Permanent Magnet Synchronous Motor Variable Frequency Drive System

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ABSTRACT

This paper discusses a permanent magnet synchronous motor (PMSM) variable frequency drive (VFD) system developed for an all-terrain Wifi-HaLow connected (802.11ah, 900 MHz) modular electric vehicle that competed in the Mars University Rover Challenge (URC). The quadrature axis flux linkage for each motor was estimated using on-board voltage and current measurements. A synchronous control algorithm tracked the electromagnetic operating parameters, which are highly dependent on variations in motor construction and load conditions. A feed-forward model-driven observer solution calculated flux linkage angles by direct-quadrature-zero transformation of three-phase shunt currents using DSP processors.

INTRODUCTION

This paper is intended as a design-project/application-note for the VFD power inverter component of a modular IoT electric vehicle system, which was named Gryphon by the Mars Rover Design Team of Missouri S&T. Gryphon competed against other electric vehicles of similar nature in the URC, which tasks collegiate teams with developing astronaut assisting rovers. Rovers are required to retrieve and deliver objects in the field, deliver assistance to simulated astronauts, service complex equipment, engage in exobiological analysis, and traverse a wide variety of terrain, all under the assumption that the telerobots are being operated by astronauts, stationed at various base locations on Mars [1].

The six VFDs present in Gryphon were installed as one collective sub-system operated as one individual IoT endpoint with a "drive board," that was connected across a wide-area wireless backhaul access link. The system was used to monitor and control six permanent magnet synchronous motors, with the drive board acting as serial communications transmission master to aggregate, transmit, and receive remote vehicle telemetry and command target values for each motor over six independent two-wire asynchronous serial ports. Each of six VFDs independently receive their own serial command target values on separate duplex streams, and respond with both sensed and derived operating telemetry over each of the six serial interfaces to be aggregated by the Drive Board. The interaction between the user, drivetrain subsystem, and other vehicle subsystems was done over a WiFi HaLow (802.11ah) 6.5 watt radio, operating in the 33 centimeter band (900Mhz) [2].

Electromagnetic operating parameters must be independently monitored for each of the six PMSM's and are highly dependent upon variations in specific motor construction and load conditions []. In order to derive motor model transformations, each of the six individual VFDs utilized their own parallel-processing DSP core, to independently execute filter algorithms concurrently to each 32-bit floating-point real-time microcontroller co-processor. Voltage and current readings acquired by each DSP core corresponded to capture triggers of enhanced hardware peripheral sub-modules. Feed-forward model-driven observers then filtered real time data on each drive, and derived flux field angles by direct-quadrature-zero transformation of each motor's three-phase shunt currents.

VEHICLE SPECIFICATIONS

The MRDT purchased commercially available 24 slot stator, 8 pole rotor Neumotor 1907-480 PMSMs for Gryphon's drive motors. These motors maintain a 480Kv motor velocity constant (back EMF constant), and were originally marketed for large radio controlled (RC) hobby aircraft. When comparing PMSM for digital electric power systems, the Kv rating of a motor in RPM/Volt describes the "low end" response and intended operating power band. The brushless motor Kv is the ratio of the motor's unloaded RPM to the peak (not RMS) voltage on the wires connected to the coils (the back EMF). "Kv" is how many unloaded rpm the motor will run for each volt that is connected to it. High winding resistance, with two windings in series for each phase, provides high torque at low rpm, which is desirable for the terrain conditions faced by rovers at the URC.

The MRDT also fabricated a custom lithium manganese nickel cell 29.6V 25A nominal operation battery pack with a battery management and power distribution system that ran MDRT open source firmware, and connected to the the RoveComm network. The Drivetrain electronics were designed at 60V, 60A max ratings, in order to add electrical headroom, and create a reasonable margin of safety for competition operating conditions.

The drivetrain sub-system as well as other rover sub-systems are addressable over the 802.11ah Point-to-multipoint network. Wireless communication to the device is accomplished through the MRDT command/telemetry distributed communication software protocol, RoveComm, which acts as the IoT IP gateway for remotely publishing and subscribing telemetry and dispatching commands to individual subsystems over duplex UDP streams. RoveComm is an open source C++ library that is compatible with both the Arduino Wiring software framework and the Texas Instruments Launchpad Boosterpack hardware standard and is currently made available on the MRDT Github repository [2].

