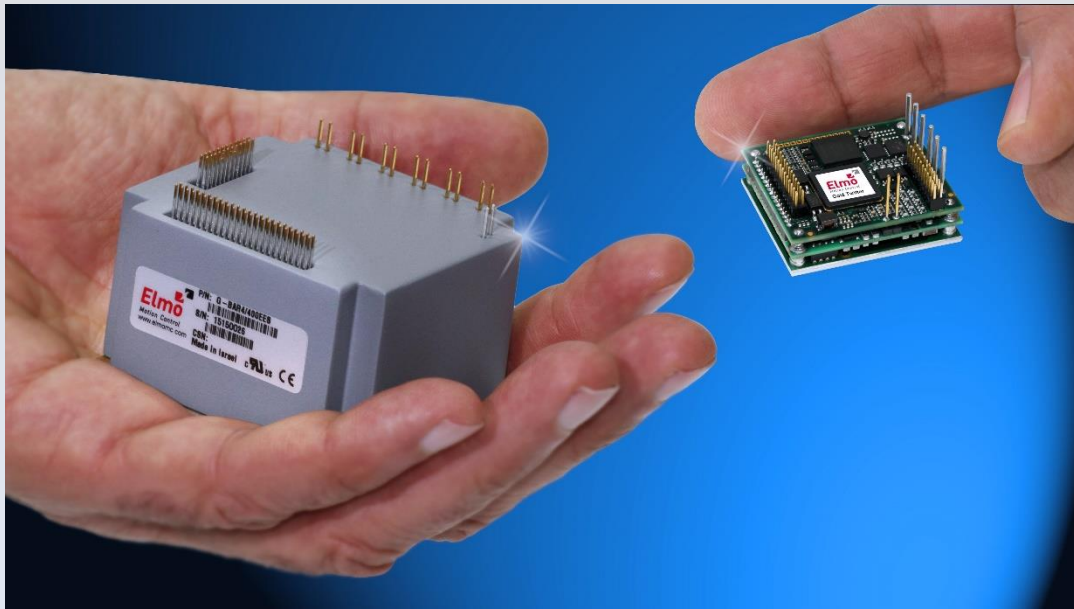


Servo System Efficiency



**Servo Drive & Servo Motor &
Power Supply**

Efficiency, Efficiency, Efficiency

Efficiency of a Servo System depends on 3 major factors:

1. The Efficiency of the servo drive:

$$\text{Servo Drive Efficiency} = \frac{\text{Electrical Output Power of the Drive}}{\text{Electrical Input Power to the Drive}}$$

2. The Efficiency of the servo motor:

$$\text{Servo Motor Efficiency} = \frac{\text{Mechanical Output Power of the Motor}}{\text{Electrical Input Power to the Motor}}$$

3. The Efficiency of Utilizing the system's electrical resources:

$$\text{BUS Utilization Efficiency} = \frac{\text{Motor's Phase@Phase Voltage Amplitude}}{\text{DC Bus Voltage}}$$

Servo Drive Efficiency

The importance of Efficiency of the servo drive:

- High efficiency means less thermal stress on components and thus increases the reliability and prolongs the life time of the drive.
- Less heat to get rid of, less/smaller heat-sinks, no fans
=Slimmer Machine & costs saving.
- Drive is Much smaller, much lighter
- Easy to be mounted anywhere on/in the machine (small, light, no heat to dissipate..)
- Simple to ruggedize and thus withstand extreme environmental conditions
- High Efficiency is also the prove of most advance & efficient design and manufacturing technologies.

Servo Drive Power Dissipation

$$\begin{aligned} \text{Losses(watts)} = & \text{Conduction_Losses} + \text{Switching_Losses} = \\ & K_{C(\text{conduction})} * I_{RMS(\text{Motor})}^2 + K_{S(\text{switching})} * V_{DC(\text{bus})} * I_{RMS(\text{Motor})} \\ & + \text{Control_Losses} \end{aligned}$$

Power Losses of a Servo Drive are function of **Motor's current** and the **DC supply Bus**

Servo Drive Power Dissipation

Two type of losses:

- Inherent application losses.
- Drive's Losses depend on:

Inherent, No influence by the Application	Influenced by the Application	
Drive's Conduction (saturation) losses	Drive's PWM Frequency	
Drive's Turn On Losses	Drive's Servo Control topology	
Drive's Turn Off Losses	Drive's sample time (T_s)	
Motor's current		
Motor's inductance	Bus voltage	Semi influenced

