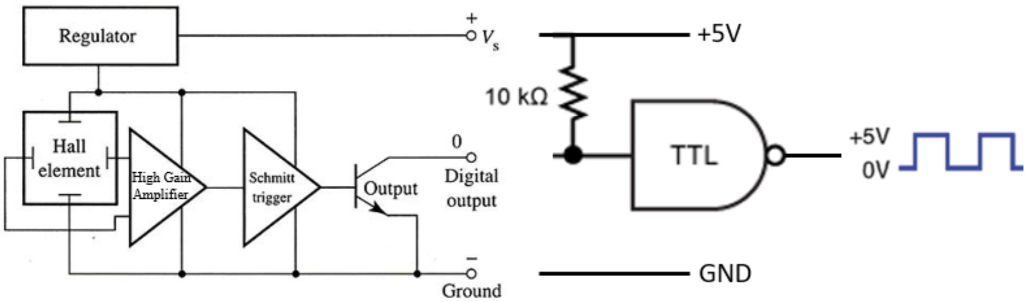

Figure 5. Hall effect switch with digital output

Two Hall effect switches are used to make a motor encoder as shown in Figure 6. The switches are placed 90° apart inside the traction motor housing so they can sense the alternating north and south magnetic fields embedded into a special ring pressed on the same shaft as the motor's rotor. The magnetic fields are sensed through a small air gap that is only a few millimeters wide. The two digital outputs produce two square wave signals as shown in Figure 7. By examining the time sequence of the peaks in these two square wave signals, the motor control circuitry can determine both the motor speed and the direction of rotation. Rotational position of the motor is not sensed, and must be determined by the motor control algorithm.

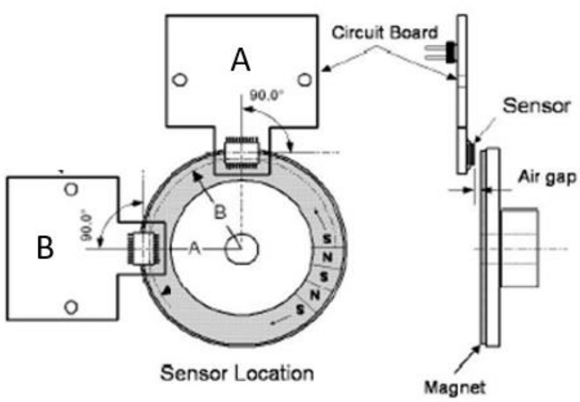

Figure 6. Two Hall effect switches 90° apart are used to make the motor speed encoder.

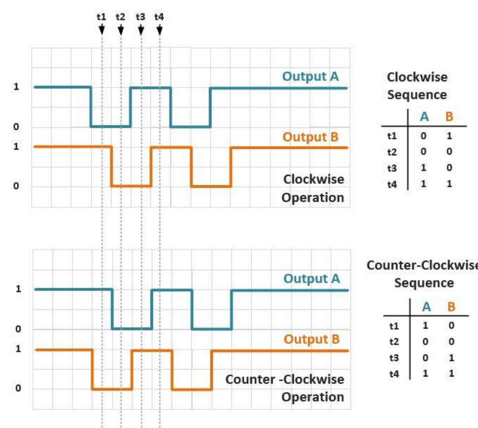

Figure 7. The two digital outputs can be used to sense the motor's speed and direction of rotation.

Figure 5 shows that the leakage current that increases with temperature is caused not only by a Hall effect sensor, which is essentially an isolated resistor, but also by a high gain amplifier, a Schmitt trigger circuit, an output transistor, and a voltage regulator, all of which are complex integrated circuit functions comprised of many active semiconductor components. All of these components must be electronically isolated from each other using reverse-biased semiconductor junctions, which can cause a leakage current that varies with the temperature. The leakage current will double with every 10°C rise in temperature. Therefore, a rise in temperature of 100°C can cause an increase in leakage current of $2^{10} = 10^3$ times, or enough to go from one milliamp to one amp. This increase of leakage current with temperature will occur even though the devices are specified to remain operable at temperatures of up to 150°C because the devices can remain functional even when the leakage current gets quite high. It is only when the leakage current gets so high that the isolation junctions become forward biased that the functionality of the device ceases. At this point, the leakage current will suddenly increase to an even higher value that is not limited by the device itself. This will cause the external +5V regulator to go into reset.

V. **Summary of Proposed Theory of Sudden Acceleration**

We have now discussed all the essentials for explaining the accelerator pedal sensor data in Figure 1. Our explanation can be summarized as follows:

A. Theory assumptions:
   1. The two accelerator pedal sensors and the motor speed sensor share the same +5V regulator and ground.
   2. The inverter logic devices, CAN controller, and DSP FOC motor controller, use a different +5V regulator and ground than the accelerator pedal sensors and motor speed sensors.
   3. The parasitic resistance of the +5V ground line between the 12V ground and the accelerator & speed sensors is on the order of 1 to 10 ohms.