PMSM VFD CONSIDERATIONS

Electrical Machines convert electrical energy to mechanical energy using magnetic field interactions as the link between the two types of energy. Electric motors are unique when it comes to their power band, creating power across changes in this magnetic field linkage by different mechanisms with different transfer characteristics that vary greatly by motor type, power source, and available sensor feedback for various control schemes. PMSM's offer compelling improvements over other motor topologies, at the expense of added sensor feedback complexity and digital control requirements.

The advantages in PMSM's are well known when compared to other motor topologies, and include higher torque and speed bandwidths, lighter weight, smaller size, greater efficiency and increased dynamic response. The permanent magnets produce a high torque-to-inertia ratio, responding quickly to control-signal changes, making them useful in dynamic traction applications. Most motors produce their maximum torque at a particular speed range, called the torque peak. Above or below the torque peak, the motor produces less torque than that maximum value. PMSM's however, can operate at all speeds while maintaining the full torque output at the rated load. Assuming ideal flux alignment waveforms from the timing controller, system efficiency is high and any applied load within operating region will only change the phase angle of magnetic of coupling between rotor and stator to take the load, keeping the physical rotor speed constant. Any load attempting to slow the rotor will induce a slippage in the rotor field, and a corresponding current increase at the inverter, and as long as power output of the drive is not exceeded and the ideal flux alignment maintained, a compensating torque will be generated in order to maintain speed [3].

Disadvantages of the PMSM are primarily due to the choice of sensor used to fulfill data feedback requirement. When wired directly to any constant frequency power source, the PMSM will not spin. Sensor feedback and digital control are required to operate the motor. A PMSM is a synchronously commutated motor, meaning that its rotor spins at the same speed as the motor's internal rotating magnetic field. A timing controller must be employed to ensure the stator field and the rotor field maintain consistent linkage [4].

Three separate torus structures in the PMSM stator are wound in a symmetrical way, with three separate coil loops wound at an angle of 120 degrees from one loop to the next, wired together with respect to a shared system ground. The rotor is made of permanent magnets mounted around the rotor perimeter and aligned such that the field strength around the perimeter of the stationary rotor maintains a static magnetic field with a single true north polarity (negative) peak and a single true south polarity (positive) peak, at rest with respect to the rotor. For any position of the PMSM rotor, regardless of changes to load, speed, and supply frequency, there is a single direction of the stator field which maximizes torque, as well as a single direction which will produce no torque. When the rotor position is such that a pole of the rotor is near a pole of the stator, the poles repel each other and torque is produced. When the rotor position is such that a pole of the rotor is balanced between two poles of the stator, the poles balance each other, and no torque is produced [3]. In order to maintain flux linkage, the stator field must magnetically rotate in sync with the physical rotation of the rotor and rotor field. This dictates that the supply voltage requires knowledge of the rotor position, in order to determine which stator coils to energize, and leads to expense increases due to the sensor-connection cables and the electronic management needed to run synchronous commutation algorithms. A microcontroller is needed to energize the stator coils at the correct moment using input from sensors indicating the position and speed of the rotor [4]. Maintenance issues center on the lifetime and reliability of the sensors.

PMSM's with motor lead voltage ranges below 120 Volt AC are often also referred to as Brushless Direct Current Motors (BLDC) due to their intended applications, rather than their topology. In the lower voltage market, the PMSM is generally still referred to as a DC motor because it's coils are typically driven by a lower voltage DC power source and a crude trapezoidal waveform applied to the stator coils in a sequential pattern by some type of digital controller instead of the expected higher voltage continuous power available at the common three phase AC industrial installation.

