A Cause of Sudden Acceleration in Battery Powered Electric Vehicles

by

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Abstract: A cause of sudden acceleration in a generic class of battery-powered electric vehicles (BeV's) is discussed. The cause is associated with the voltage compensation algorithm used in all such vehicles to correct the motor operating point for changes in DC link voltage that accompany changes in the state of charge (SOC) of the high voltage battery. Normally this battery voltage compensation causes an increase in the motor speed of 25% or less. But when the battery voltage is sensed during a negative voltage spike caused by the inrush current of an electric motor turning on, then an incorrect DC link voltage reading results that causes the standard compensation algorithm to increase the motor speed by over 300x. This condition persists until another DC link voltage reading is taken many minutes later. In the meantime, the motor operating point associated with a released accelerator pedal is suddenly increased to an operating point in the field weakening region. If the motor stator voltage then exceeds the incorrectly sensed DC link voltage of the high voltage battery, then an unstable condition exists in the control electronics in which control of the motor operating point is lost. The motor torque can then increase without control, resulting in sudden unintended acceleration without the driver pressing on the accelerator pedal.

Introduction

This paper discusses a cause of sudden acceleration in a generic class of battery-powered electric vehicles (BeV's) having similar design features. By discussing the operation of a generic class of vehicles, design features that cause sudden acceleration can be discussed without naming any specific vehicle manufacturer or any specific vehicle model in the paper. This guarantees that the paper will not cause financial damage to any specific vehicle manufacturer that might elicit a cease and desist order demanding removal of the paper from publication under threat of being sued for damages to the manufacturer's reputation and stock price. Such an order can be used by vehicle manufacturers to eliminate discussion of potential defects in their vehicles while claiming that their vehicles have no such design defects and while benefitting from media articles from friendly authors and postings from friendly users that blame the driver for sudden acceleration.

The class of vehicles to be discussed in this paper has the design features listed below. These features can be found in vehicles from multiple vehicle manufacturers, avoiding the implication that they narrow the class to a single vehicle manufacturer. This suggests that sudden acceleration in BeV's is an industry-wide problem, and not just a problem for a single vehicle manufacturer.

Control system features of vehicles in this class:

1) Two or more pedal position sensors are used to convert the driver's depression of the accelerator pedal into a voltage input to the vehicle control system.
2) A pedal map converts the accelerator pedal position sensor output into a motor torque request.
3) An inverse motor map converts the motor torque request into (i_d*, i_q*) current commands or (torque*, flux*) commands needed to operate the motor at the desired torque and speed.

4) Field oriented control (FOC) algorithms are used to control the motor (i_d, i_q) currents to the reference (i_d*, i_q*) or (torque*, flux*) commands.
5) Motor control algorithms vary with the motor speed region.
6) Vehicles with multiple electric motors use a torque distribution system between the pedal map and the inverse motor map to distribute the total vehicle torque as needed between front and back electric motors as well as between left and right rear motors if used.

Electric drive motor features of vehicles in this class:

1) Drive motors consist of interior permanent magnet synchronous motors (IPMSM). Other motor types such as induction motors (IM) or surface permanent magnet synchronous motors (SPMSM) are also possible, but are used less often.
2) Torque dependence on speed varies with motor speed region.
3) Torque depends only on motor current in the region below base speed.
4) Field weakening is required when operating the motor above base speed.
5) Voltage limiting is required when operating the motor at the highest speeds.
6) Motor operated in regen mode provides negative torque to slow the vehicle.
7) Slowing down with regen instead of brake recharges battery and increases driving range
8) Regen torque provides deceleration levels of about 0.2 to 0.3 G.
9) Regen allows one pedal driving.
10) One or more electric motors are used per vehicle.
11) Some vehicles in this class control regen with the brake pedal instead of the accelerator pedal. This changes regen operation, but does not change the motor control features.
12) Exception not included in this class:
    a) Hybrid vehicles add an internal combustion engine to either recharge the battery or to apply torque in parallel or in series with the electric motor.

Battery features of vehicles in this class:

1) Vehicle battery consists of:
    a) Modules internally wired as a parallel combination of strings of battery cells with multiple cells in each string wired in series.
    b) Cells strung in series within a module provide a module voltage of about 40V to 50V that is intermediate between the cell voltage and the full battery voltage.
    c) Parallel strings within a module provide a much higher module current than a single cell.
    d) Modules in series provide the desired vehicle battery voltage and current.
2) Vehicles have a similar high voltage DC battery voltage of 400V maximum or 360V average. A battery voltage of 800V maximum is also possible in this class, but its use is limited by the availability of components having a higher breakdown voltage.
3) Battery voltage varies with battery state of charge (SOC).
4) Vehicles have a similar battery voltage range of 300V to 400V for the 400V battery.
5) An inverter powered by the DC battery bus provides three-phase AC voltages to the motor's stator windings while regulating the motor's torque by varying the stator currents.
6) An electric power steering motor draws power from the 12V battery bus
7) Exceptions not included in this class:
    a) Some eV's use a DC/DC converter between the battery and the drive motor

I. Control System Operation for This Generic Class of BeV's

Figure 1 shows a block diagram of the control system design used in this generic class of vehicles. This block diagram was created from information obtained from multiple academic technical papers and theses dealing with electric motor control. [1,2,3,4,5,6,7,8] It was not obtained from any vehicle manufacturer. It is assumed, however, that this block diagram applies to all the vehicles of this class of BeV's because the control of electric motors in these vehicles has the same fundamental motor control issues as the control of electric motors used in a host of other industries. Therefore, there is a rich technical open literature dealing with electric motor control design and operation that applies to this widespread need for control.

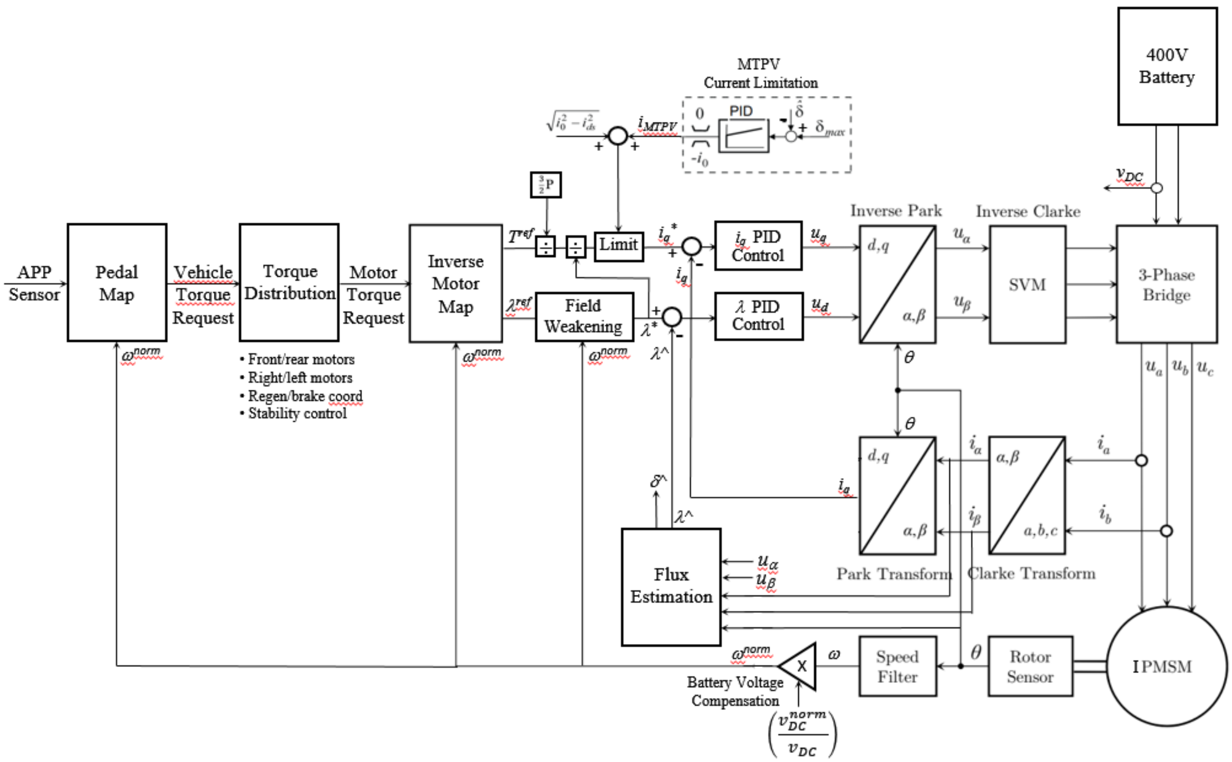

Figure 1. Block diagram of the control system of a typical vehicle in this class of BeV's. This diagram uses (torque, flux) reference coordinates. An alternate diagram using (i_d*, i_q*) reference coordinates is shown in Appendix A.