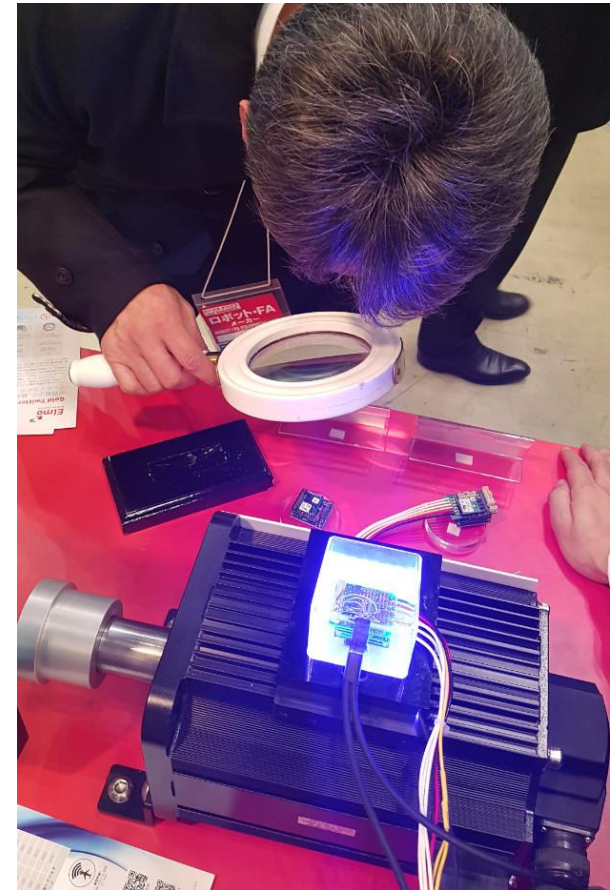
Servo Drive Power Dissipation

The anomaly of the Power Losses of a Servo Drive is that the a drive can dissipate max power even with zero power is at the output
How Come?

Servo Drive Efficiency

Example of the GOLD Twitter demo motor

- A 4500W @ 50A motor.
- Phase 2Phase resistance is 0.045 ohm
- V bus 85VDC
- Drive's Output current of 50A
- Motor's at stall condition:
 - Output power at ZERO speed is 57W
($0.045 * 50^2 / 2$)
 - Output voltage is $\approx 1.6V$ RMS
 - Drive's Losses are 42W , efficiency is $\approx 57 / (42 + 57) \approx 57\%$
 - Input power is 42W+57W. Output power is 57W