Several techniques exist to operate the synchronous motor, all involving some form of digital control. The most popular technique commonly available in the low voltage market is to monitor the rotor position using Hall-effect sensors and apply a digital power commutation as a trapezoidal energizing sequence by switching the dc bus supply voltage in order to vary the current of the motor. By using Hall-effect sensors, motor flux linkage can be phase-found with zero initial movement. Bipolar Hall-effect sensors incorporate multiple magnets into a simple structure referred to as a ring magnet to measure voltage (back emf) on an internally applied current [].

In a typical low voltage permanent magnet motor, the three latching bipolar Hall sensors are mounted on the stator at 120 degree spacing with respect to the rotor axis of revolution. Latching Hall-effect sensors act as a sample and hold capture and require both positive and negative magnetic fields to operate. A magnet presenting a south polarity (positive) magnetic field of sufficient magnetic flux density will cause the device to latch to its on state, even after the magnetic field is removed. When a north polarity (negative) magnetic field of sufficient strength is presented, the device reverts again to an off state. Regardless of the number of stator coils and rotor poles, each particular possible position is only available once per rotation, describing one electrical cycle for each complete mechanical revolution. When taken together, the three binary outputs of the Hall-effect sensors form a three-bit word, resulting in 8 possible digitally coded position readings, with only 6 codes representing valid positions. Readings of “000” and “111” are typically considered illegal values, and may be ignored or flagged by the digital controller as a fault condition, indicative of a bad connector, a wire harness that has been cut, or the Hall-effect power supply has died. The motor’s electronic controller may energize the three stator coils sequentially in response to the Hall readings, turning off on one phase and simultaneously switching on the other two phases at each state. This creates trapezoidal waveforms via a process known as commutation to generate a rotating electric field [4].

To produce torque on the shaft, the timing between control current flowing through the coil and the position of the shaft must be as accurate as possible. It can be easily seen that with a six-step sensor technique there is no possibility of keeping the angle between the rotor magnetic field and the stator magnetic field precise. The real angle varies from 60° to 120°, leading to inefficiencies and instabilities. Any error in the Hall-effect sensor switching point and any delay in the sensor’s response to changes in the magnetic field leads to lower bandwidth and accuracy. Inaccuracy in the commutation in lower effective torque and introduces a torque ripple commonly referred to as cogging torque, that will impact stability, reliability, efficiency of the overall system performance [4].

Pulse Width Modulation, or PWM, generates a chopped output waveform from a steady voltage by periodically switching transistors on and off []. Each of the three motor terminals are switched, either at the voltage supply, or the system ground, for any given instant. By it's nature, a motor is effectively a passive integrator, or inductive low pass filter, and when the PWM is intrinsically filtered by the inductance in the motor, the power output waveform is the average of the applied voltage over time. By varying the duration of the periodic on state, a variable voltage may be applied, allowing voltage control of the motor's speed. Motor terminal PWM, however, is not generally viable on the three phase outputs of small, high speed synchronous motors, as they are typically designed with very low inductance and high resistance. If PWM is applied by the power transistors of the three-phase inverter to the motor terminals on such a motor, the current waveform will rapidly and frequently magnetize and demagnetize the metal, causing high thermal losses and magnetic hysteresis [3].

Electronic speed controllers intended for these motors, typically utilize a second PWM signal at a high frequency (above 10Khz) coupled to an inductor and the capacitor to set the DC supply voltage itself at the desired level, called variable DC link. The motor power stage still uses the same six power transistors to fully turn on and off the three-phase commutation, however the DC bus voltage level is controlled by the two additional transistors in the variable DC link. The variable DC link six-step inverter controls the base voltage on the motor by filtering high frequency PWM, while the discretely switched commutation is performed by the three-phase power phases of the inverter. The digital controller can buffer the captured the Hall-effect sensor readings and utilize them in the voltage scalar controller. Each new arriving edge of any Hall sensor signal calls the interrupt routine commutation algorithm. As there is a delay between the Hall sensor edge and the current commutation, the current is not symmetrical, and commutation advance is usually generated using a timer countdown in order to compensate. The timer countdown period is calculated using a lookup table of timing sequences for each commutation sector and the time between two particular commutation edges in the previous step. Two problems arise that usually necessitate additional sensors. First, as the Hall-effect sample rate is a function of the rotor rotation rate, and at low speeds, when the motor is going really slow, the signal gets contaminated with quantization noise, and the decrease in reaction time leads to complexity and instability. Second, in drive train applications, low end torque, which is proportional to current, not voltage, can be quite high, leading to large spikes in current draw. To address these issues, current sensors are usually added, in order to provide the required current mode [].