B. Known facts:
   1. The motor speed sensor is composed of two Hall switches.
   2. The two Hall switches are located inside the motor housing of the traction motor, exposing them to the high temperatures attained by the traction motor. Traction motor heating occurs faster when the vehicle is operated at low speeds and in the regen mode.
   3. The leakage current of the two Hall switches in the motor speed sensor increases as a result of their temperature being raised by heating of the traction motor. The Hall switches remain operational as their leakage current rises to the point where the reverse-biased isolation junctions in the Hall switches become forward biased. At this point their functionality ceases and the leakage current increases without bound.
   4. Speed sensor functionality and leakage current becomes normal again when the motor temperature decreases after the vehicle is turned off.

C. Theory predictions:
   1. As a result of assumptions 1-3 and facts 1-4, an anomalous increase in the accelerator pedal position sensor output can be produced without the driver pressing on the accelerator pedal. Specifically,
      a. The anomalous increase in APP sensor output voltage is caused by a voltage drop in the APP sensor ground line as a result of the temperature-dependent speed sensor leakage current passing through the parasitic ground resistance. As the temperature of the drive motor increases, the motor speed sensor leakage current increases, causing the output of the accelerator pedal sensor to rise. This creates the peaks in the accelerator sensor output shown in Figure 1.
      b. As the leakage current continues to increase, at some point the reverse biased isolation junctions in the Hall effect switches become forward biased, causing a huge increase in the Hall encoder leakage current. At this point the +5V regulator powering the APP sensor and the motor speed sensor goes into reset, causing the APP sensor output to fall to zero as shown by the transitions at t = 2.3 sec, 4.3 sec, and 6.3 sec in Figure 1.
      c. The +5V regulator stays in reset for a fixed amount of time, creating the four periods of zero sensor output lasting for exactly 1.0 seconds accurate to 0.1 second as shown by the peaks in Figure 1.
      d. After the 1.0 second reset time is over, the +5V regulator turns on again, causing the motor speed sensor to turn on again. The leakage current of the motor speed sensor starts to rise again, making the APP sensor output rise again. This is shown by the upward transitions in Figure 1 at t = 3.3 sec, t = 5.3 sec, and t = 7.3 sec.
      e. The sequence a) through d) repeats until the vehicle is shut off by shutting off the +12V supply that powers both +5V regulators.

2. The increase in accelerator pedal sensor output created by the above mechanism causes the vehicle to accelerate without the driver's foot being placed on the accelerator pedal. For the first peak in the accelerator pedal data of Figure 1 the effect is the same as the driver pressing on the accelerator pedal.
    a. But when the accelerator pedal sensor signal falls at t = 2.3 sec in Fig 1, as a result of the APP sensor voltage regulator going into reset, the power to the motor speed sensor is turned off while the motor is still running at a non-zero speed.
    b. As a result, the FOC motor controller loses knowledge of the motor speed, causing the motor control algorithms to lose knowledge of the rotor position.
    c. The result is that during the valleys of the pedal sensor output shown in Figure 1, while the motor speed sensor is turned off, the FOC motor control algorithms become unstable, causing the motor speed to increase in an uncontrolled fashion. This increase in motor speed is not shown in Figure 1. But it is shown in Figure 8 below, which shows actual measured and estimated results for a speed sensor failure in real AC induction motor controlled by a DFOC algorithm as used by Tesla in all their vehicles.[1]
    d. During the peaks of the sensor output shown in Figure 1, the motor speed sensor is turned on again, allowing the FOC algorithm to adjust to the new higher motor speed sensed by the motor speed sensor.
    e. The result is that, as the accelerator position sensor output cycles up and down causing the peaks and valleys shown in Figure 1, after the first peak the motor is no longer under the control of the accelerator pedal position sensor, but continues to increase in speed due to instability of the motor control algorithm. The result is sudden unintended acceleration without the driver's foot being on the accelerator pedal.

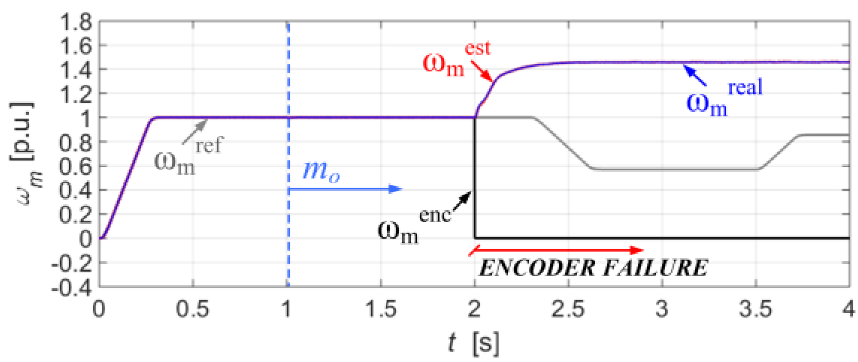

Figure 8. Measured motor speed (ω_m^{real}) and estimated motor speed (ω_m^{est}) for a total failure of the speed sensor in a real ACIM motor controlled by a DFOC structure, as used by Tesla in all their vehicles. The drive is started from zero speed and brought up to the nominal speed of 1 power unit, then at t = 1s a load m_0 is placed on the motor. The speed sensor failure occurs at t = 2s, when the motor speed sensed by the motor speed encoder (ω_m^{enc}) changes from ω_m^{ref} = 1 power unit to 0 power units. At this time the measured and estimated motor speeds increase from one power unit to 1.4 power units as a result of instability in the DFOC algorithm.[1]

