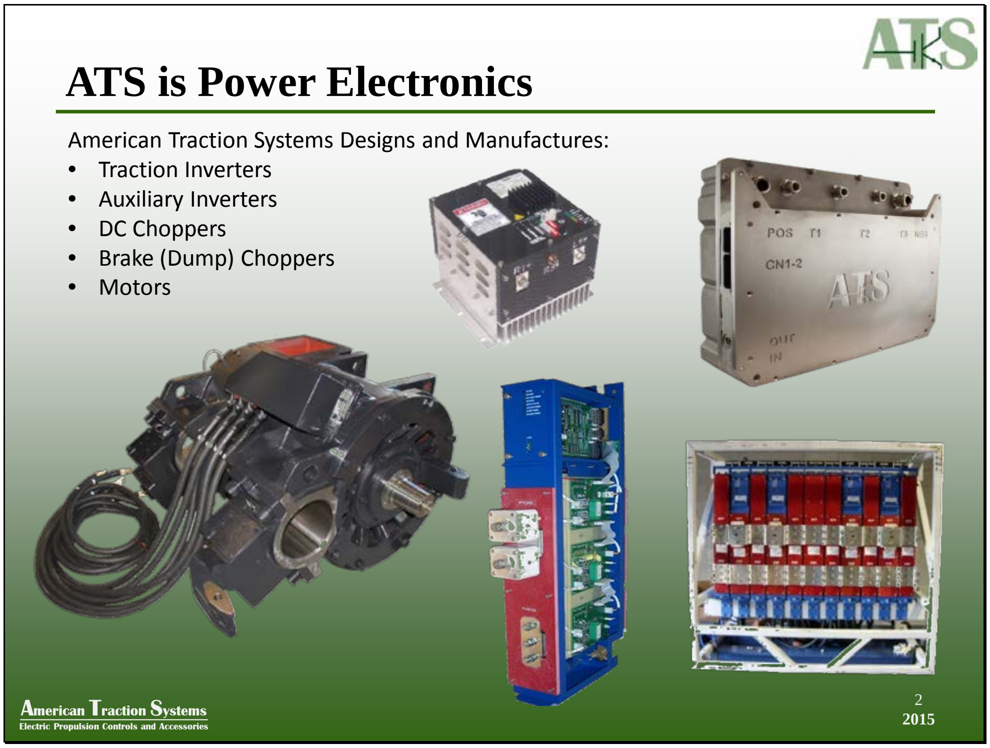
ATS has a long lineage going back to Saftronics in 1968. It was founded by Bonne Posma. He later started Saminco which designs power electronics for mining applications and ATS branched off from Saminco to diversify into above ground applications in 2008.

The majority of ATS' business is in above ground rail applications such as specialty locomotives and trolleys. ATS is also offering power electronics solutions in the marine and rubber-tire markets. ATS offers power electronics at the power levels suitable for rubber-tire vehicles from automobiles to buses, heavy-duty trucks, delivery trucks, class-8 trucks, military vehicles, super-cars, and other heavy-duty vehicles.

If you have taken a ride on a trolley in New Orleans or taken the ferry from San Francisco to Alcatraz or out to the Statue of Liberty, you could have already been on a vehicle propelled by ATS power electronics.

ATS provided the inverters to the TARDEC Ultra Lightweight Vehicle (ULV).



ATS designs and manufactures power electronics focusing on traction:

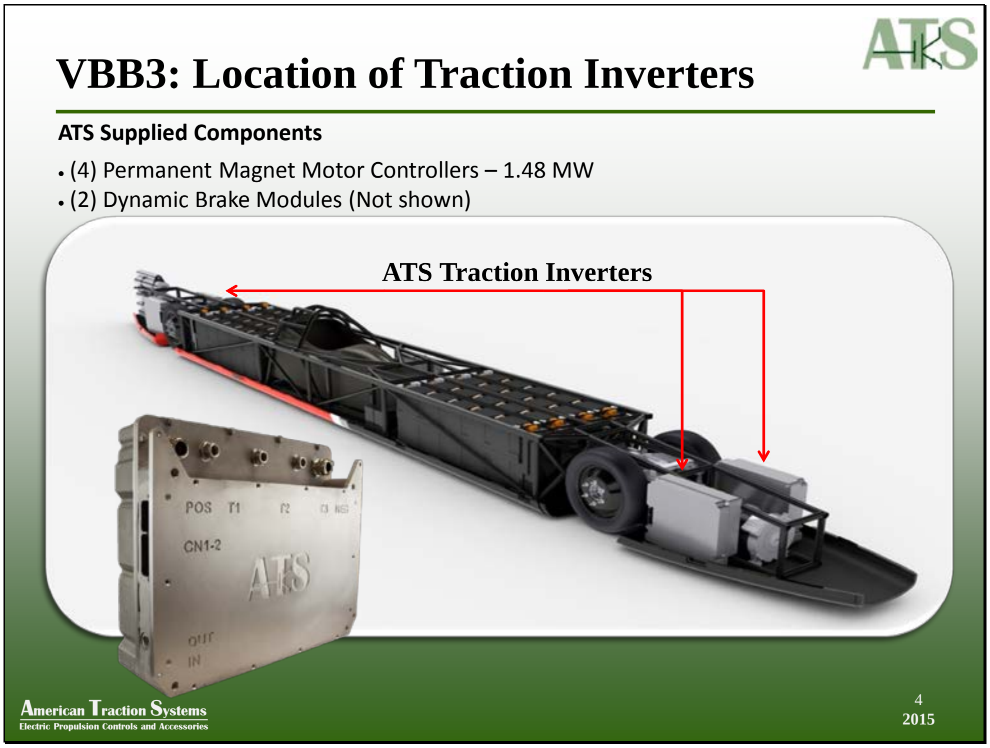
- AC motor (inverter) and DC motor (chopper) controllers for traction
- Auxiliary inverters (VFDs) for supplies (HVAC, radio, headlights, pumps, blowers, etc.)
- Locomotive Induction Motors

Venturi Buckeye Bullet 3

- Battery Powered Land speed streamliner designed by students at The Ohio State University
- Record Runs at the Bonneville Salt Flats of Utah
- Mission: To be the first electric vehicle to go 400 MPH
- Driver: Roger Schroer

American Traction Systems
Electric Propulsion Controls and Accessories

3
2015

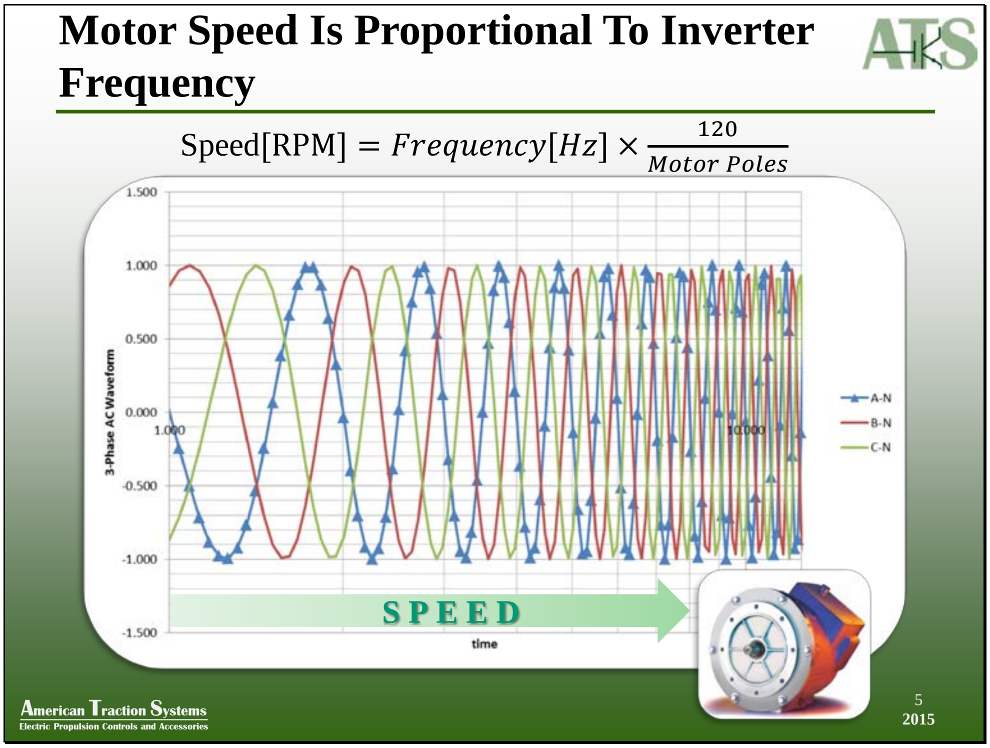


Venturi Buckeye Bullet 3 Specs:

- Weight: 8000lb
- Battery: (4) 850V Lithium-Iron Phosphate batteries
- Motor: (4) 370kW Permanent Magnet Motors (1480kW total)
- Inverter: (4) ATS PML7-600 Inverters (max current 600A_{RMS})

In 2013, the Bullet accelerated to only 90 MPH before the inverters overheated.