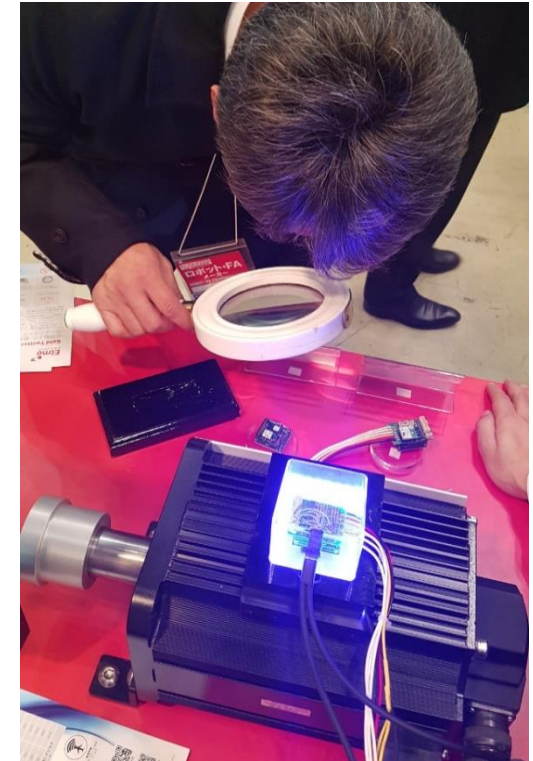


Servo Drive Efficiency

Example of the GOLD Twitter demo motor

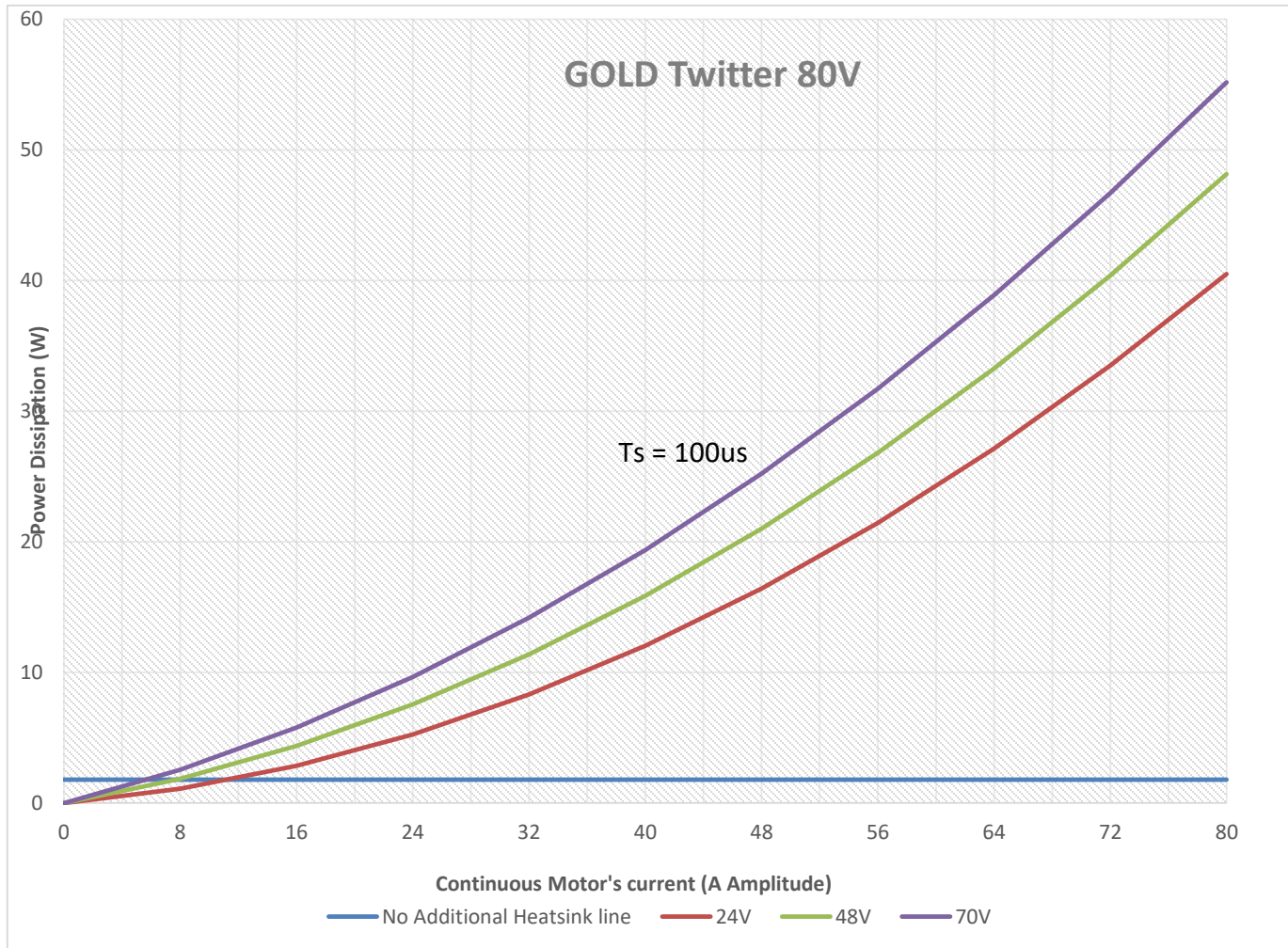
- At the same Bus of 85V & the same output of 50A ,
- But at max Drive's output power (max Speed @ max torque) the
 - At Drive's output voltage $\approx 83V$, the output power is 4000W
 - Drive's losses are the same 41W and the efficiency is $4000/(4000+41) \approx 99\%$

At The Same DC bus, Same output current, but Different output voltage/power result the Same Losses