In Figure 1, two or more accelerator pedal position (APP) sensors are used to convert the driver's depression of the accelerator pedal into a voltage input to a pedal map. The pedal map, which is usually a look-up table, then generates a vehicle torque request based on the APP sensor input and the current vehicle speed. The vehicle torque request is then distributed across the front and rear motors of the vehicle, and possibly the right and left motors, as needed for proper motor efficiency, proper braking, and stability control until it becomes a motor torque request for each individual electric motor. The motor torque request and motor speed then become the inputs into an inverse motor map that supplies as outputs the required (torque, flux) values or (i_d, i_q) motor currents needed for the motor to achieve the desired motor torque and motor speed used as inputs[1]. The inverse motor map is usually a look-up table whose outputs

[1] The term "inverse motor map" comes from the observation that the physical motor converts current inputs into torque and speed outputs. Therefore, the inverse operation to the physical motor corresponds to supplying torque and speed as inputs to a map that supplies the motor currents as outputs. Clearly, the inverse motor map operation must be a true mathematical inverse of the original motor operation, or else the control system will have defects.

become the reference inputs or set-points for the PID controllers that control the currents within the electric motor. The PID controllers then compare the actual (torque, flux) values or (i_d, i_q) currents within the electric motor to the reference (torque*, flux*) or (i_d*, i_q*) set-points supplied by the inverse motor map to control the (torque, flux) values or (i_d, i_q) currents in the motor by driving the difference between the two PID inputs to zero. By using a field-oriented control (FOC) control scheme as shown in the blocks to the right of the PID controllers, these PID controllers can operate at a DC level in the fixed laboratory frame even as the currents in the electric motor vary in magnitude and phase in a rotating frame fixed to the motor's rotor. The FOC control blocks are carried out using high-speed digital computations that convert the DC current values in the fixed laboratory frame to stator current values in the rotating current frame and then back again to the fixed frame. The conversion between the fixed and rotating frames is done by using forward and inverse Park transformations while forward and inverse Clark transformations convert two orthogonal coordinates into three-phase stator drive coordinates and back again. The physical conversion into stator currents is done indirectly by turning on and off high voltage drive transistors in a DC to AC inverter that pulse width modulates the current drawn from a high voltage DC link into three-phase currents applied to the motor stator windings. Current and voltage sensors on the stator terminals then provide the phase currents and voltages that are sent back to the PID controllers to provide proper control.

The content of the inverse motor map is shown in Figure 2. The inverse motor map is a table that contains the reference (torque*, flux*) commands or (i_d*, i_q*) PID set-points for each of the motor operating points falling below the maximum torque versus motor speed curve shown in Figure 2. The driver determines the torque value of any of these operating points, and the vehicle speed automatically determines the motor speed. As the vehicle speed changes, the motor operating points follow a curve in the torque/speed plane. A similar map in the torque/speed plane but mirrored across the motor speed axis has negative torque values that determine the regen level at which the motor operates while slowing down.

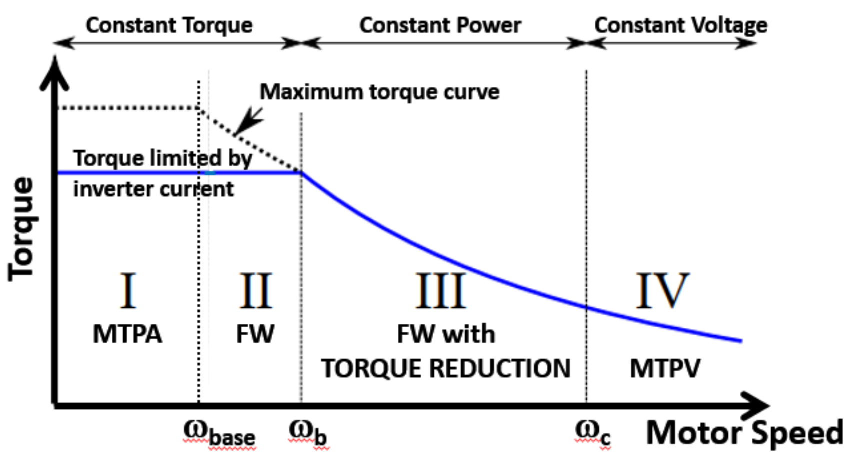

Figure 2. The inverse motor map is a table that contains the reference (torque*, flux*) values or (i_d*, i_q*) set-points for each of the motor operating points falling below the maximum torque versus motor speed curve shown in the figure.

Motor torque varies differently with motor speed in each of the four sub-regions of this table. In region I the motor torque is determined only by the motor current, which can be limited either by the maximum inverter current or by the maximum motor power. The motor operating points in this region are usually calculated to provide the maximum torque per ampere (MTPA) of current in order to obtain the most efficient use of the battery. As the motor speed increases in Region I, the back EMF of the motor increases until it becomes equal to the DC battery voltage at a speed known as the base speed, ω_{base}. Operation of the motor above base speed then becomes impossible without limiting the EMF by field weakening. As the motor speed increases, this field weakening causes the maximum motor torque to decrease inversely with the motor speed as shown in Region III. If the motor torque is not limited by the inverter current, then this field weakening Region III begins at the base speed. But if the maximum motor torque is limited to a lower torque value by the maximum inverter current, then the maximum torque can remain constant for a while in a Region II before torque reduction is needed. As the motor speed increases with field weakening, a speed is reached at which further field weakening to reduce the back EMF voltage is impossible. Operation above this speed in Region IV of the table requires voltage limiting in addition to field weakening. This causes the maximum torque to decrease inversely with the square of motor speed in Region IV. In Region IV the operating points are usually calculated to provide the maximum torque per volt (MTPV) of applied voltage.

The existence of these four speed ranges explains the inclusion of the field weakening block in Figure 1 as well as the MTPV circuitry shown in the figure. Further details explaining how the algorithms carry out these functions will not be discussed at this time. The flux estimation block is needed to compute a flux value from the sensed stator currents and voltages that can be used in the feedback to the PID controller that sets the flux value for the motor. Flux estimation algorithms vary with motor speed because some algorithms become unstable at low motor speeds while others become unstable at high motor speeds. Often a weighted sum of algorithms is used with the weighting factors changing with motor speed.

Figure 2 shows that the boundaries of the four speed ranges of the inverse motor map depend upon the value of the back EMF voltage relative to the DC battery voltage. This means that different algorithms must be used in each speed range to calculate the motor operating points at the proper DC battery voltage. The look-up table used for this map usually assumes that the battery voltage used for this calculation is the maximum DC voltage of the high voltage battery. For this class of vehicles this voltage is usually 400 volts. Since the table values remain fixed, this voltage value remains fixed also.

Now, it is well known that that DC voltage of a high voltage battery varies with the state of charge (SOC) of the battery. Figures 3 and 4 show how much this voltage varies with the state of charge. For the two different battery chemistries shown, the DC battery voltage decreases from about 400V to 300V as the battery state of charge decreases from 100% to about 10%. This implies a voltage drop of about 25%. This size of a voltage drop will have a noticeable effect on electric motor performance unless something is done to compensate for it.

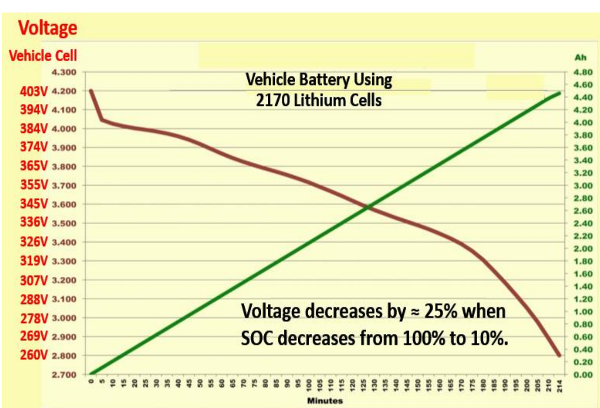

Fig 3. Voltage versus state of charge (SOC) for a lithium battery using 2170 type cells.

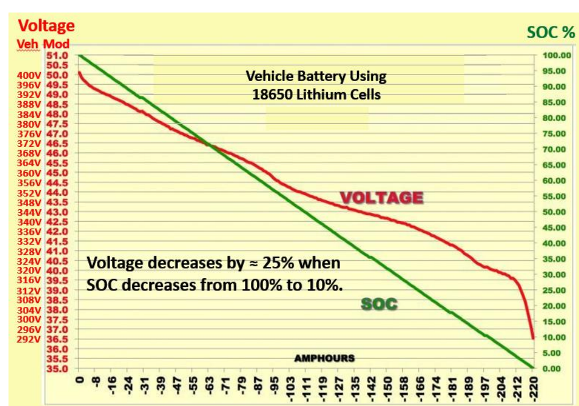

Fig 4. Voltage versus state of charge (SOC) for a lithium battery using 18650 type cells.