For motors with a high enough inductance and low enough resistance, motor terminal PWM may be employed. A PWM sinusoidal commutation sequence improves operation, but usually necessitates more sensor complexity. Sinusoidal commutation operates in much the same way as the traditional six-step trapezoidal commutation, but typically utilizes an higher resolution sensor or encoder to measure rotor position, and a lookup table of trigonometric values to determine the PWM commutation sequence [4].

One of the most economical techniques used to measure motor current is to use a precision resistor placed at a strategic location in the motor drive circuit, with one end of the shunt resistor connected to the ADC's ground reference, usually grounded to the negative rail of the drive's DC bus to eliminate any common mode signals. In a three phase motor, assuming no winding shorts, it is only necessary to read two of the motor currents, since the third current will be the negative sum of these two currents. Some drives use an optional third resistor shunt so they can detect winding shorts [].

Motor and Hall sensor geometry inaccuracies cause many unwanted conditions to occur. If high voltage builds up on the DC supply, the variable DC link inverter will switch to connect the bus to a drain resistance to ground, called a brake resistor, to reduce voltage. In the case of overvoltage, undervoltage, overcurrent, or incorrect commutation edges within a certain number of commutations, a base block circuit may be utilized to block the base of each power transistor and enforce an off state. A fault LED may also be displayed at the controller [].

Most externally mounted incremental encoders measure the rotational motion of the axle shaft. The angles are measured at constant time intervals, giving the measurements needed to compute speed, delta angle, and delta time. Speed is computed by dividing the delta angle by the delta time. With an integer sine and arcsine lookup table stored in memory and integer computations used for speed, computed trigonometric relationships can determine the magnitude of the PWM duty cycle to approximate a sinusoidal waveform during commutation. Position information from the encoder is used to synthesize two sinusoids, one being 120 degrees phase shifted from the other and these signals are then multiplied by a throttle or torque command so that the amplitudes of the sine waves are proportional to the desired output. Unlike Hall sensors, high-resolution incremental optical encoders only measure changes in relative position. Direction, velocity and acceleration may be derived in software, but it is not possible to determine the absolute position of a stationary axle, at rest with respect to the encoder [].

Successful motor commutation requires some initial phase-finding technique when the location of the field vector unknown at power-up. The Stepper phase finding technique consists of energizing the stator winding and tracking the initial rotor movement to the nearest magnetic pole. To avoid incorrect phase finding at a null position of zero torque condition, the technique implements a small open-loop commutation move and allows the motor to cog and stutter slightly before encoder acquisition occurs, and the closed loop commutation sequence can begin. Even with a high resolution position encoder where precise velocity information may be available, at slow speeds the signal is likely to be contaminated with quantization noise []. The encoder will also increases system cost and complexity. Encoder cables and mounting considerations add critical points of failure to the system.

While a high-resolution encoder driven sinusoidal commutation is an improvement over Hall-effect driven trapezoidal commutation, it is still not the optimal control sequence for the PMSM. The motor is an inductive system with complex field linkages changing with respect to time. Any load induces temporary slip in the rotor flux linkage with respect to the rotor. Instantaneous voltage is the applied control variable, however it is only the instantaneous component of the current waveform that lags the rotor flux at 90 degrees as transferred to the rotor via the rotor-stator field linkage that contributes to motor torque output. All other voltages and currents are converted to system inefficiencies, such as heat, and cogging torque. In sinusoidal commutation, commutation is performed first and is followed by some control of the resulting sinusoidal current command signals. The controllers in a sinusoidal system are therefore exposed to the time variant currents and voltages of the motor, and motor performance is limited by bandwidth and phase shift of the controllers [].