The purpose of this presentation is to show how ATS was able to improve its motor control scheme and get the Bullet to higher speeds.

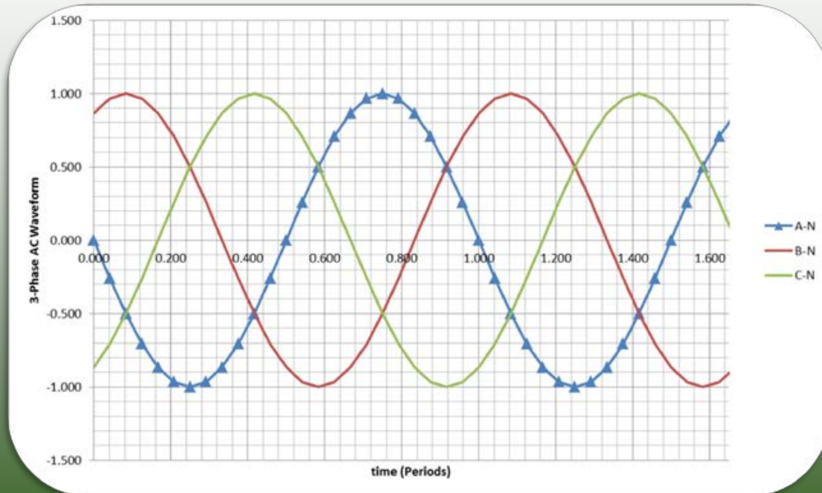


A brief explanation of speed in inverter terms:

- Speed to an inverter and motor is frequency and is proportional to the number of motor poles.
- The inverter produces 3 sine waves to run the motor.
- The faster the inverter produces these sine waves, the faster the motor speed is.
- In the case of permanent magnet motors such as the one in the Bullet, that frequency can be pretty high: 880Hz.
  - For comparison, most industrial motors run @ 60Hz, 200Hz for a traction induction motor and 533Hz for the Tesla Model S motor.

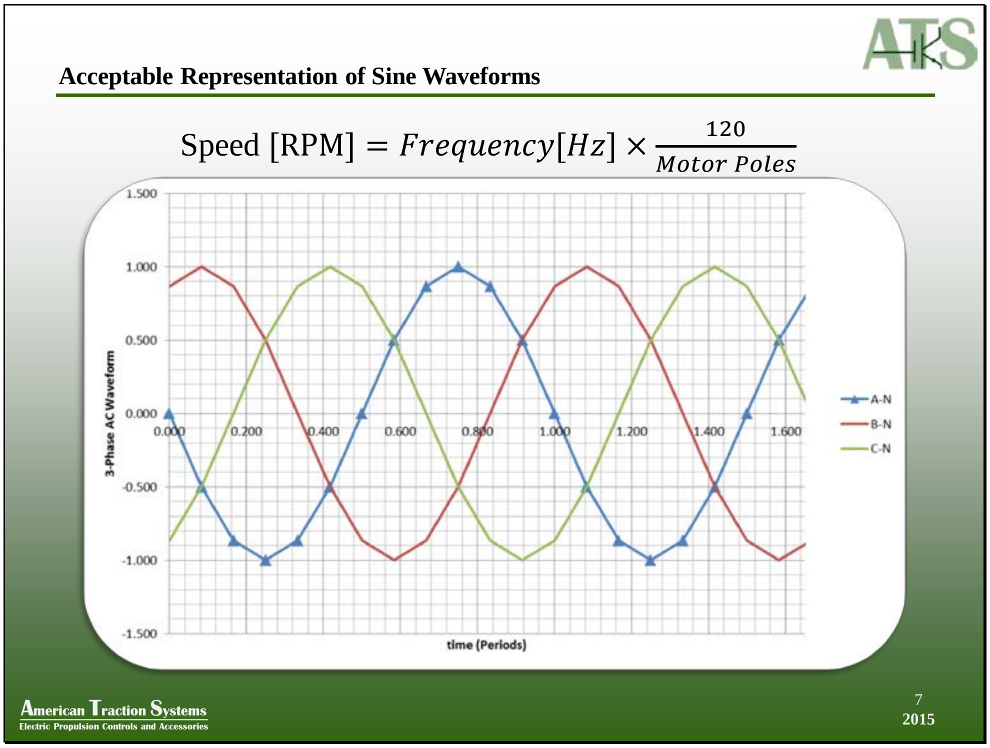
Good Representation of Sine Waveforms

$$\text{Speed [RPM]} = Frequency[Hz] \times \frac{120}{Motor\ Poles}$$

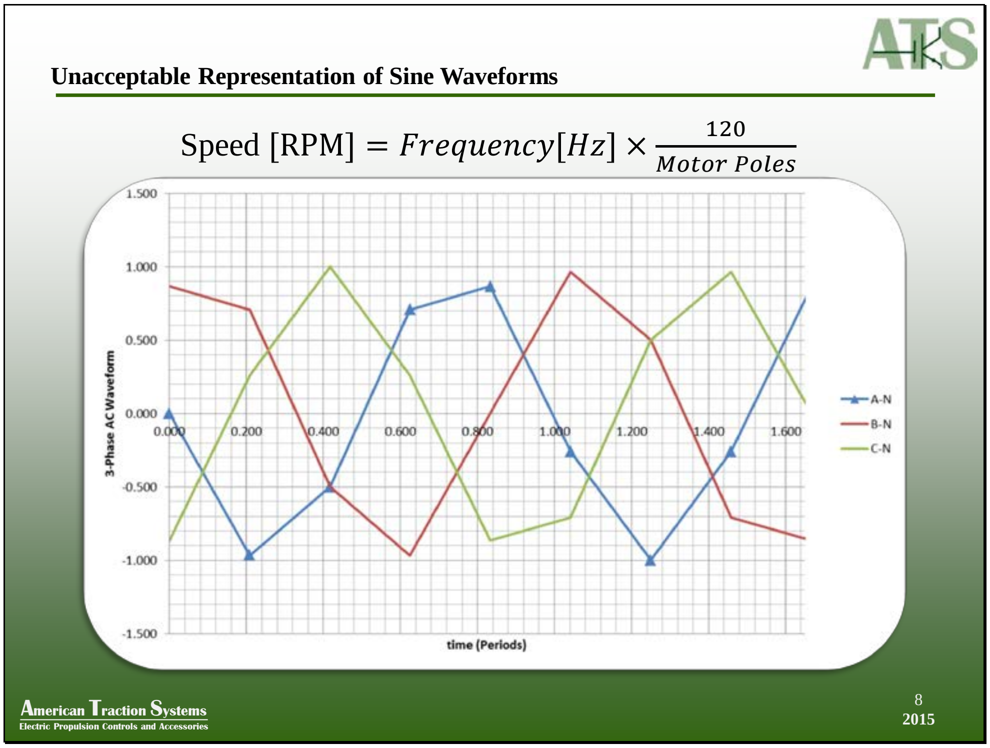


American Traction Systems
Electric Propulsion Controls and Accessories
6
2015

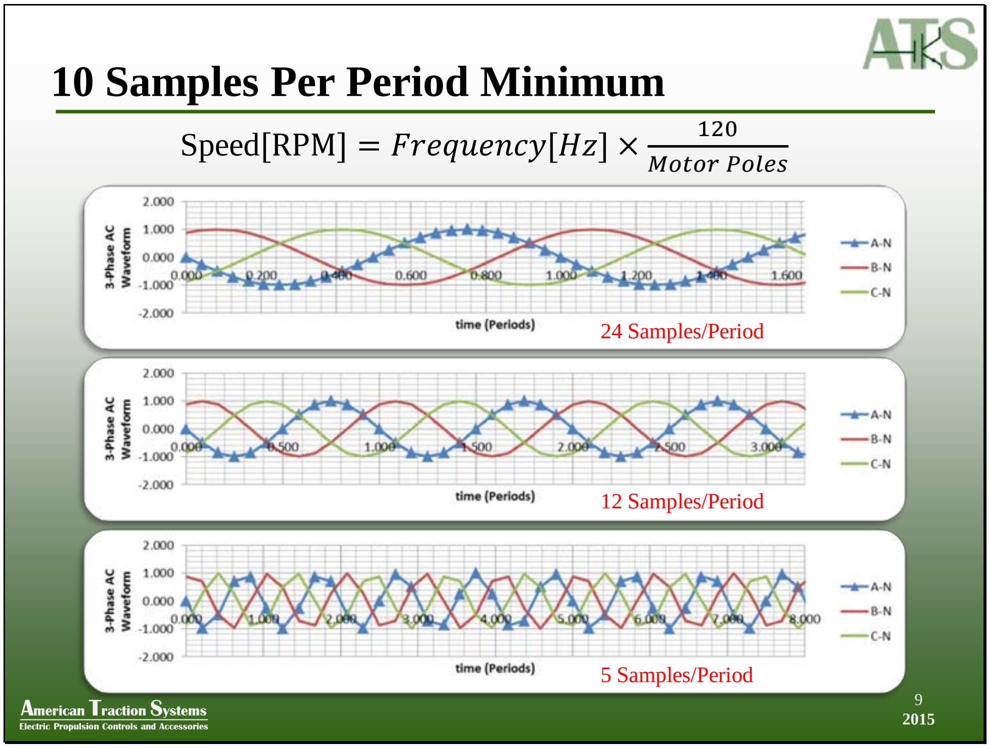
In this case there are 24 samples to represent a sine waveform shown with blue triangles and the sine waveform is constructed well.