Figure 5 shows what happens when the torque and power of vehicles in this class are measured during a dynamometer test in which the state of charge (SOC) of the high voltage battery is varied between tests. One finds that as the battery state of charge decreases, the torque curves shift to the left to lower motor speeds while the maximum torque remains constant for all SOC values. A decrease in the battery state of charge from 100% to 10% causes the torque curve to shift to a lower speed that is about 25% lower.

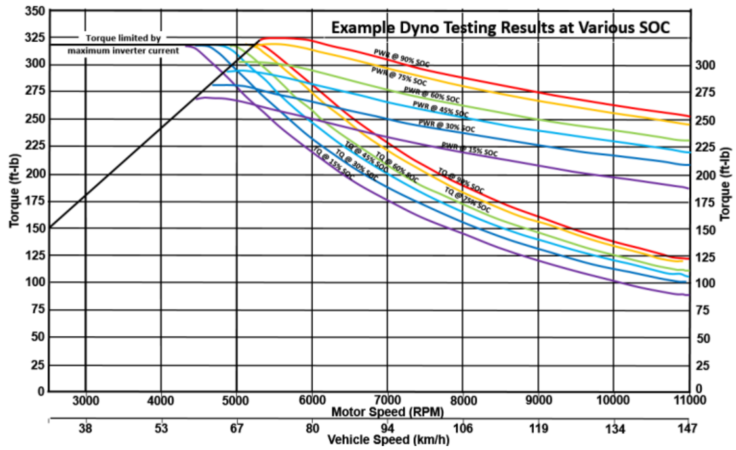

Figure 5. Dynamometer testing[9] shows that the vehicle torque and power curves shift to lower motor speeds as the state of charge of the high voltage battery decreases. The maximum torque for all curves remains constant because it is limited by the inverter current.

Figure 6 shows what this same data would look like if the maximum motor torque is limited by the high voltage battery instead of by the inverter current. In this case the torque values above the inverter current limit become visible. They show that the speed changes in the torque curves result from changes in the battery voltage associated with the changing SOC values. As the SOC values decrease the battery voltage decreases, causing the field weakening region to shift to lower motor speeds. This causes the motor base speed to shift to lower motor speeds. A decrease in the SOC from 100% to 10% causes a decrease in battery voltage from 400V to 300V, or about 25%. This causes a shift in the motor speed of about 25%.

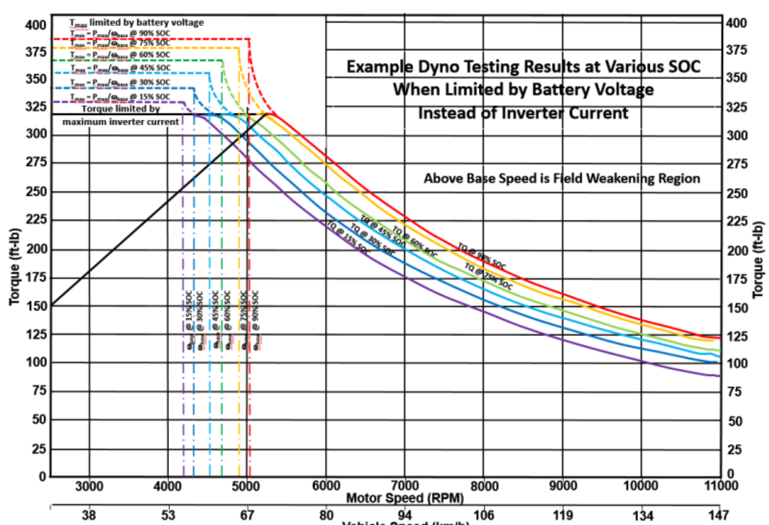

Figure 6. If the torque curves in Figure 5 were limited by battery voltage instead of inverter current, then the same data would look like this, showing that the speed shifts in the torque curves are caused by battery voltage changing as a result of SOC changes.

So how does the motor control system deal with these changes in the maximum torque curve with SOC when the inverse motor map is a look-up table that has a single fixed maximum torque curve with four different regions that are defined relative to a fixed battery voltage of 400V? The answer is shown in Figure 7. Figure 7 shows that as the battery voltage decreases to cause the torque curves to shift to the left, the control system senses the DC battery voltage and shifts the curves back to the right by the inverse ratio of the battery voltages, causing each curve to realign with the curve in the inverse motor map. This correction results in a maximum increase in the motor speed of about 25% that offsets the maximum decrease in motor speed of about 25% caused by a battery voltage shift of 25% associated with a maximum change of SOC value from 100% to 0%. This so-called battery voltage compensation is shown in the lower right hand corner of the control system block diagram shown in Figure 1 above.

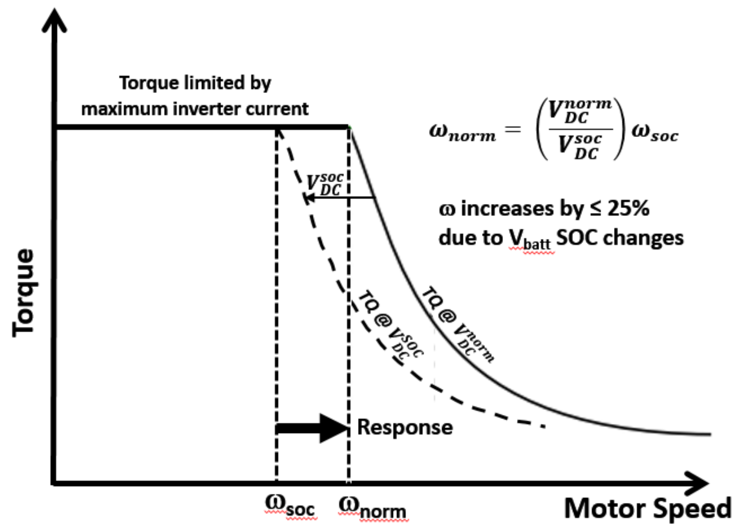

Figure 7. When the battery voltage decreases from the normal 400V value with decreasing SOC, causing the torque curve to shift to a lower motor speed, the control system senses the battery voltage and multiplies the motor speed by the inverse ratio of battery voltages to bring the torque curve back to its original 400V value. This is called battery voltage compensation.

Figure 8 shows what happens to the operating points in the inverse motor map when battery voltage compensation is applied. The operating point associated with the lower battery voltage is shifted to the right to a higher motor speed by the voltage compensation value to cause a different operating point to be selected whose torque/speed value corrects for the lower battery voltage that is currently active. This shifts all operating points by the same compensation value. In particular, the operating point associated with a released accelerator pedal[2] is shifted by this compensation value, which results in a shift in motor speed of about 25% maximum as the SOC changes from 100% to 0%. This causes the motor operating point of the released accelerator pedal to remain in the MTPA region where the torque depends only on the motor current. The result is only a small change in the motor speed and no change in the motor torque. This means the battery voltage compensation corrects exactly for the changes in battery voltage with SOC, allowing the motor to operate normally at all times. This is exactly how the control system is expected to work as designed.

[2] The inverse motor map often specifies a small positive torque at the lowest motor speeds in order to give the vehicle a small speed that mimics creep in an internal combustion vehicle with an automatic transmission. Sometimes this creep function can be turned on and off by the driver, but sometimes the positive torque remains present even when the creep function is turned off.

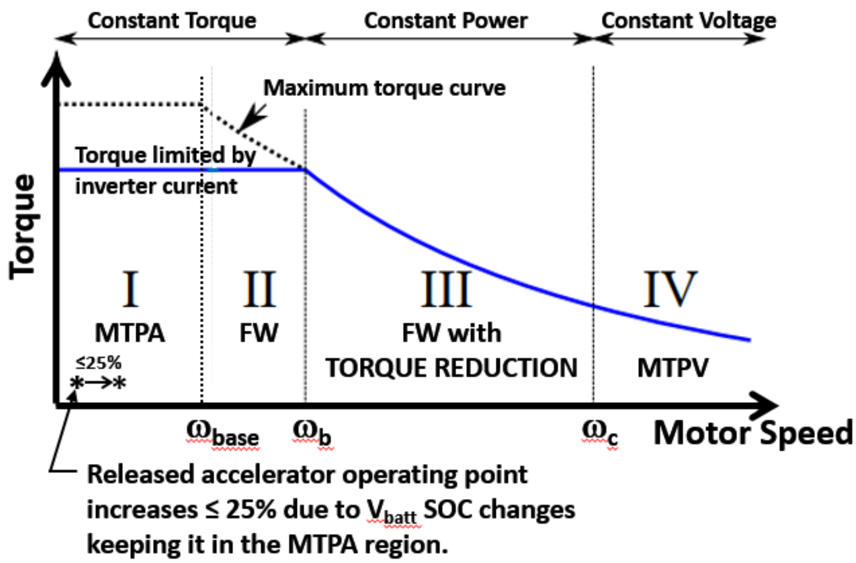

Figure 8. Battery voltage compensation causes a shift in the motor operating point within the inverse motor map as the battery voltage changes with decreasing SOC. This shift in motor operating point is normally a maximum of 25% in speed, which causes the motor operating point of the released accelerator pedal to remain in the MTPA region where the torque depends only on the motor current. This produces no change in the motor torque.