MRDT PMSM VFD

Flux field orientation seeks to optimize the torque production of a PMSM by utilizing real time matrix transformations and filters to precisely separate the torque producing flux linkage components from the flux linkage components that only contribute to cogging, heating, hysteresis, speed, and other forms of parasitic power absorption []. The transform operations are well known, and in order to efficiently execute the mathematical calculations and abstract the application from the details of the implementation, these operations have traditionally been implemented in custom OEM ASIC's, or a third party license agreements for FPGA IP cores, to be installed in industrial drives alongside microcontrollers, typically in stationary installations, and typically at standard industrial voltages of 120, 220, and 408 VAC.

The cost of digital signal processing cores capable of hardware accelerated mathematical operations that model motor flux in real time has fallen significantly over the last decade, primarily due to Moore's law, which describes the exponential growth in silicon processing and computing density that has occurred over the past half century. Recent digital motor control DSP hardware solutions now often come preloaded with many parameterized application programmer interface definitions, allowing access to Read Only Memory (ROM) function calls for object oriented instantiation of common field orientation modules related to flux tracking operations.

The 2017 MRDT PMSM VFD leverages the vendor specified algorithms available in ROM on the Texas Instruments C28x DSP core, utilizing hardware accelerated implementations of rotor flux position and motor parameter estimating sliding mode observers, tightly coupled to Clarke and Park transforms feeding current mode PI filters. With only simple and direct PWM triggered ADC measurements internal to the drive itself, optimal dynamic torque response is provided without external sensor readings, thereby eliminating the added cost, complexity, and fragility of the various motor shaft sensor implementations, while still providing an improved motor performance when compared against traditional low voltage synchronous commutation schemes. By acquiring the position of rotor flux, stator current vector, and their linkage components at orthogonal angles, the VFD may derive the optimal applied signals necessary for optimal torque production at the motor.

The flux oriented coordinate transformations are collectively referred to as the DQ transform, and this technique is able to realize the optimal control sequence for the PMSM by leveraging the ability to align a complex plane consisting of a direct (D) axis and quadrature (Q) axis oriented with respect to the flux vector. The result is transformation from that of a complicated flux coupled AC motor magnetic field model, into a simple linear system of a two axis. A direct flux axis represents a single scalar motor flux variable responsible synchronous speed, and the second axis represents the single scalar motor flux variable responsible for flux linkage induced torque. Speed and Torque producing flux may therefore be directly monitored and controlled independently. As part of the coordinate transformation, an estimation of the motor's speed and the position of the rotor can also be derived from the observed stator currents, effectively removing the need for any encoder from the design, and reducing the system cost and fragility [4].

The zero-direct-quadrature transform, also called the alpha-beta transform, is often used in the context of electrical engineering with three-phase circuits to rotate the reference frames of AC waveforms such that they become DC signals. In reality, any three phase values of the PMSM are oscillating in such a way that the net vector is spinning about the Z axis, in a balanced system. From Trigonometry, in order to specify a vector's magnitude and angle, a coordinate system with only two axis is needed, removing the redundant phase. It is possible to rotate the reference frame, and therefore model the machine as a single sine axis coil and a single cosine axis coil, such that changes due to net vector spinning are canceled out. Simplified calculations can then be carried out on these DC quantities before performing the inverse transform to recover the actual three-phase AC results [4].

The Clarke transformation is a motor specific implementation on the zero-direct-quadrature transformation, modeled as a tensor that rotates the reference frame of a three-by-three element matrix in an effort to simplify analysis. Typically, motor terminal currents are measured by triggering ADC channels at the peak of the PWM cycle, at the instance where all upper power switches are on, to avoid any PWM transients. This requires synchronous trigger channels from the enhanced PWM modules to the ADC modules. The two shunt currents for an isolated stator are scalar values readings are taken for each phase, added together, and the sum is negated, in order to derive the third phase. This is then reflected about the magnetic axis to get the third vector. The three current vectors exist in the stationary coordinate frame where a, b and c are the phase axes, with α and β being a fixed Cartesian coordinate frame aligned to phase a. The forward Clarke transform operation uses three multiplications and a single subtraction to convert the three balanced abc phase currents into two phase-balanced αβ currents. Despite the effectiveness of this transformation, many complications still arise. The initial dynamics of the system are highly nonlinear, and the rotor flux is not usually measurable. Quantities such as the rotor resistance value vary considerably with conditions, and have a significant impact on the system. When tracking a variable speed signal with respect to a stationary signal, an inherent sample and tracking skew is created, inducing phase delay to the system. In the αβ frame, the expression of torque still depends on the position of the rotor flux and still prevents any easy solution of the electrical differential equation [4].