The explanation just provided for the accelerator pedal sensor log data in Figure 1 explains how the peaks and valleys in Figure 1 are created during a sudden acceleration incident without the driver pressing on the accelerator pedal. But it is also possible that sudden acceleration without driver input can occur without having peaks and valleys in the log data. The same explanation applies to these incidents if one considers that the magnitude of the leakage current produced by the motor speed encoder is sufficient to cause an increase in the ouput of the two accelerator pedal position sensors, but is not high enough to cause the isolation junctions of the encoder to become forward biased, which makes the +5V regulator go into reset. The sudden acceleration in this case is produced entirely by the anomalous increase in the output of the accelerator pedal sensors without the driver pressing on the accelerator pedal, and not by absence of a motor speed signal causing instability in the motor control algorithm. The accelerator pedal sensor log data in this case will show a continuous increase in the pedal sensor outputs without the valleys of zero amplitude as shown in Figure 1.

VI. A Fix for Sudden Acceleration

Sudden acceleration cannot be eliminated merely by preventing the output of the accelerator pedal position sensor from rising as a result of an increase in the motor speed sensor leakage current, which can easily be accomplished by using separate +5V regulators for the two types of sensors. This does not work because the motor speed sensor leakage current will still rise with temperature until the reverse-biased isolation junctions become forward biased, causing the +5V regulator to go into reset. This turns off the motor speed sensor, leaving the FOC motor control algorithms without rotor position control, and causing algorithm instability with an inevitable sudden increase in motor speed. The result is sudden acceleration without an increase in the accelerator pedal position sensor output.

The same reasoning applies to using different +5V regulators for the two accelerator pedal position sensors. This does not work because it does not address the real cause of the sudden acceleration; namely, the leakage current of the motor speed sensor.

The authors of the paper in reference 1 propose a fault tolerant solution to the loss of a motor speed sensor in a situation similar to Tesla's. Their solution is to compare the speed sensed by the external motor speed sensor to the motor speed estimated by a speed-sensorless DFOC motor control algorithm. The motor power is then turned off when the two speed values differ by greater than some pre-determined value. This will cause the vehicle to lose power in much the same way an internal combustion engine does when the electronic throttle goes into the limp-home mode. The suddenness of losing drive torque due to turning off the motor power suddenly may cause a problem if done while driving at high speeds. But this suddenness may be an advantage in preventing damage in tight situations like parking lots with people and structures close by.

Of course, a better solution would be to have a motor speed sensor that does not create as much leakage current as the present sensor. This might be possible if a semiconductor technology other than bulk silicon is used, such as gallium arsenide or silicon-on-insulating substrate. But a motor speed sensor using these more exotic technologies is at least several years in the future.

VII. Conclusion

Real accelerator pedal sensor data from the log file of a Tesla S sudden acceleration incident has been provided. After giving an explanation for how the data was obtained from the two accelerator pedal position sensors, the data was examined. It was concluded that changes in the accelerator pedal sensor output caused the sudden acceleration. The alternating peaks and valleys in the accelerator pedal sensor data appeared to show that the driver was stabbing at the accelerator pedal. This led Tesla engineers to conclude that the driver was the cause of the sudden acceleration. But the four valleys indicating that the accelerator pedal was released had a duration of one exactly second accurate to 0.1 second. This accuracy in the duration of four successive pedal release times could not have been caused by a human driver. Instead, the peaks and valleys in the output of the accelerator pedal sensor appear to have been caused by a thermally induced leakage current in the motor speed sensor, which is housed inside the hot drive motor housing, and which shares a common+ 5V power and ground with the accelerator pedal position sensor. An explanation of how this leakage current originates, and how it increases the output of the accelerator pedal position sensor while the accelerator pedal is released by the driver, was provided. The explanation reveals that the four identical pedal release times are caused by the +5V regulator powering the accelerator pedal and motor speed sensors going into reset at high temperature, turning off the sensors for a fixed time duration of exactly one second. While the motor speed sensor is turned off, the algorithms controlling the vehicle's drive motor become unstable, causing the motor speed to increase without control. This causes sudden acceleration to occur without the driver pressing on the accelerator pedal. This explanation provides a testable theory of sudden acceleration in the Tesla S vehicle. The theory applies to all Tesla S and Tesla X vehicles as a result of commonality in the design of their traction motor/inverter assemblies.

VIII. References

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[1] Kamil Klimkowski and Mateusz Dybkowski, "*A Fault Tolerant Control Structure for an Induction Motor Drive System*", Automatika, Journal for Control, Measurement, Electronics, Computing and Communications, Volume 57, (2016), p638-647.