In this waveform, only 12 samples are available to produce a sine waveform or only 3 samples per 90 degrees.



In this waveform, there are 5 samples to produce 360 degrees of a sine waveform or only 1 - 2 samples per 90 degrees.



When producing a frequency, we have to consider how often the inverter updates its signals.

- In this 1st waveform, the blue dots show that there are 24 samples to represent each revolution of a sine waveform. In this situation, the sine waveform is adequately constructed.

- This 2nd waveform shows a faster motor speed with only 12 samples per period. This is also a good representation of a sine waveform, but clearly isn't as good as the 1st 24 sample/period waveform. You can already see that if the inverter's output is updated at the same rate, the quality of the signal goes down as the motor increases speed.

- This 3rd waveform is an even faster motor speed and now only 5 samples per period. The inverter may be able to spin a motor with this poor sample to period ratio, but it will likely be very rough and could go unstable.

- Typically, 20 samples per period is a good sample rate, but the inverter can go as low as 10 samples per period and still provide a decent enough representation of a sine waveform to control a motor.

Max Fundamental Frequency Dictates Min Sampling Frequency

$$Frequency[Hz] = \text{Speed[RPM]} \times \frac{Motor\ Poles}{120}$$

$$883.3[Hz] = 10{,}600[\text{RPM}] \times \frac{10}{120}$$

Rounding to 900Hz for simplicity:
If f_1 = 900 Hz
Then f_{SW} ≥ **9 kHz**

$$\text{T}= \frac{1}{f} = \frac{1}{9000\ Hz} = \mathbf{111.1\mu s}$$

American Traction Systems
Electric Propulsion Controls and Accessories

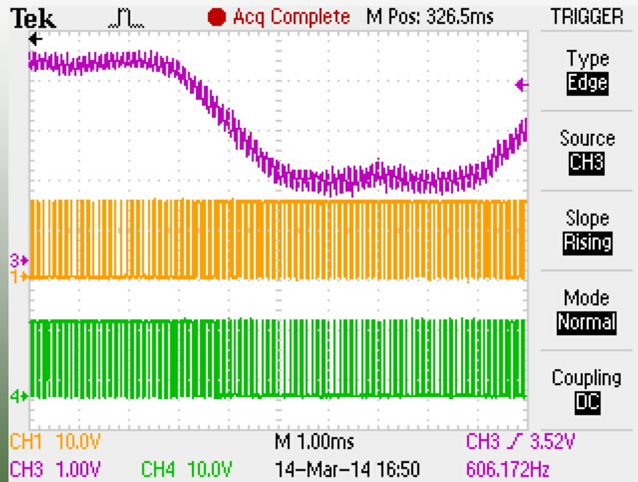
10
2015

In the case of the Remy HVH250, it has a maximum frequency of 883 Hz.

For the sake of simple calculation, the frequency is rounded up to 900 Hz.

Applying the 10 sample/period minimum sample frequency, the inverter would require a 9 kHz sample frequency.

Rate of Refreshing the Inverter Output is the Switching Frequency



American Traction Systems
Electric Propulsion Controls and Accessories

11
2015

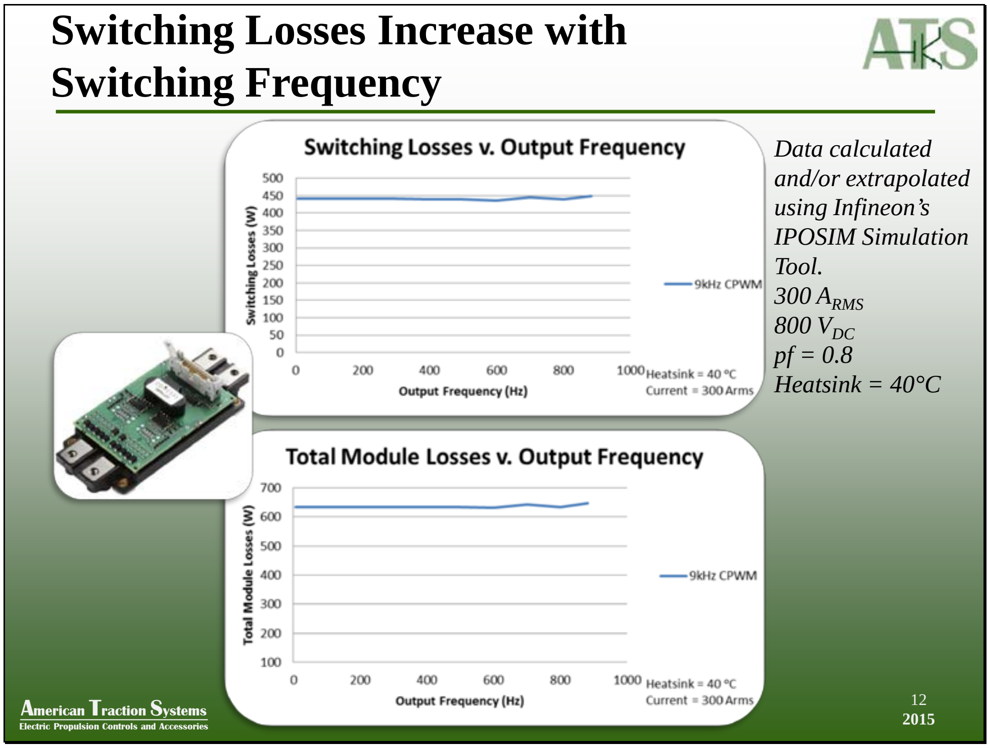
Thus far, the term sample frequency has been used to refer to how often the inverter samples data from the outside world to control the motor. This rate is the rate used to update the control of the IGBTs: the high powered transistors that switch on and off to produce the sinusoidal waves shown.

When a switch occurs, the voltage must go from the positive supply voltage level to the negative level or vice versa. That may be five, six, seven hundred Volts or more. It's called Pulse Width Modulation and is the essence of today's power conversion since it is the most efficient method of varying voltage and power. Yet, inverter designers constantly struggle for improving efficiency of power converters. While conduction losses are mostly a property of an IGBT, switching losses is something that can be affected by controlling IGBTs in a smarter way.

This picture here shows in orange, the bottom, and in green, the top signals, going to phase A of the inverter. They switch on/off, on/off, repeatedly and generate (after filtering) the waveform in pink.

Every occurrence of this switching means the inverter has updated its output to the motor. The more often it updates the output, the better the sine wave can be represented.

The rate that this switching occurs is referred to as the **switching frequency**.



In the case of switching losses for a 600A 1200V Infineon Econodual IGBT switching @ 9 kHz as described before for the Bullet, the switching losses are nearly 450W. You could power your headlights, tail lights, and a pretty sweet stereo if the switching loss waste didn't exist.

The graph shows that the 450W is pretty straight across the speed range. This is for one IGBT! Just one of four inverters on the Bullet has six of those IGBTs.

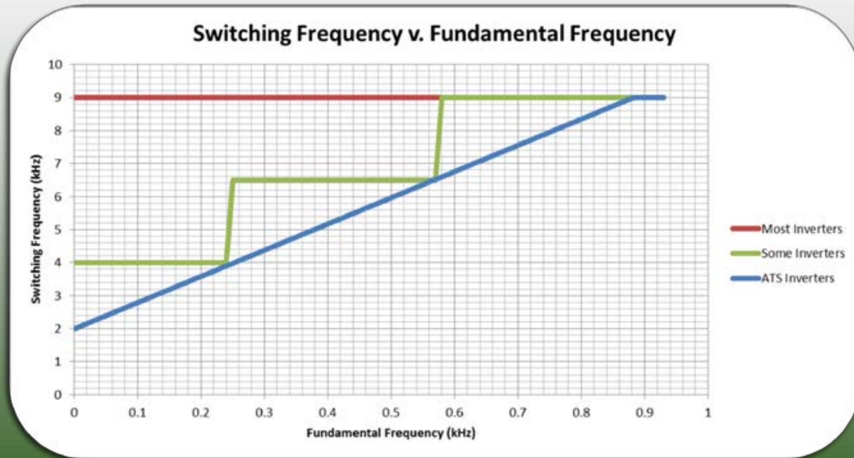
So, there are a combined total of 2.7kW just in switching losses per inverter! This is energy and money basically burning up. Gone. Again, burning up is meant to be taken literally. The losses produce heat and it can be difficult to dissipate 2.7kW of heat especially when the vehicle already weighs 8000lb.