The inputs to the flux estimator are the motor output phase currents and voltages expressed in α-β coordinate frame, and it is possible to fully reconstruct the system state from these output measurements, using a filter based estimation technique to track a series of measurements observed over time.

Tracking Filters, or Alpha/Beta filters, are second order low pass Infinite Impulse Response filters in which feedforward compensation is added to minimize the phase delay. When a simple second order low pass Infinite Impulse Response filters is implemented as two cascaded integrators, the output of each stage can be monitored and act as the derivatives of the tracking variable. For example, in a cascaded two pole IIR filter tracking rotor position, the rotor velocity may be taken of the first integrator feedback section, and rotor acceleration may be taken off the second integrator feedback section, effectively estimating two variables with respect to the filtered measurement variable [4].

Sharp-cut-off notch filters can help eliminate narrow-band mechanical resonance, removing energy that would otherwise excite resonant modes and possibly make the system unstable. In a second order filter, a zero may be added at the same location as the unstable pole to cancel the pole by pole-zero cancellation, effectively converting the system to a more stable first order response [4].

In the standard series two pole amplifying integrator realization of the PSMS tracking filter, complex poles may be avoided, by setting the amplitude of the inner gain to the same quantity as the R over L of the motor under operation. R over L refers to the ratio of resistance and inductance values that would be measured over the total inductive path of the stator winding, and is effectively the inverse of the system's time constant. Once this operating point is realized, the amplitude and phase of the filter may be set independently. Any gain change in the tracking system shifts the amplitude ratio up or down, but does not affect the phase angle. Any change in the time delay affects the phase angle, but not the amplitude ratio [5].

The Park transformation is next adopted in order to completely eliminate the effect of time-varying inductances, by combining all stator and rotor quantities into single rotating reference frame. The Park operation transforms the two-axis orthogonal stationary reference frame quantities into rotating reference frame quantities. Similar to jumping onto a merry go round before taking photos of a subject, the transform jumps the αβ stator field reference on the rotating frame of the rotor field, resulting in a two phase DQ system [5].

In a two-phase DQ system that rotates at the electrical speed of the rotor, the D axis is directly aligned with the electrical position of the rotor flux and produces no torque. In this frame, the electrical expression of the torque becomes identical to the phase alignment of the Q axis, and is independent from the rotor position. In practice, the Forward Park transform takes the angle of the rotor flux and calculates trigonometric expansions by utilizing lookup tables pre calculated for the expected operating ranges [5].

Finally, discontinuous control may also replace the equivalent continuous measurement information about the unmeasured flux states. By switching estimate states asymptotically closer to true unmeasured values, the Sliding mode brings the estimated state error to zero in finite time. When employing the flux estimator to replace a shaft encoder, the location of the field vector is still unknown at power-up. Consequently, the field vector location must be determined using some initial phase-locking technique. The Dither technique locates the field position through high frequency (10k+) PWM injection. By setting a known stator vector orientation with a very high frequency at very low duty cycle, the filter can wait several microseconds to observe the initial direction of the field acceleration, as calculated from changing current response. Based on the initial acceleration, the angular extent of the region containing the armature field vector can be continually reduced in the sliding mode, by repeated process of successive approximation. The Dither technique is only applied to a static rotor at rest, and once the system has been initialized to a tracking state, the Field Orientation routine takes over, and the Dither ceases. The goal is to have smallest possible time and position change during the sequence of dithering. When the Dither is initialized, the sliding mode quickly converges the system by application of a discontinuous control signal, in order to force the system to slide along the normal continuous behavior, in discrete steps. The estimation error switches rapidly from one continuous structure to another with some inherent zig-zag like overshoot, before converging to a localized window of stable observation. This nonlinear high gain observer method has attractive noise resilience properties and provides quite similar to the common Kalman filter. Despite the statistical noise and other inaccuracies, good acquisition of a field orientation can be made by the model-driven filter to produce estimates of unknown variables that tend to be even more accurate than those based on a single physical shaft measurement alone [5].