II. Control System Operation With Voltage Spikes

While the control system works correctly under normal circumstances for all vehicles in this class, a condition unexpected by many designers can cause improper operation in some vehicles. This unexpected condition is the presence of negative-going voltage spikes on the output of the DC link voltage sensor. These negative-going voltage spikes cannot be present on the DC link itself because of the large capacitance of several hundred farads placed on this link to keep the RMS voltage variations below a specified amount. Therefore, the negative-going voltage spikes must originate somewhere else in the system and then find their way into the output of the DC link voltage sensor.

Figure 9 shows a block diagram of the electronic power system found in this class of BeV's. It shows that the DC link voltage sensor is actually common to two power busses; namely, the high voltage DC link and the 12V battery supply bus. Therefore, these negative-going voltage spikes may be produced on the 12V battery supply bus. They are likely to be produced by the function that draws the most current, which is the electric power steering function that draws over 100 amps peak at times during normal operation. The negative-going voltage spikes are produced by the inrush current of the electric power steering motor when it turns on.[3] This happens because the motor windings are essentially a wire that causes a direct short to ground when the motor is first turned on until a magnetic field can build up in the motor to limit the current through the windings. This temporary short to ground causes an extremely high current through the motor that pulls the 12V DC bus voltage down from 12V or less to near zero volts until a magnetic field builds up in the motor to limit the current. At this time the 12V supply

[3] The power steering motor turns on only when a torque assist is needed to help the driver turn the front wheels while a load is being placed on the steering mechanism that makes it harder to turn. This can happen when a driver turns the steering wheel at low speed when the friction between the front tires and the road becomes greater as the speed decreases. This condition is found most often when turning into a perpendicular parking space while slowing the vehicle to a stop. This condition happens to be the same condition that leads to a majority of sudden acceleration incidents.

voltage increases back to its original value of 12.6V or less. This field buildup may take several hundreds of microseconds to occur, during which a negative voltage spike is created on the 12V DC supply bus.

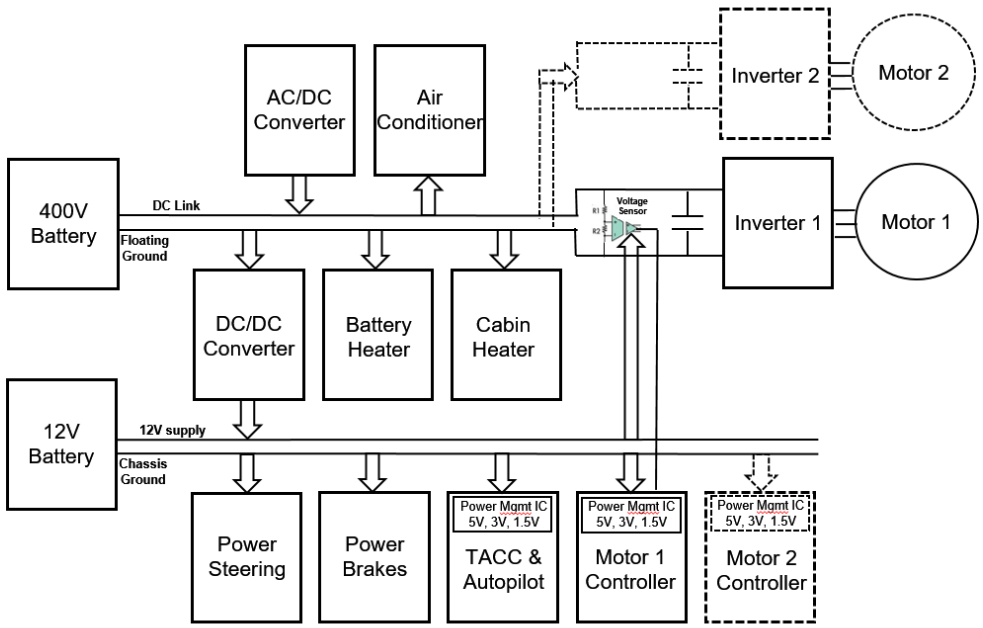

Figure 9. Block diagram of the power system in battery-powered eV's of this class. The DC link voltage sensor is common to both the high voltage DC link and the 12V battery supply bus. Therefore, negative-going voltage spikes on the output of this sensor can originate in the 12V supply bus instead of the DC link, which has a very high capacitance on it that prevents negative-going voltage spikes.

To understand how these negative-going voltage spikes get into the output of the DC link voltage sensor, it helps to know how such sensors operate. Figure 10 and Figure 11 show two types of isolated voltage sensors, a simple inexpensive type having a maximum temperature of 105°C and a more robust and more expensive type having a much higher temperature range. It is not known which type is used by vehicles in this class of eV's. But both types of sensors have similar features. Both sensors have a high voltage section and a low voltage section separated by a high voltage dielectric. The two sections communicate across the dielectric either by using an analog IR LED signal or a digital modulator signal. This not only allows different voltage levels to be used in each section, but it also maintains a floating ground in the high voltage section while providing a normal chassis ground in the low voltage section. The high voltage section is powered by the high voltage being measured, which in this case 400V. It is connected to the DC link by means of a two resistors forming a voltage divider. It draws only a few milliamps, so it's practically invisible to the battery and the inverter on the DC link. The low voltage section is usually powered by a regulated 5V supply found in a power management integrated circuit located on one of the motor controller boards. The 5V output of the voltage sensor is then divided down to a voltage level of about 3V that is compatible with the A/D converter in the DSP found on the same board that is used to control the motor.

We can now explain how the negative-going voltage spikes produced on the 12V battery bus get into the output of the DC link high voltage sensor. First, they pass from the 12V battery bus to the 5V regulator in the power management integrated circuit. They do this when the power management IC senses that a negative-going voltage spike is present on the 12V battery bus, at which time it goes into reset, causing the 5V regulator to turn off. When the power management

IC comes out of reset, the 5V regulator turns back on again. This interruption in the 5V regulator output within the power management IC causes an interruption in the sensor bias of the DC link voltage sensor that produces a negative-going voltage spike on the sensor output. The voltage spike has a voltage of zero volts and a duration equal to the duration of the reset in the power management IC, which is a just few tens of microseconds longer than the original negative-going voltage spike on the 12V supply bus. An interesting feature of the power management IC, however, is that the 3V regulator to the A/D converter and the 1.5V regulator to the digital part of the DSP do not turn off during the reset of the power management IC.[4] Therefore, the A/D converter can continue to operate and digitize the output of the DC link voltage sensor that now has a negative voltage spike on it.

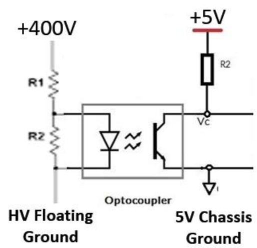

Fig 10. Simple inexpensive voltage sensor good to 105°C

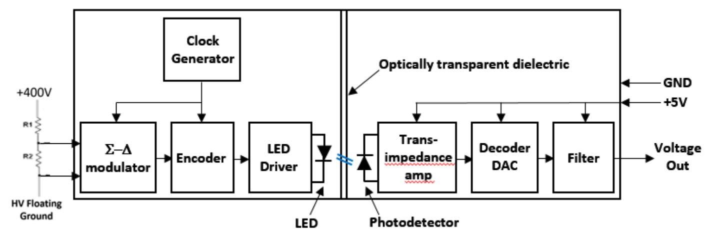

Fig 11. More robust and more expensive voltage sensor for temperatures above 105°C

Even though there may be negative voltage spikes on the output of the DC link high voltage sensor, the A/D converter may not always see them. Figure 12 shows how this can happen. In Figure 12 the top trace shows that the voltage on the DC link usually falls in the gray area within 25% of the maximum battery voltage of 400V. There are no spikes on this DC link voltage.

The second trace shows that negative-going voltage spikes can exist on the 12V battery bus that have a voltage close to zero volts. These spikes occur randomly and have a duration of several hundred microseconds. They are caused by the inrush current of an electric motor turning on, which is usually the electric power steering motor that has an extremely high current capability.

The third trace shows that these negative-going spikes get transferred to the 5V power supply when the 5V power suppply is reset during a voltage spike on the 12V power bus. The spikes on the 5V power supply then get transferred to the output of the DC link high voltage sensor when the 5V bias supply turns off and then back on again.