In the case of the Buckeye Bullet, the car was only capable of going 90 mph before the inverters overheated at a 85°C heatsink temperature. This is even after the team was stuffing the cooling tanks with bags of ice to bring the starting inverter heatsink temperature to 10°C.

At the time, it was a multi-million dollar land speed car that couldn't go faster than a soccer mom's mini-van.

Varying Switching Frequency Optimizes Switching Losses

The latest ATS inverters use millions of switching frequencies to minimize switching losses.



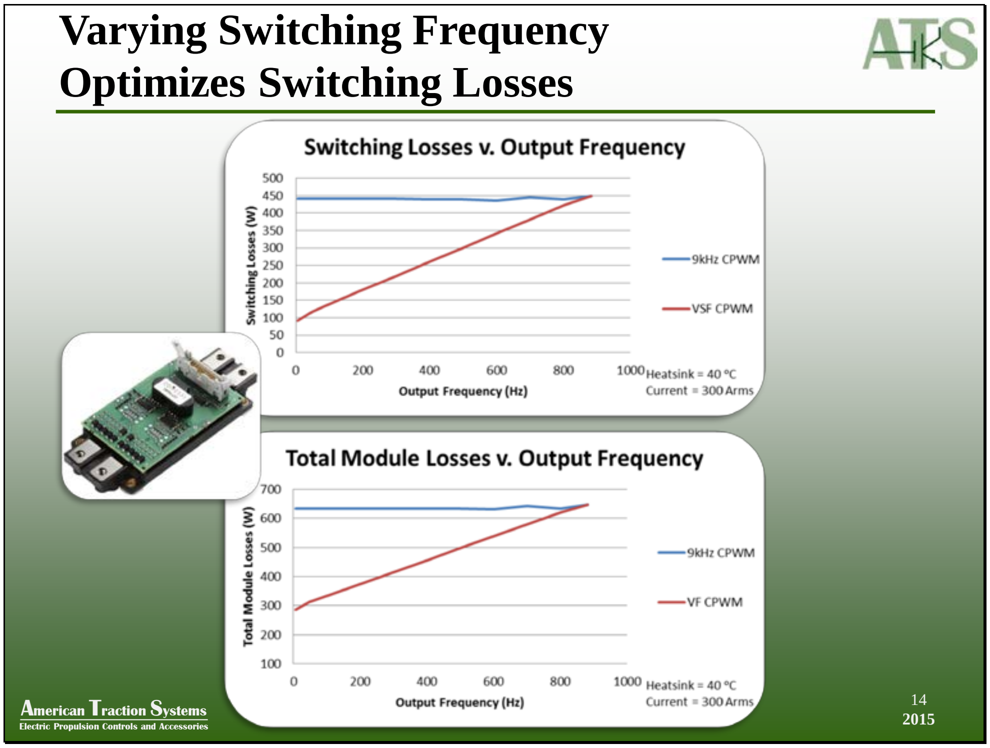
American Traction Systems
Electric Propulsion Controls and Accessories

13
2015

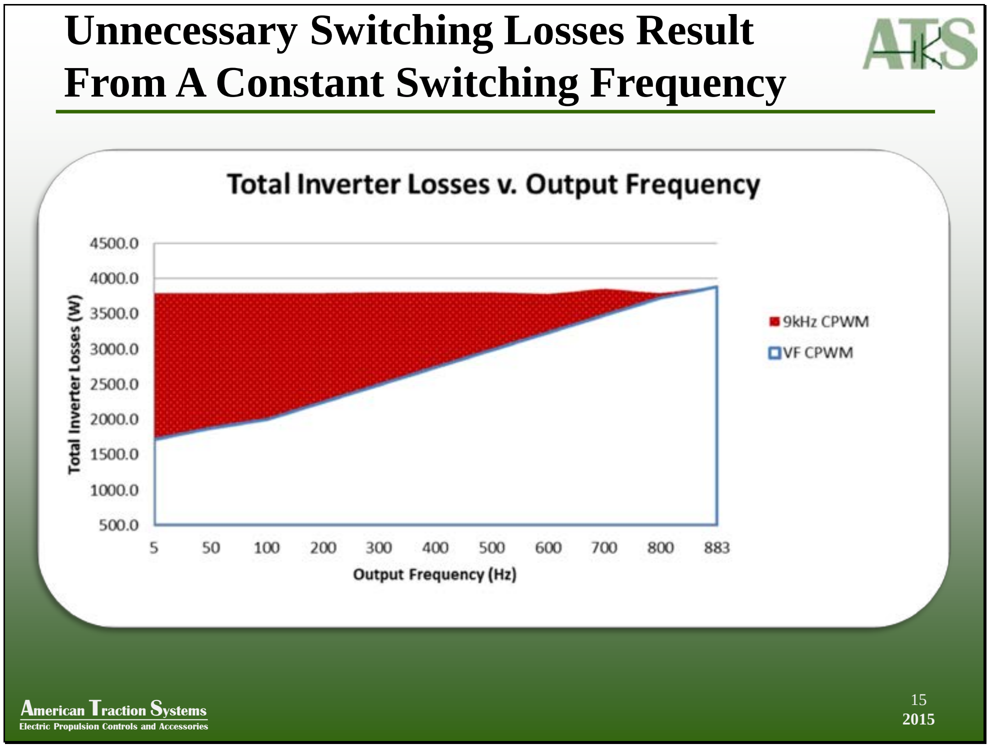
Out of this necessity, ATS engineers, Alex Shipillo and Salvatore Torre looked for some ways to battle this problem. They implemented some techniques in the Bullet inverter that can benefit inverters in all applications.

Now, a 9 kHz switching frequency is needed for 900 Hz, but 9 kHz isn't needed for 90 Hz.

- Most inverters have one switching frequency designed for their max speed (shown in red).
- Some inverters have a couple switching frequencies: low/high speed or low/mid/high speed (shown in green),
- The latest ATS inverters now have millions of switching frequencies (shown in Blue).

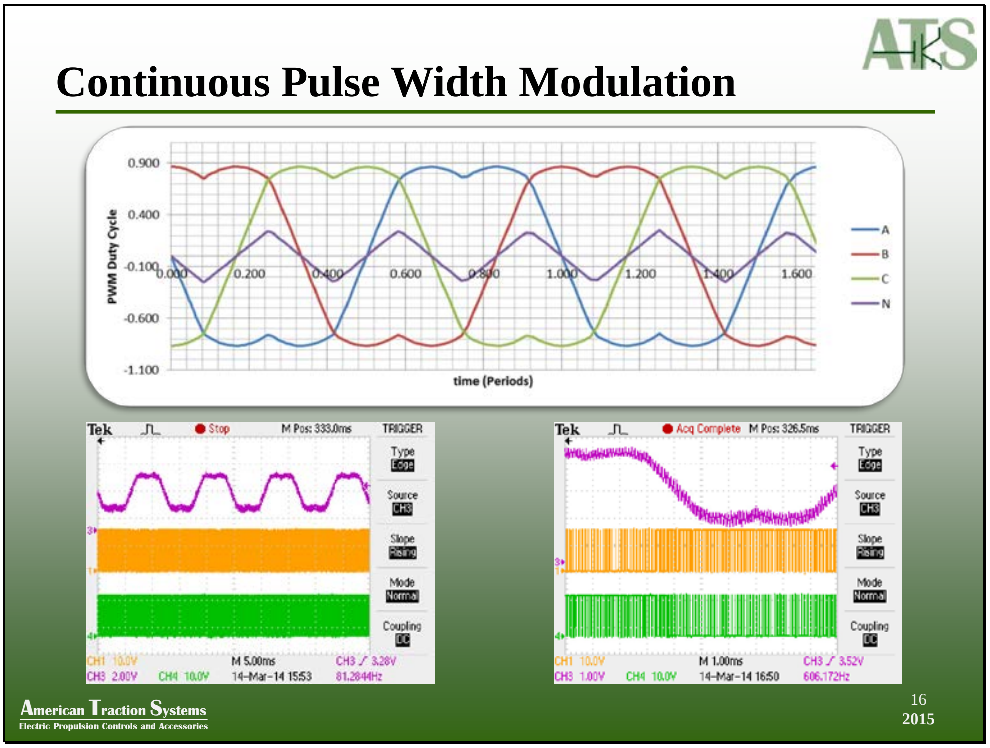


The switching losses while utilizing variable switching frequency decrease from 450W at a constant 9kHz switching frequency to less than 100W at low speed and increase linearly to 450W as the motor speed and switching frequency increases to max speed.