For motors with unknown parameters, equivalent measurement information about the unknown resistance and inductance values of the motor can also be estimated, using identification mode of the controller. Successive series of high frequency injection vectors are applied, first in the voltage mode, and next in the current mode, to the motor terminals at very low average voltages. The small deltas in the current readings drawn during the injection are utilized to perform run time parameter identification routines, commonly referred to as a motor Autotune routine, or Motor Identification routine. In the same manner that the Dither technique leverages the inductive time response of the motor and the convergent tracking capability of the sliding mode, the Motor Identification routine repurposes these same filters to calculate system parameters, by monitoring the system response of the predetermined motor terminal signal injection test sequences. Parameters needed by the real-time responsive control mode of the drive are extrapolated by the Autotune routine, and saved in non-volatile memory. Autotuning a motor is typically recommended upon first time connection to any drive capable of executing the routine [5].

CONCLUSION

In the 2015 URC, the MRDT fielded a Rover utilizing six commercially available trapezoidal digital motor controllers, marketed for electric scooter applications, and utilizing a Hall-effect commutated controller without adequate overcurrent sense and protection. Hall-effect sensor failure was a major source of a multitude of system fault conditions. Cable runs from the sensor were plagued by intermittent connections leading to electrical jitter and motor stutter. Errors in Hall-effect readings led to improper timing sequences and cogging torque. Misaligned commutations increased as discrete segment switching motor cogging became more pronounced with increases in quantization noise. With inadequate overcurrent sensing, fault conditions led to back emf build up across the DC Link Bus. With no motor telemetry available from the drives, the operators continued to drive the vehicle beyond specified overcurrent limits and through periods of high jitter commutation misfires. These effects were especially pronounced at low or zero speed, even for light loads. Without adequate protection diodes to freewheel and drain off reverse current, the power transistor stages become back-biased, the capacitors vented, and the integrated circuits smoked from thermal runaway, catastrophically destroying a motor drive during the competition's terrain traversal, and leaving the Rover unable to finish the task.

In 2016, MRDT fielded a more expensive commercially available Hall-effect commutated trapezoidal digital motor controller with added overcurrent sense and protection. Hall-effect cabling issues still led to overcurrent conditions and backfires in the commutation and lack of telemetry still led to operation of the vehicle beyond specified overcurrent limits. The added overcurrent protection functionality did, however, register the fault condition, shutting down and protecting a motor drive from failure during the 2016 competition. The Rover was only able to recover by remotely power cycling the drive's individually regulated bus via a separate power controller IoT endpoint subsystem, thereby clearing the run-time fault condition and allowing the Rover to complete the task.

The most recent 2017 URC, Gryphon was the only Rover fielded to operate a model-driven observer tracking the quadrature axis flux linkage of each individual motor. As a result, Gryphon showed a dynamic torque response on the Mars-like terrain. Gryphon also presently has a variety of embedded endpoint IoT device subsystems that may benefit in the future from the data acquired by model-driven observers at each motor. As new iterations are developed, captured motor data from competition tasks may be analyzed to better target operating conditions for specific motors and specific terrain. An autonomy controller on Gryphon presently has access to a GPS, IMU data, and a preloaded satellite acquired map of the competition terrain. In the future, by subscribing to motor data locally, topological terrain where high torque output or instantaneous power applied is measured may be tagged by autonomic software routines, in order to facilitate terrain learning classifications. Motor capabilities may be directly incorporated into strategic navigation of the terrain, with the rover itself cataloging areas to approach indirectly, to approach at speed, or to avoid all together. The modular drivetrain system provides a framework for which to developed added value for a distributed network of electric vehicle capabilities.

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