The lowest trace shows what happens when the output of the DC link voltage sensor is digitized by an analog-to-digital (A/D) converter with and without any negative-going voltage spikes. The trace shows that the A/D converter has a sample time of only 10 microseconds or so, which is an extremely short duration. These samples are also taken at a very low rate, on the order of one sample every few minutes or so, because the DC link voltage doesn't change very rapidly. Therefore, most of the time when the A/D samples the DC link voltage, the correct DC link voltage is obtained. However, once in a very great while, as the A/D converter sample is being taken, a negative-going voltage spike randomly occurs. This causes the A/D converter to digitize the extremely low voltage of the voltage spike, which is near zero volts, instead of the true DC link voltage of the high voltage battery. The probability of this happening is a random event having a very low probability because the durations of the negative-going spike (~ 200 us) and

[4] This is likely to allow the DSP to keep providing PWM commands to the SiC power transistors in the inverter to prevent the back EMF of the motor from blowing the power transistors if they shut off while the vehicle is moving at high speed.

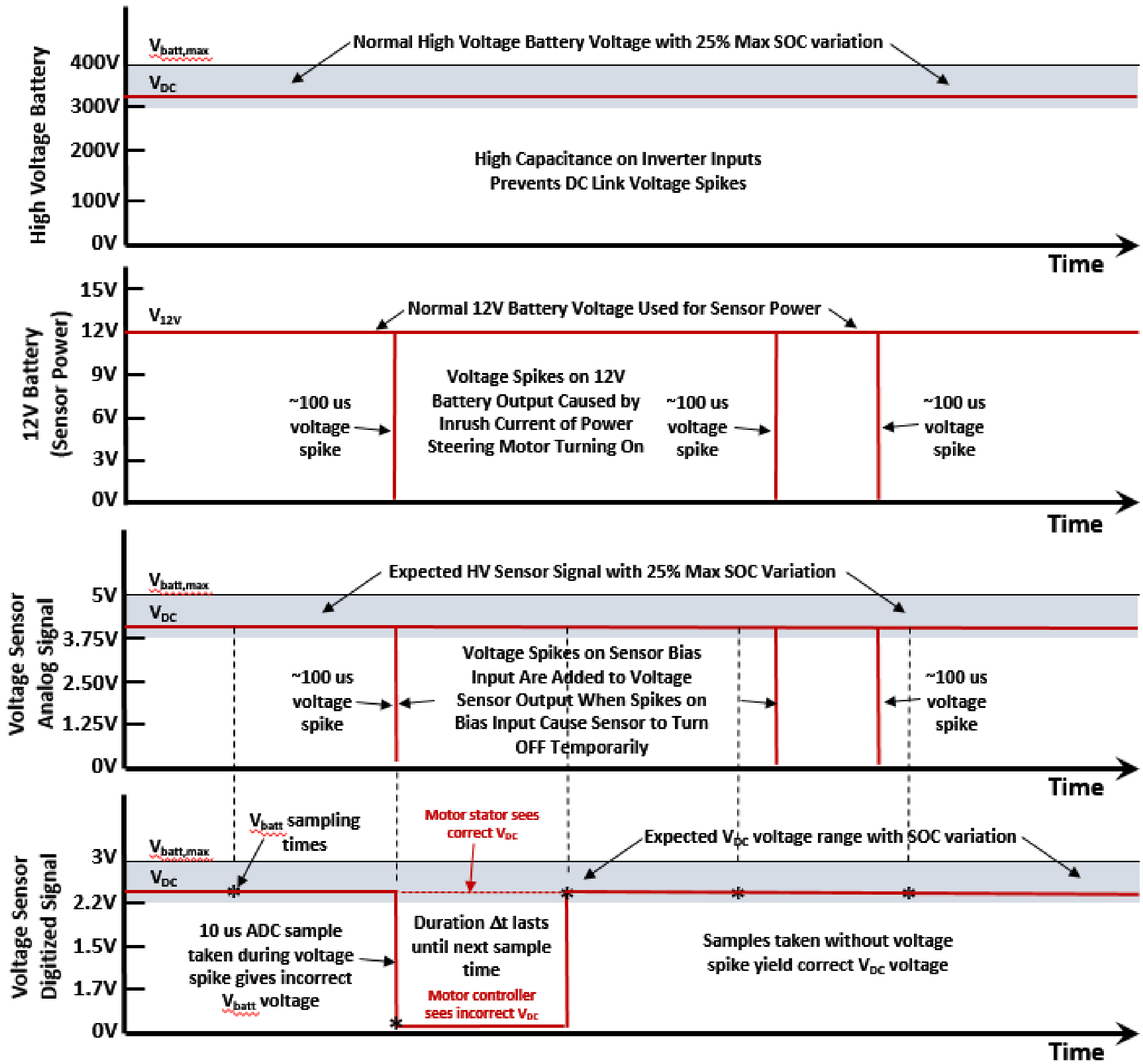

Figure 12. The high voltage DC battery voltage usually falls in the gray area within 25% of the maximum battery voltage of 400V. There are no spikes on this DC link voltage. But random negative-going voltage spikes on the 12V battery bus can have a voltage close to zero volts. These spikes get transferred to the 5V power supply when the 5V power suppply is reset during a voltage spike on the 12V power bus and then to the output of the high voltage DC voltage sensor through its 5V bias supply. When the A/D samples the output of the high voltage DC battery voltage sensor with these spikes, most of the time the correct DC battery voltage is obtained. But if the A/D converter samples the output of the high voltage DC voltage sensor during a negative voltage spike, then the motor controller sees an incorrect votage close to zero volts. Meanwhile, the voltage seen by the motor stator remains at the correct DC battery voltage of 300V to 400V. This discrepancy in voltages lasts until the next A/D sample is taken, and has an adverse effect on control system performance.

the A/D sample time (~10 us) are extremely small while the times between the A/D samples and between the negative-going voltage spikes are orders of magnitude larger (~minutes). Nevertheless, such a random coincidence of A/D sampling and spike duration is possible and it determines the incident rate for sudden acceleration in this class of vehicles.[5]

The bottom trace also shows that once an incorrect DC link voltage is obtained by this random process, the incorrect DC link voltage lasts until the next A/D sample, which can be several minutes later. In the meantime, the voltage that the stator of the electric motor sees remains at the true DC link voltage value of between 300V to 400V while the voltage that the control system sees is the incorrectly digitized A/D value of approximately 0V. This large discrepancy in voltage values has an adverse effect on the control system operation. Yet, after a new A/D sample is taken, this large discrepancy in voltage values is no longer present, and the control system behaves normally again as though nothing happened. This ability to "heal" afterward explains the inability to find a vehicle defect after a sudden acceleration incident. In fact, not only does the control system operate correctly in this case both before and after the voltage discrepancy, but also during the discrepancy. It is merely a temporary change in the voltage environment that causes the adverse effect on the control system, and not a defect in the control system itself. But this incorrect voltage can be avoided by testing the sampled voltage immediately after sampling and then sampling again if the voltage is abnormally low. This could prevent any adverse effects from happening.

So what adverse effect does the incorrect high voltage DC battery voltage obtained by the A/D converter have on control system operation? Table 1 shows that this incorrrect battery voltage causes the torque vs. motor speed curve to shift to an extremely low motor speed on the order of a few RPM.

Table 1. The extremely low voltage obtained by the A/D converter during a negative voltage spike causes the torque vs motor speed curve to shift to an extremely low motor speed on the order of a few RPM. In contrast, the smaller voltage changes associated with SOC reduction produce a ≤25% change in motor speeed.

V_{batt}	SOC	ω_e
400V	100%	5200 RPM
390V	90%	5050 RPM
375V	75%	4900 RPM
355V	60%	4650 RPM
335V	45%	4500 RPM
315V	30%	4300 RPM
300V	15%	4200 RPM
3V	(0%)	42 RPM
1V	(0%)	14 RPM

When this happens, Figure 13 shows that the battery voltage compensation algorithm then increases the motor speed by the inverse amount of 300x to 400X. Figure 14 shows how this affects the motor operating point selected in the inverse motor map. In this case the battery voltage compensation causes a shift in the motor operating point within the inverse motor map in response to an incorrect battery voltage obtained during a negative voltage spike. The shift in motor operating point causes a 300x to 400x increase in motor speed, which causes the motor operating point of the released accelerator pedal to shift into the field weakening region with torque reduction. This causes the control system to apply a field weakening algorithm to the

[5] It should be possible to calculate the random rate of occurrence of a coincidence between an A/D sample and a negative-going voltage spike from the data given. This has not been done yet.

operating point that looks at the stator voltage with respect to the DC battery voltage. If the stator voltage exceeds the DC battery voltage, then the operating point lies in an unstable region in which the control system loses control of the motor torque.