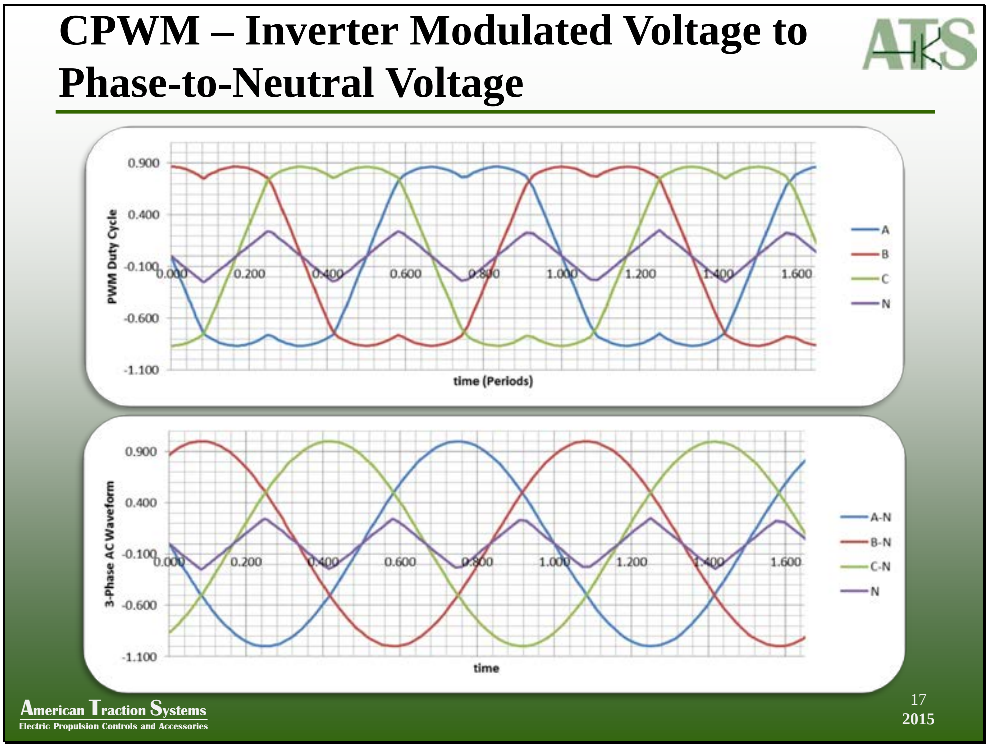
This chart emphasizes the unnecessary losses in red.

- All of those losses can be eliminated with software.
- With fewer losses, there is less heat, and it is easier for the cooling system of the vehicle to keep the inverter in operation.

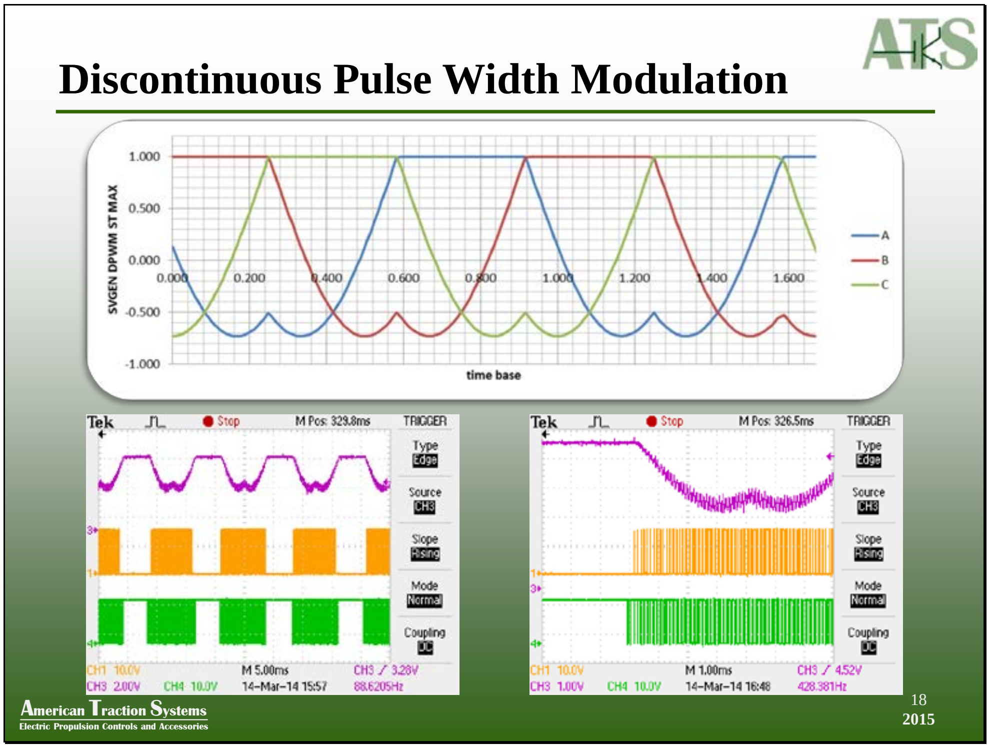


The oddly shaped sinusoidal-like waveform with camel humps represents the PWM duty cycles of each phase that make a sine wave.

- -1 represents 0% duty cycle
- 0 represents 50% duty cycle
- 1 represents 100% duty cycle



When the voltage pulses in each phase come together at the motor, not magically, but algebraically, they combine as three balanced sinusoidal waveforms (shown in the bottom graph). Notice that the neutral point moves up and down (shown in purple).



Here is another trick:

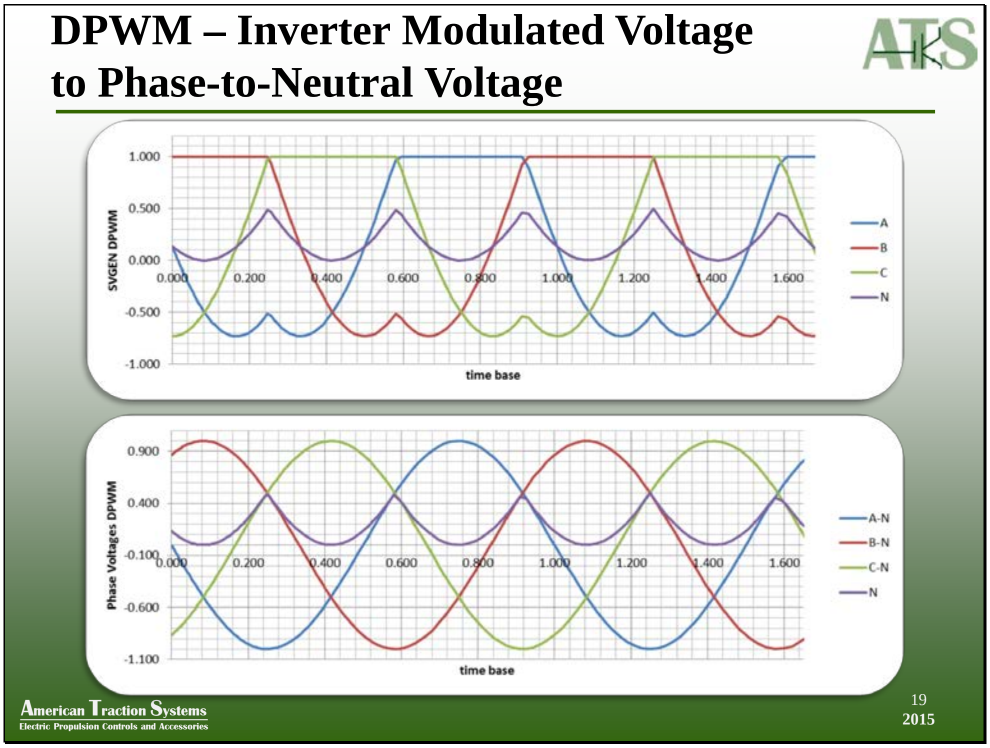
Discontinuous PWM or DPWM:

- The duty cycles look like the ones shown in the top graph. Notice that there are now only “camel humps” on the bottom and thus the state of one of three phases is never switching. In this particular version of DPWM, one of three phases is always at a 100% duty cycle or fully-on.

The charts below show the bottom and top PWM signals of phase A.

Notice the areas in which IGBT switching does not occur. If there isn’t switching, there aren’t switching losses.

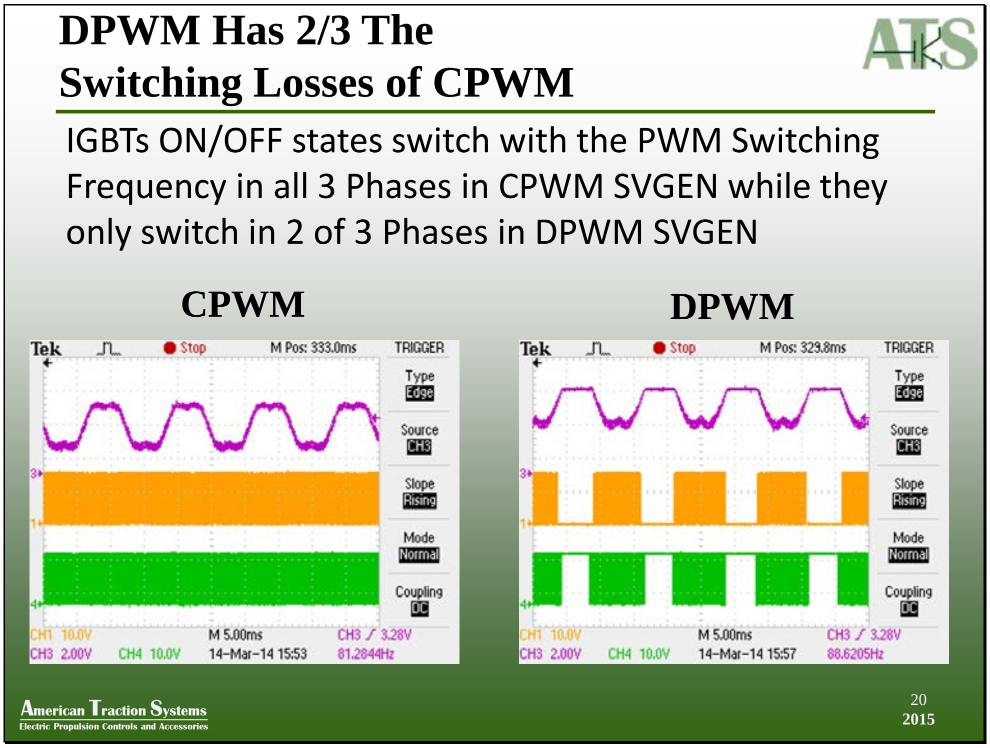
Since only two of the three signals are changing, the switching losses are only 2/3 that of Continuous PWM.