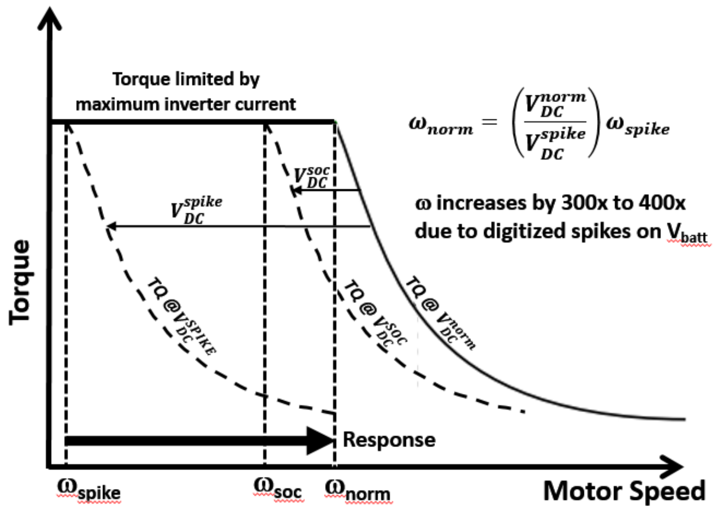

Figure 13. The extremely low incorrect battery voltage obtained by an A/D converter during a negative voltage spike causes the torque vs. voltage curve to shift to a motor speed value close to zero RPM. The battery voltage compensation algorithm then shifts it back to a higher value by the inverse amount of 300x to 400x.

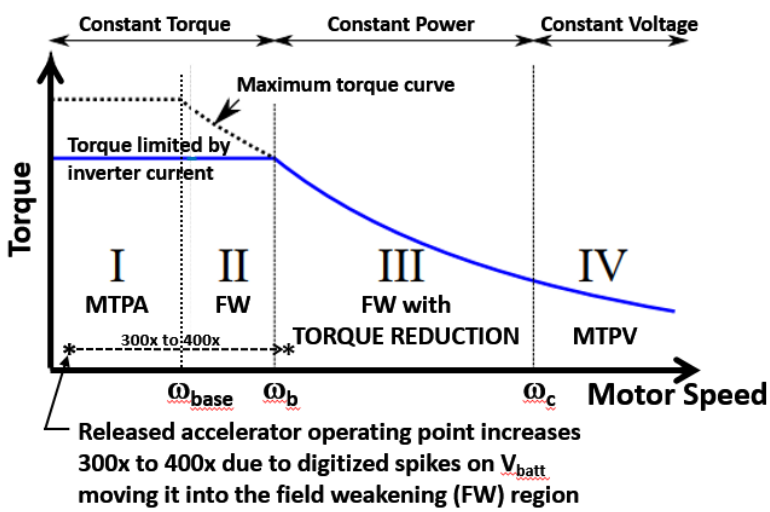

Figure 14. Battery voltage compensation causes a shift in the motor operating point within the inverse motor map in response to an incorrect battery voltage obtained during a negative voltage spike. The shift in motor operating point caused by a voltage spike is between a 300x to 400x increase in motor speed, which causes the motor operating point of the released accelerator pedal to shift into the field weakening region with torque reduction. This causes the control system to apply a field weakening algorithm to the operating point that looks at the stator voltage with respect to the DC battery voltage. If the stator voltage exceeds the DC battery voltage, then the control system is in an unstable region in which it loses control of the motor torque.

Simulation results obtained by a team of academic researchers [10,11,12] show that if the stator voltage exceeds the DC battery voltage, then the operating point lies in an unstable region in which the control system loses control of the motor torque. Figure 15 shows the LUT-based FOC motor control scheme they simulated along with battery voltage compensation to correct the shift in the torque curve caused by SOC reduction in a high voltage battery voltage. Their simulation included a VCT block that could be excluded to show how the present battery voltage compensation scheme can lead to unstable operation or added to show how their proposed VCT scheme prevents unstable operation.

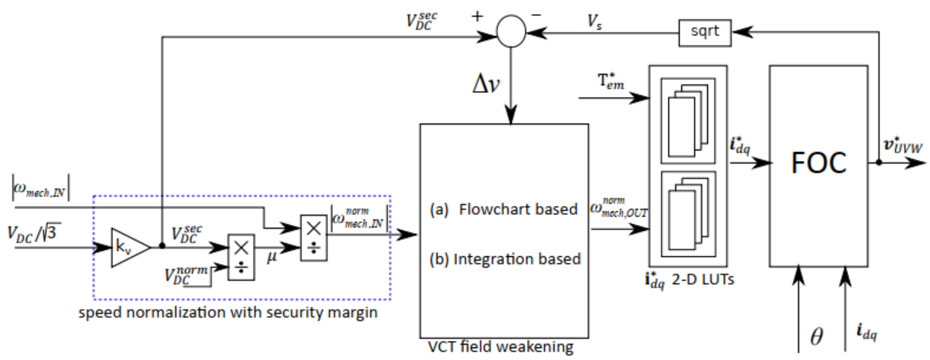

Figure 15. A LUT-based FOC motor control scheme was simulated that used battery voltage compensation to correct the shift in the torque curve caused by SOC reduction in a high voltage battery voltage.[10,11,12] The VCT block could be excluded to determine whether the normal battery voltage compensation scheme could lead to unstable operation or added to show how a proposed VCT scheme could prevent such unstable operation.

Figure 16 shows the results they obtained. For these simulations the battery voltage was changed only a small amount from its normal value as typical of normal SOC variations, so large variations caused by voltage spikes were not assumed. Figure 16 shows that even with normal changes in the voltage of the high voltage battery with SOC shanges, one can encounter unstable operation in the field weakenting region if the stator voltage exceeds the battery voltage. This unstable operation allows the motor torque to increase without limit as shown in Figure 16.

A similar situation can exist when a negative voltage spike causes the digitized battery voltage to be sensed as being lower than the stator voltage when the motor operating point is set at a low motor speed while the accelerator pedal is either not being pressed by the driver or while it is being pressed only a very small amount. The former situation can happen when the vehicle has a small positive motor torque that simulates creep in a conventional vehicle with an internal combustion engine and an automatic transmission. In these cases the motor torque is not increased if the motor operating point stays in Region I because the motor torque is a function of motor current in this region. But if the battery voltage compensation algorithm translates the motor speed to a much higher speed, the motor operation enters into field weakening region III, where the field weakening algorithm compares the stator voltage to the voltage of the high voltage battery. If it then finds that the stator voltage exceeds the voltage of the high voltage battery, then the algorithm cetermines that the motor is in an unstable region and loses control of the torque. The torque can then increase without limit, causing sudden acceleration.

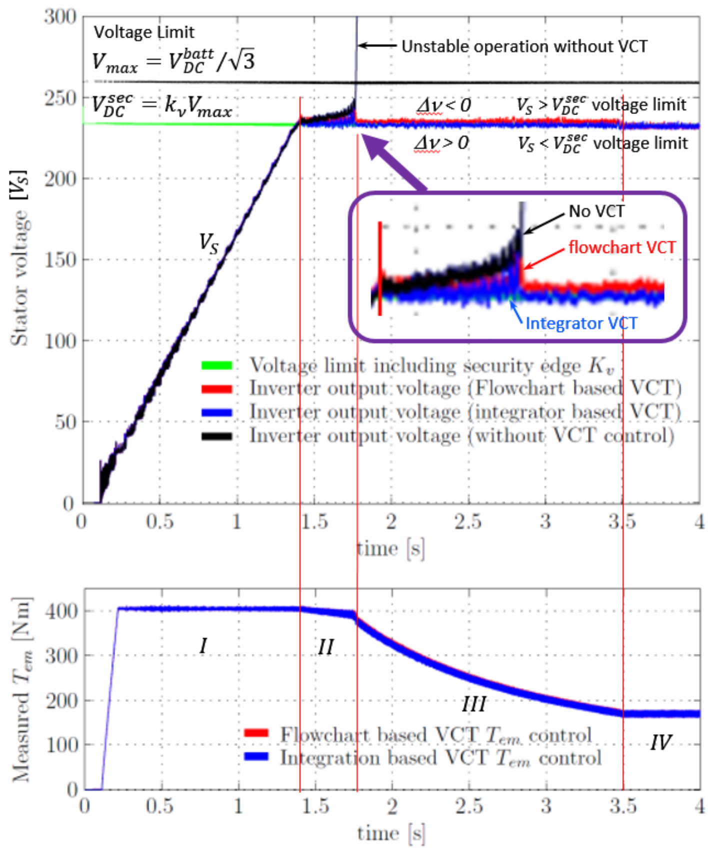

Figure 16. Simulation results [10,11,12] show that as the motor operating point increases along the maximum torque curve, the stator voltage increases with increasing motor speed. As the motor speed passes through the field weakening region II, with the present battery voltage compensation scheme the torque begins to increase when it shouldn't because the stator voltage exceeds the secure voltage of about 240V. As the speed enters into field weakening region III, when the stator voltage exceeds the battery voltage, control becomes unstable leading to the torque increasing without limit (black trace above). The proposed VCT algorithm prevents such unstable operation (red and blue traces above) .