Look up at the top graph: It shows varying neutral point of DPWM.

But hey, look at the bottom graph: The phase voltages in the bottom graph are identical to CPWM.

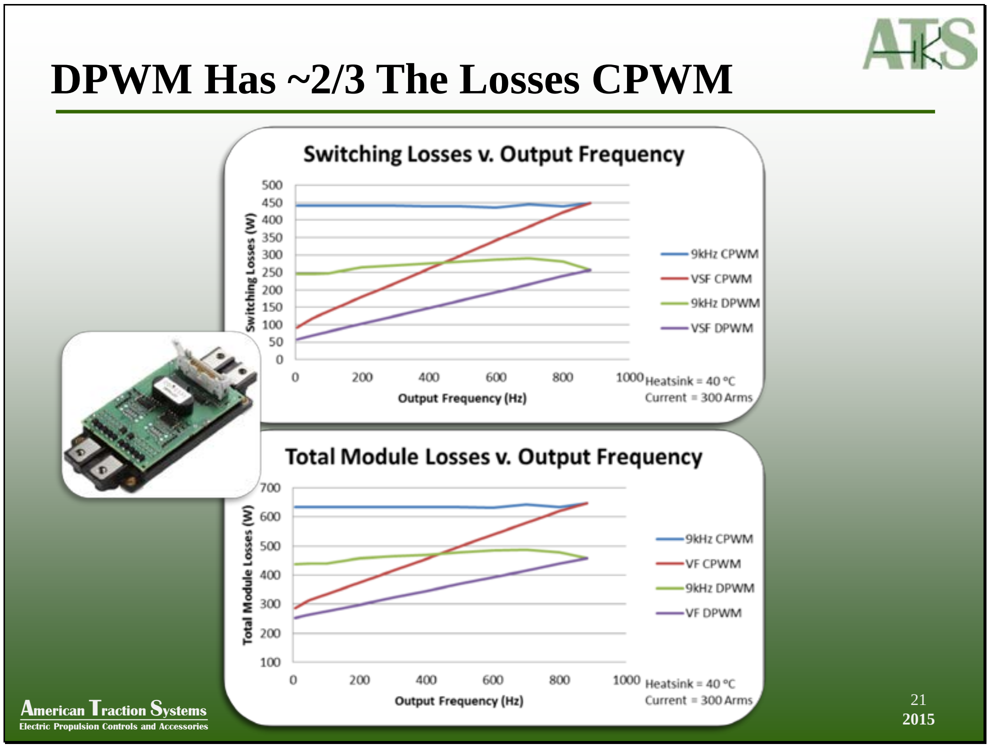
So, the inverter can produce the exact same phase-to-neutral voltages by only switching two of three phases at a time.



This is a side-by-side view of CPWM and DPWM. Again, notice the extra white space in DPWM.

All of that white that is green and orange in CPWM is energy savings in DPWM.

DPWM does have its drawbacks, mainly higher torque pulsations than with CPWM. If the application can support those higher torque pulsations, DPWM is an option to further reduce switching losses.

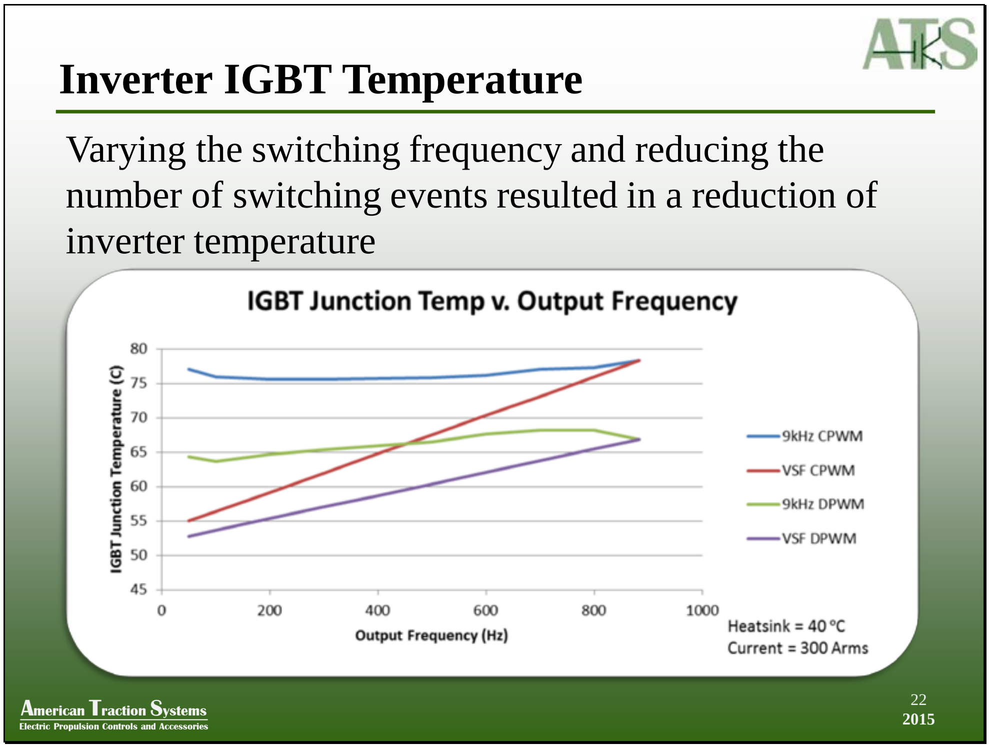


Now, the switching loss vs frequency plots have been updated with DPWM switching at 9 kHz (shown in green).

- The switching losses are much less than CPWM @ 9 kHz: ~275 W vs ~450 W. Notice at about 450 Hz, the losses of DPWM cross the losses of variable frequency CPWM. This is at a 6 kHz switching frequency. It is no coincidence that 6 kHz is 2/3 of 9 kHz.

Furthermore, the switching loss vs frequency plots have been updated with variable frequency DPWM. The losses are even less:

- Ex: 150 W at 450 Hz under VSF DPWM vs 275W at 450 Hz under VSF CPWM & 9 kHz DPWM.

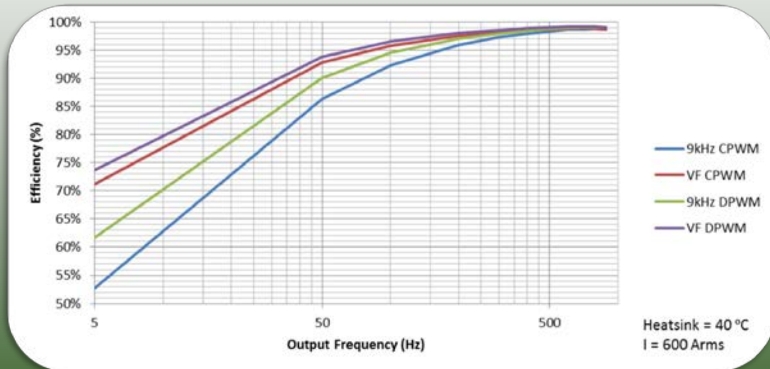


Since one of three IGBTs is taking a break (not switching) at all times, the IGBTs can operate cooler

- Notice that the inverter using DPWM operates about 10 degrees cooler at 880 Hz and over 20 degrees cooler at low speed.