Figure 17 shows a proposed flowchart-based voltage constraint algorithm for avoiding the instability caused by the stator voltage being higher than the voltage of the high voltage battery[10,11,12]. And Figure 18 shows a proposed integration-based voltage constraint algorithm having the same objective [10,11,12]. The algorithms work by adjusting the motor speed either higher or lower to keep the stator voltage below a secure voltage level that is slightly below the voltage of the high voltage battery. The data in Figure 13 show that both of these algorithms work as expected, with the integration-based algorithm being slightly better than the flowchart-based algorithm. Figure 19 shows how either of these two algorithms fit into the block diagram of a complete motor control system.

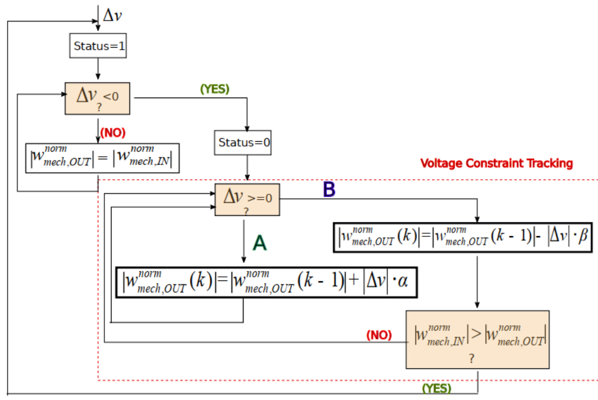

Fig 17. Proposed flowchart-based voltage constraint tracking (VCT) algorithm[10,11,12]

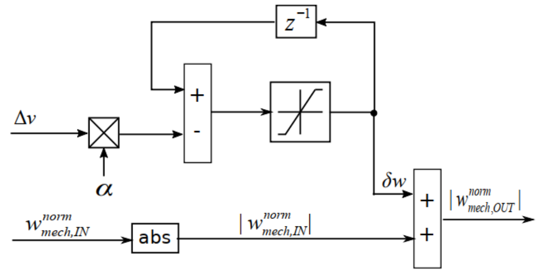

Fig 18. Proposed integration-based voltage constraint tracking (VCT) algorithm[10,11,12]

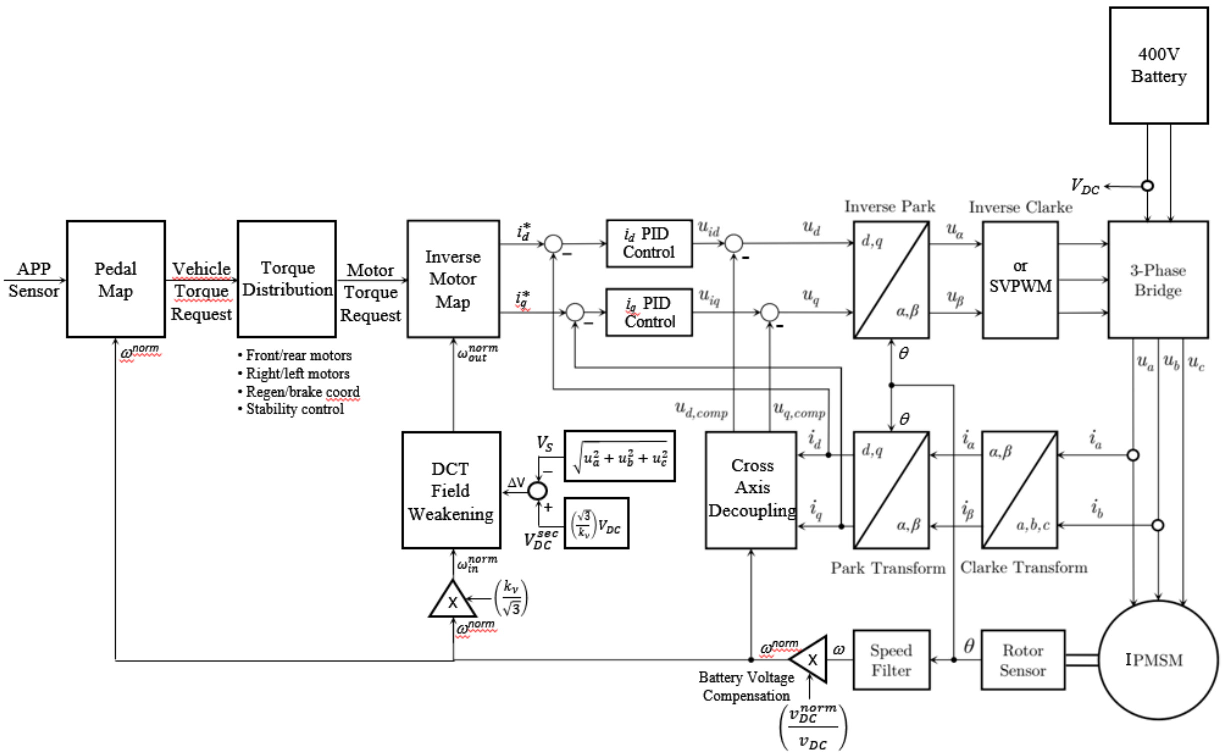

Figure 19. Block diagram of a complete FOC-based motor control sytem using a voltage constraint tracking algorithm for field weakening that can prevent loss of torque control when the stator voltage exceeds the voltage of the high voltage battery.

III. Elimination of Sudden Acceleration

Knowing that sudden acceleration is caused by negative voltage spikes on the 12V battery bus that change the output of the DC link sensor allows one to come up with possible mitigation measures for eliminating the sudden acceleration. Adding more capacitance to the 12V supply line to eliminate the large negative-going voltage spikes is futile because the inrush currents are so high. But the following techniques for dealing with the spikes may be considered:

1) Test the sampled voltage of the high voltage battery before using it and then do one of the following:

a. If the sampled battery voltage is found to be less than some normal voltage like 300V, then don't change the supply voltage from the previous value.
b. If the sampled battery voltage is found to be less than some normal voltage like 300V, then use some default battery voltage like 300V instead.
c. If the sampled battery voltage is found to be less than some normal voltage like 300V, then resample the battery voltage and again compare it to some normal battery voltage like 300V. Then use it only if it exceeds 300V.

2) Take two samples of the voltage of the high voltage battery about 1 millisecond apart. Then compare the two samples and use the higher voltage sample.
3) Add a circuit to the input of the power steering motor that limits the inrush current to the motor during start-up until after the magnetic field in the motor has built up.

Only by eliminating the negative-going spikes on the 12V supply bus, or by preventing them from affecting the sampling of the DC link voltage sensor output, will one be successful in eliminating the sudden acceleration caused by this mechanism.

IV. Correlation with APP Sensor Data

The mechanism discussed in this paper can cause a change in the pedal map output by increasing the value of the motor speed input. The change will depend upon the difference in map values before and after battery voltage compensation is applied to the motor speed, which will normally cause only a slight change in the motor torque from its accelerator pedal-released value. This mechanism, however, cannot change the value of the APP sensor input to the pedal map. Therefore, if the EDR data from an accident shows that the APP sensor reading increased during an accident, this would appear to rule out the proposed mechanism as a cause of sudden unintended acceleration. The only way to explain an increase in the APP sensor reading during an incident while this mechanism is active is if the APP sensor reading corresponds to output of the pedal map instead of the input to the pedal map. In other words, the APP sensor reading would not be from the APP sensor at all, but from the output of the pedal map. This suggests that the origin of the APP sensor data should be explored.

V. Summary of the Proposed Cause of Sudden Acceleration in BeV's

A cause of sudden unintended acceleration in a generic class of battery-powered electric vehicles (BeV's) having similar design features has been discussed. The cause is associated with the voltage compensation algorithm used in all such vehicles to correct the motor operating point for changes in DC link voltage that accompany changes in the state of charge (SOC) of the high voltage battery. Normally this battery voltage compensation causes an increase in the motor speed of 25% or less that corrects for the decrease in motor speed caused by a lower battery voltage due to a decrease in the SOC. But when the battery voltage is sensed during a negative voltage spike caused by the inrush current of an electric motor turning on, then an incorrect DC link voltage reading results that causes the standard compensation algorithm to increase the motor speed by over 300x. This condition persists until another DC link voltage reading is taken many minutes later. In the meantime, the motor operating point associated with a released accelerator pedal is suddenly increased to an operating point in the field weakening region. If the existing motor stator voltage then exceeds the incorrectly sensed DC link voltage, then an unstable condition exists in the control electronics in which control of the motor operating point is lost. The motor torque can then increase without control, resulting in sudden unintended acceleration without the driver pressing on the accelerator pedal. Measures have been proposed to eliminate the sudden acceleration by testing the DC link voltage immediately after sampling and limiting it to less than the maximum 25% change normally seen from the maximum battery voltage of 400V.