Inverter Efficiency

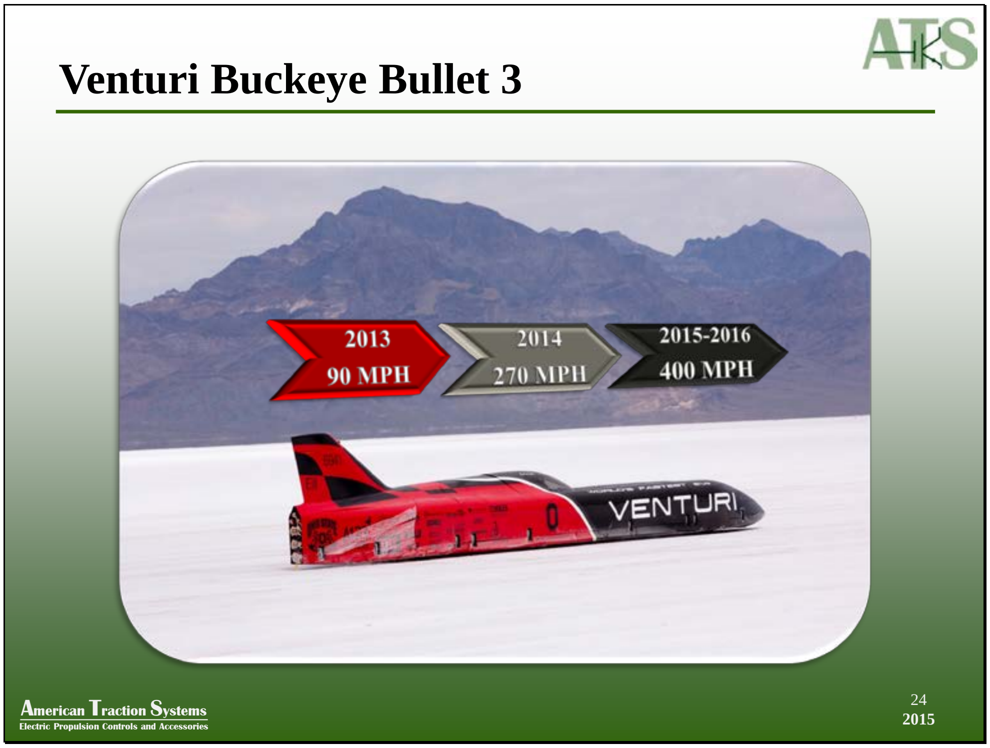
Varying the switching frequency and reducing the number of switching events resulted in a significant increase of efficiency at low speed and high torque



American Traction Systems
Electric Propulsion Controls and Accessories
23
2015

These techniques all have an effect on the efficiency of the inverter:

- At low speeds, the efficiency is 65% - 70% with 9 kHz and 80% - 85% efficiency with VF DPWM.

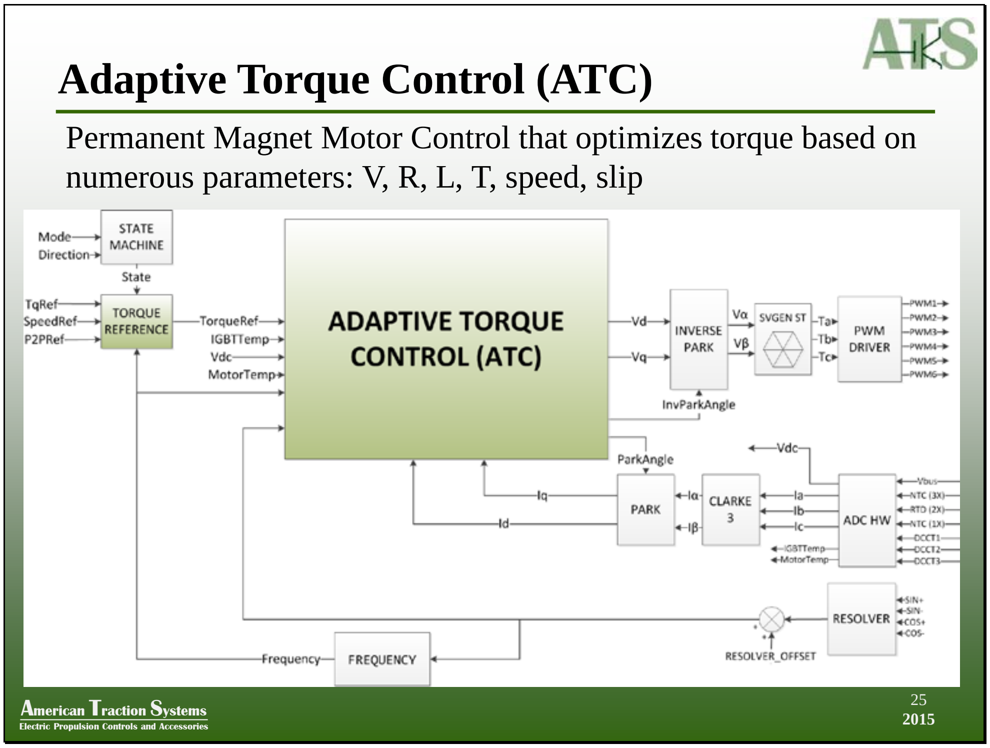


As a result of the switching technique efforts applied to the inverter software, the Bullet went from overheating at only 90 mph in 2013 to reaching its 1st gear top speed of 270 mph in 2014.

In 2015-2016, the Buckeye Bullet team is striving for 400 mph! In August, the team reached a top speed of 288 mph.

That’s a long way away from 400, but they will get there so stay tuned.

In summary, the switching frequency of a permanent magnet controller is high enough (8 to 10 kHz) at high speed (800 to 1000 Hz) that the inverter is susceptible to overheating at low speed. Variable switching frequency can reduce the losses immensely and without the losses, less heat is generated thus preventing the drive from overheating.

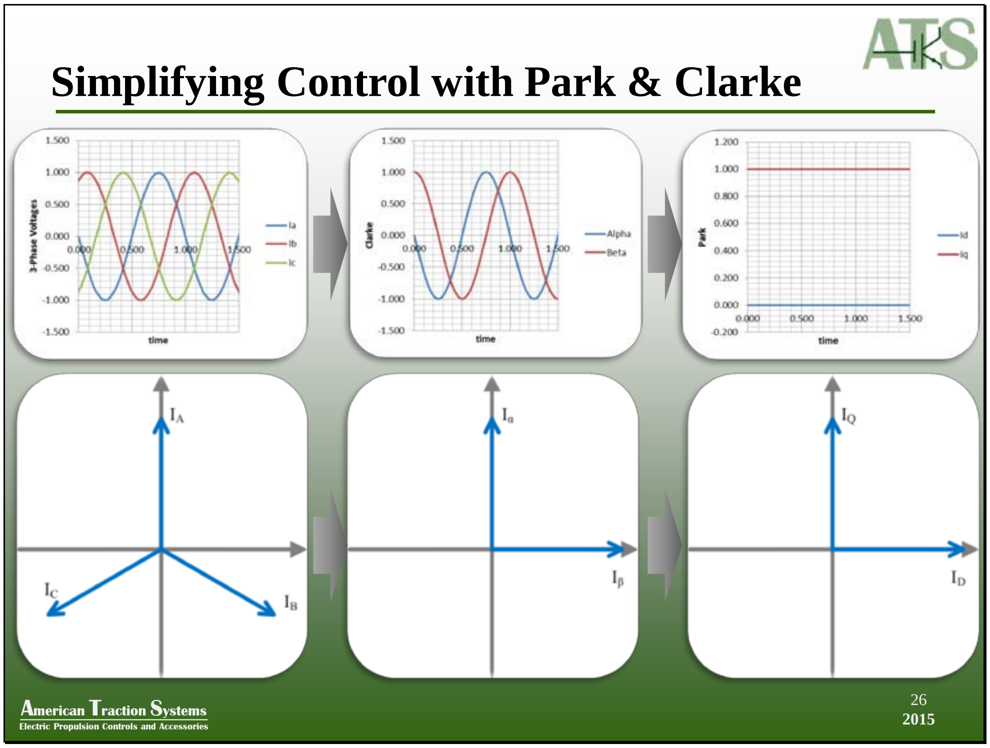


Furthermore, now that cooling the inverter has been addressed and an inverter can operate an inverter to high speed under high load, the performance or torque should be addressed:

ATS is proud to introduce Adaptive Torque Control of Induction and Permanent Magnet AC motors. This slide shows a high-level block diagram of Field-Oriented Control (FOC) with Adaptive Torque Control.