Appendix A. An Alternate Control System Diagram

Figure A.1 shows an alternate control system block diagram using (i_d*, i_q*) reference coordinates instead of (torque, flux) reference coordinates. This control system design avoids the need to estimate the stator flux in the feedback path from the stator voltages and currents to the input of the flux PID controller as seen in Figure 1 of this paper. It also includes a cross-axis decoupling capability that removes effects in either the i_d or i_q channel caused by terms in the other channel. Otherwise, this design includes all the functions found in Figure 1 including field weakening, MTPV voltage reduction, and battery voltage compensation, and all the discussion associated with Figure 1 applies to this design also. This design is a usable alternative to the design of Figure 1 in any vehicle in the class of BeV's discussed. It was placed in this Appendix only to allow a more coherent discussion of the block diagram shown in Figure 1 of the paper.

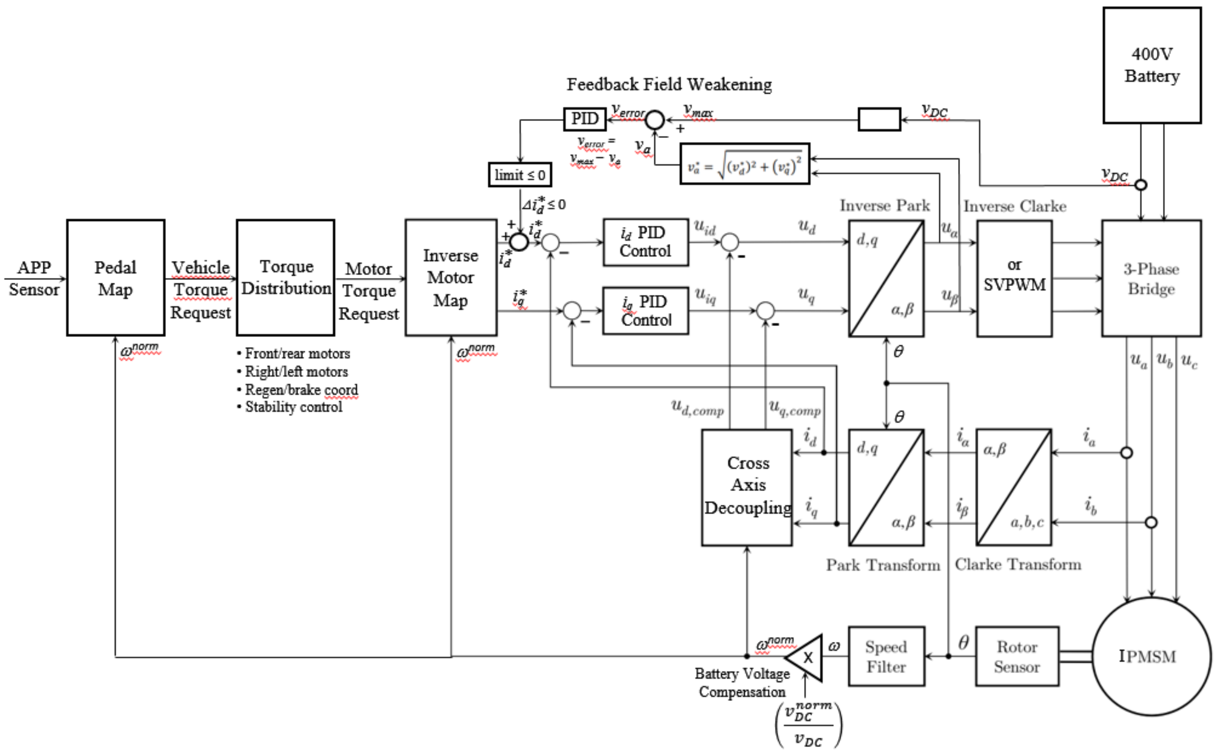

Figure A.1. Alternate control system diagram using (i_d*, i_q*) reference coordinates

Appendix B. Torque Curve Displacements Caused by Battery Voltages Sampled During a Voltage Spike

Figure 6, repeated below, explained how the torque curves shift to lower motor speeds as the battery voltage is lowered due to decreases in the battery state of charge (SOC). If the torque at lower motor speeds is limited by the maximum inverter current, then all the torque curves will have the same maximum torque. But if the torque at lower motor speeds is limited by the battery voltage, then the torque curves will shift downward as the battery voltage decreases with SOC. Therefore, by adjusting the maximum inverter current to limit the torque to values below the torque associated with a minimum value of 0% SOC, decreases in the maximum torque values of the curves with lower battery voltage can be masked. Under normal conditions of vehicle operation this setting of a maximum inverter current works to mask the variations of torque with battery voltage because the battery voltage cannot decrease any further after SOC has reached a zero percent state of charge.

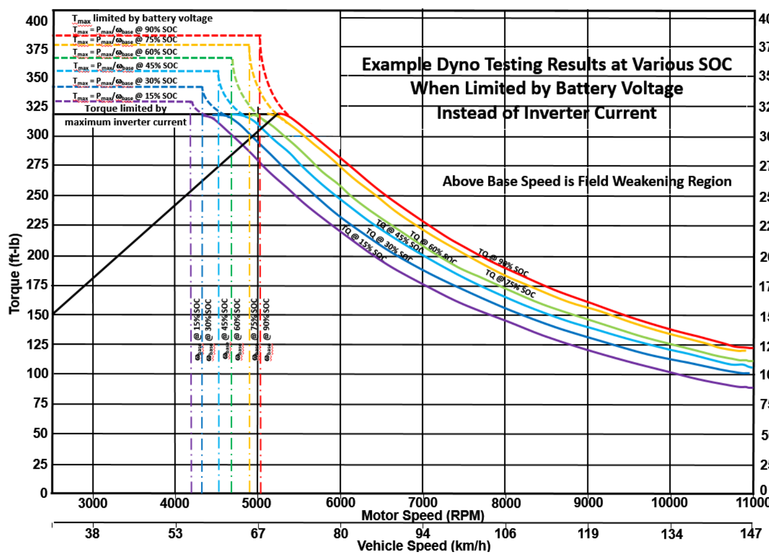

Figure 6. If the torque curves in Figure 5 were limited by battery voltage instead of inverter current, then the same data would look like this, showing that the speed shifts in the torque curves are caused by battery voltage changing as a result of SOC changes.

But if a negative voltage spike can cause the A/D converter to incorrectly sense a battery voltage that is lower than the normal value at 0% SOC, then the lower battery voltage detected by the A/D will cause the control system to believe that the torque curve has shifted to a much lower voltage. In this case, the maximum inverter current no longer masks the changes in torque with decreasing (incorrect) battery voltage. So the torque curves will shift again to lower torque values with decreasing (incorrect) battery voltage as shown in Figure B.1. This implies that the maximum torque becomes limited to a very low torque value when the battery voltage is sensed during a negative voltage spike. This produces no change, however, in how the control system reacts to the motor operating point. It still translates the motor operating point to a higher motor speed based using the ratio of the normal battery voltage (400V) to the incorrectly sampled battery voltage (near 0V). This causes an increase in motor speed of nearly 400x, which places the new operating point in the field weakening region with torque reduction. The field weakening algorithm then compares the stator voltage to the (incorrectly digitized) battery voltage. And if the stator voltage exceeds the (incorrectly digitized) battery voltage, then the control system concludes that the motor operating point is in an unstable region where the motor torque can increase without limit.

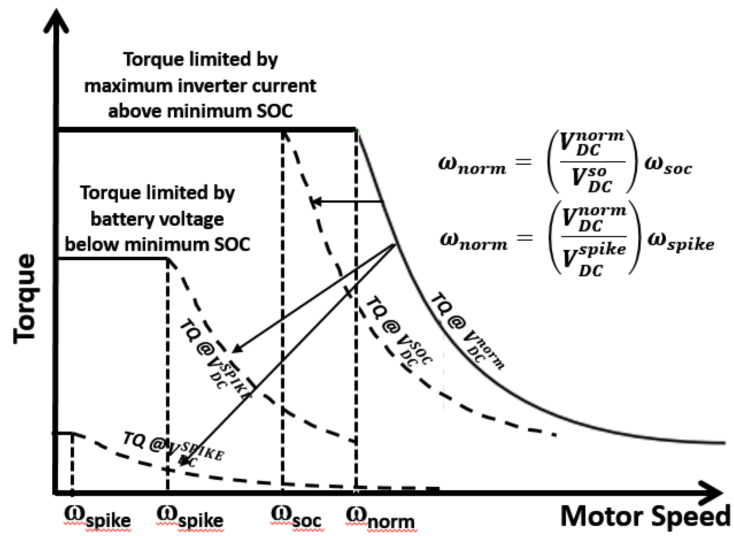

Figure B.1. When the battery voltage continues to decrease below the minimum SOC limit as a result if the A/D (incorrectly) digitizing the battery voltage during a negative voltage spike, then torque curves are no longer limited by the maximum inverter current. Therefore, their decrease in torque with decreasing battery voltage becomes visible, and one can see that that the maximum torque becomes limited to a very low torque value when the battery voltage is sensed during a negative voltage spike. This situation may not be anticipated by some control system designers.

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