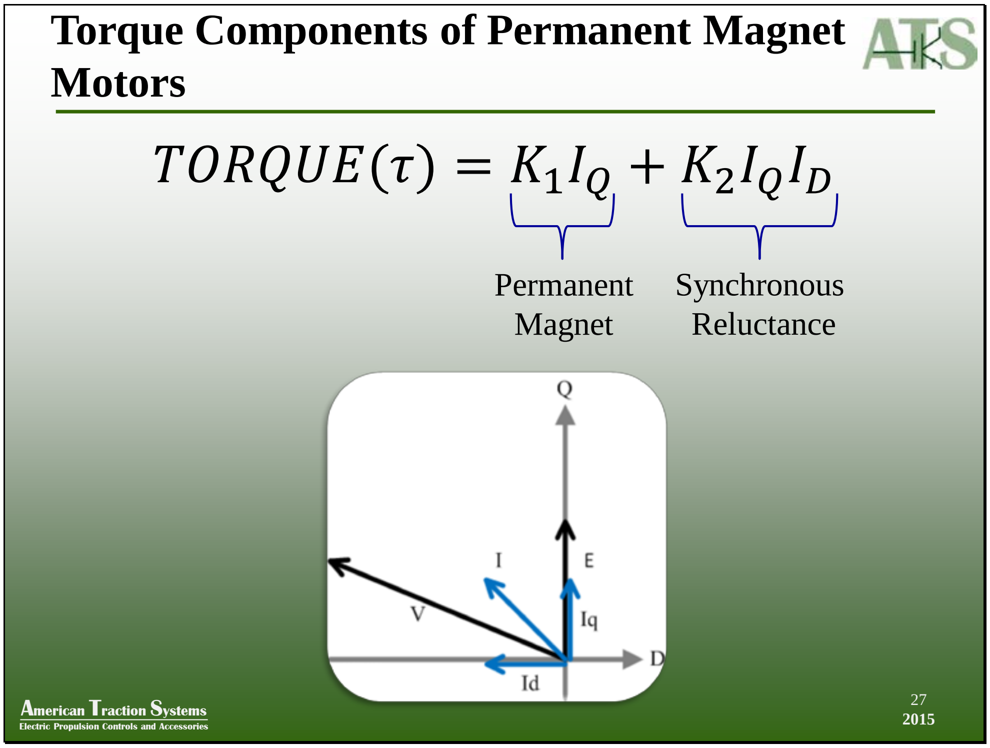
Adaptive Torque Control:

- is a more accurate Field-Oriented Control including zero power factor capabilities
- optimizes torque by accounting for varying supply voltage, motor inductances & resistances, motor temperature, speed, and slip
- Features power limiting governors which are regulated by over voltage, under voltage, over IGBT and motor temperatures, and over speed conditions
- Operation at or near the breakdown torque of the motor in induction motors
- Utilization of the synchronous reluctance effect to maximize torque at a given voltage in permanent magnet motors
- Uses models based on the physics of the motor and not lookup tables
- Dozens of programmable parameters to setup and tune the controller to many different motors



Here is a simplified view of how Field-Oriented Control works:

- The charts on the left show three balanced sinusoidal current waveforms separated by 120°.
  - It is very difficult to control three sinusoidal signals at a time
- The charts on the left are transformed using the famous trigonometric equations known as the Clarke Transform into the charts in the middle: only two waveforms I_α and I_β separated by 90°. This is called the Stationary Frame.
- Furthermore, using the famous Park Transform the charts in the middle are transformed into the charts on the right which turns two sinusoidal waveforms into two nice flats lines. This is called the Rotational Frame.
  - It is in this rotational frame domain that modern motor control algorithms operate. It is called the DQ domain. (Direct/Quadrature)
    - The Direct Axis is in direct phase with the flux of the motor
    - The Quadrature Axis is 90° out of phase (or in quadrature) with the flux of the motor.



This plot shows the D & Q axis of the permanent magnet motor.

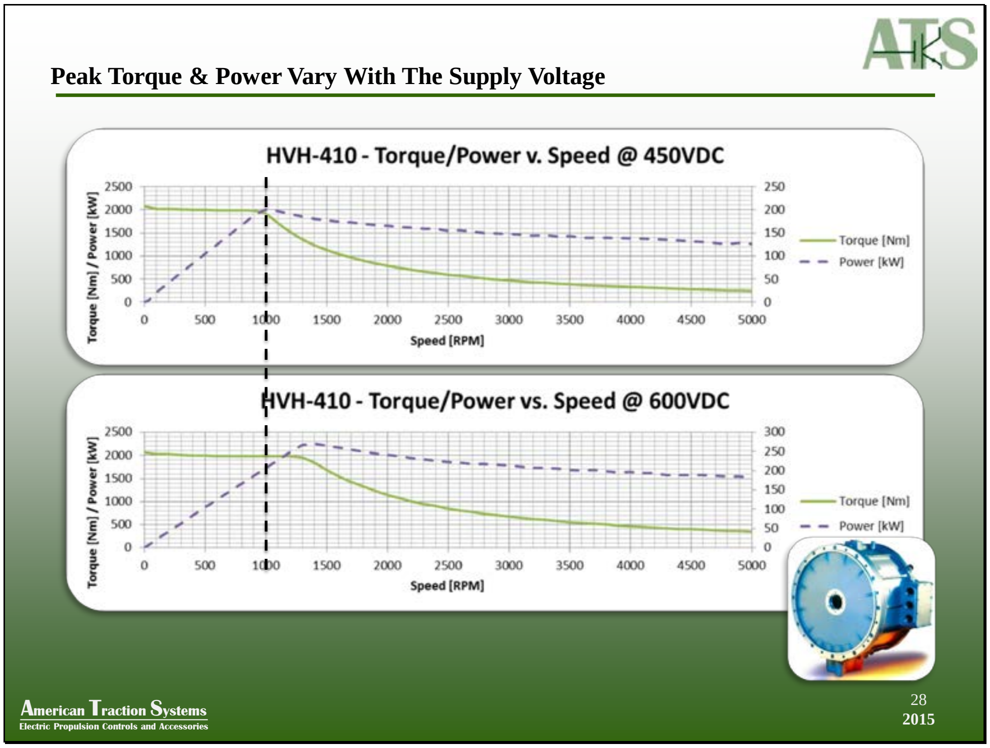
There are two components of torque:

- Permanent magnet torque
  - It is proportional to the Q-axis current
- Synchronous reluctance torque:
  - It is proportional to the D-axis current times the Q-axis current

The practical control challenge with this type of motor is to keep optimal balance between the two components of torque while keeping motor voltage away from saturation. Again, this needs to be done in a broad range of speeds and supply voltages.

ATS' Adaptive Torque Control has to be and ***is*** substantially adaptive to operational parameters to accomplish this.

- These operational parameters are all user-programmable: So these controllers will work on a wide variety of motors.

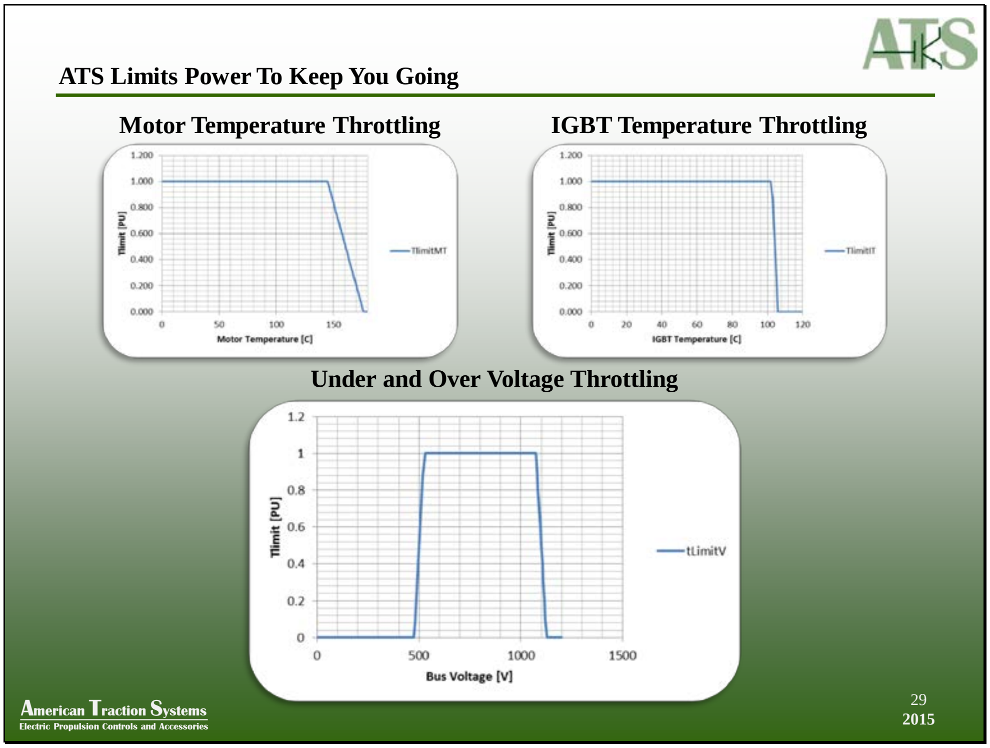


DC Bus Voltage varies with consumption and load.

- As the battery is depleted, the voltage is consumed
- Under load, the supply voltage sags

Base speed is the speed at which the inverter will run out of voltage to produce more torque.

- The graphs in this slide show that the base speed varies with voltage. ATS inverters compensate for this varying base speed to provide optimal torque
- If the motor control algorithm doesn’t compensate for a varying base speed, optimal torque/power cannot be achieved.



Of course, ATS inverters have protection hardware and software, but will the consumer be satisfied if it shuts off? ATS inverters with Adaptive Torque Control have power-limiting governors built-in to keep the inverter running for as long as possible:

- Motor is too hot, slow down.
- Inverter is too hot, slow down.
- Voltage is too low, slow down.
- Voltage is too high, ease up on the electric brakes.
- The consumer would rather limp home than be towed home.