Servo Drive Efficiency

Let's look at the amazing G-TWIR80/80

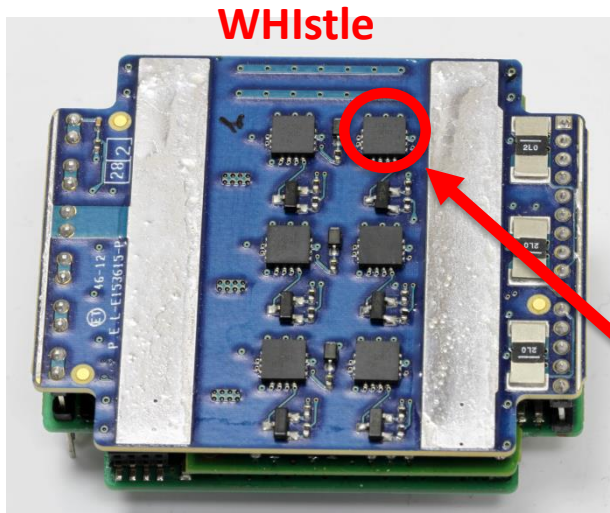


Power Dissipation 80/80

	VDC	Amp.	Power Dissipation Watt	Electrical Power Output	Power Efficiency	Ts us	PWM Multiplier
G-TWI R80/80	48	16	4.4	665	99.3%	100	1
	48	32	11.4	1330	99.1%		
	48	64	33.3	2660	98.7%		
	48	80	48.2	3325	98.6%		
	72	16	5.9	998	99.4%		
	72	32	14.4	1995	99.3%		
	72	64	39.4	3991	99.0%		
	72	80	55.8	4988	98.9%		

FASST

The extra ordinary efficiency is accomplished by Elmo's Fast And Soft Switching Technology

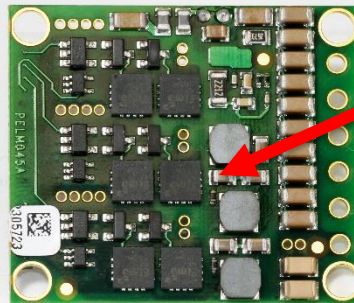


The dramatic improvement is carved from the new generation of Elmo ASIC components; FID, FET & IGBT Drivers, which drives stronger, faster and yet softer and in much smaller footprint.

The FID optimizes all 4 states of the PWM Power conversion:

- OFF State
- Turn On
- On State
- Turn Off

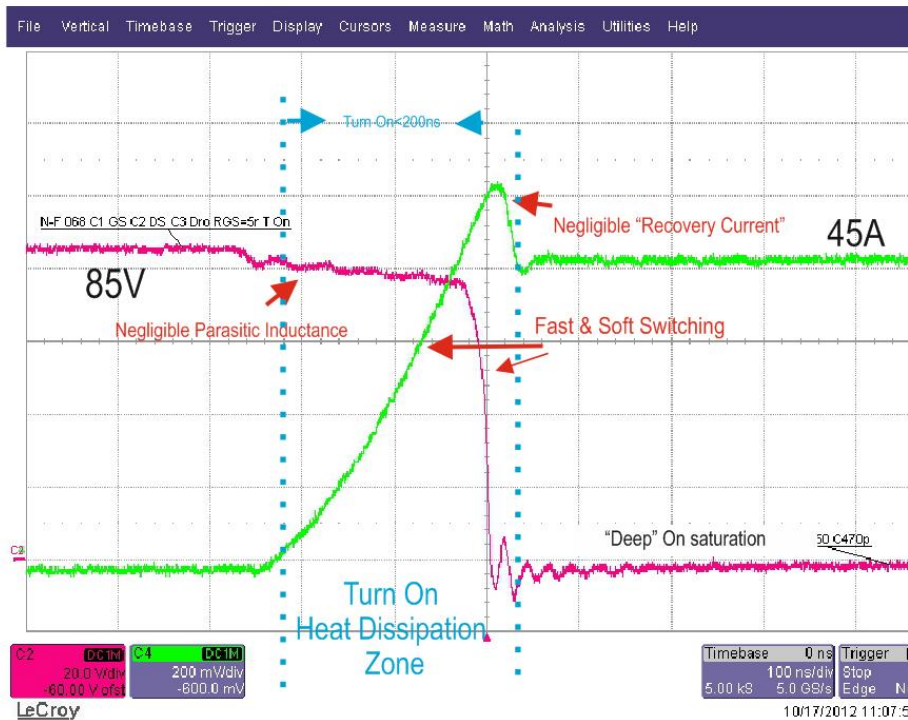
TWitter



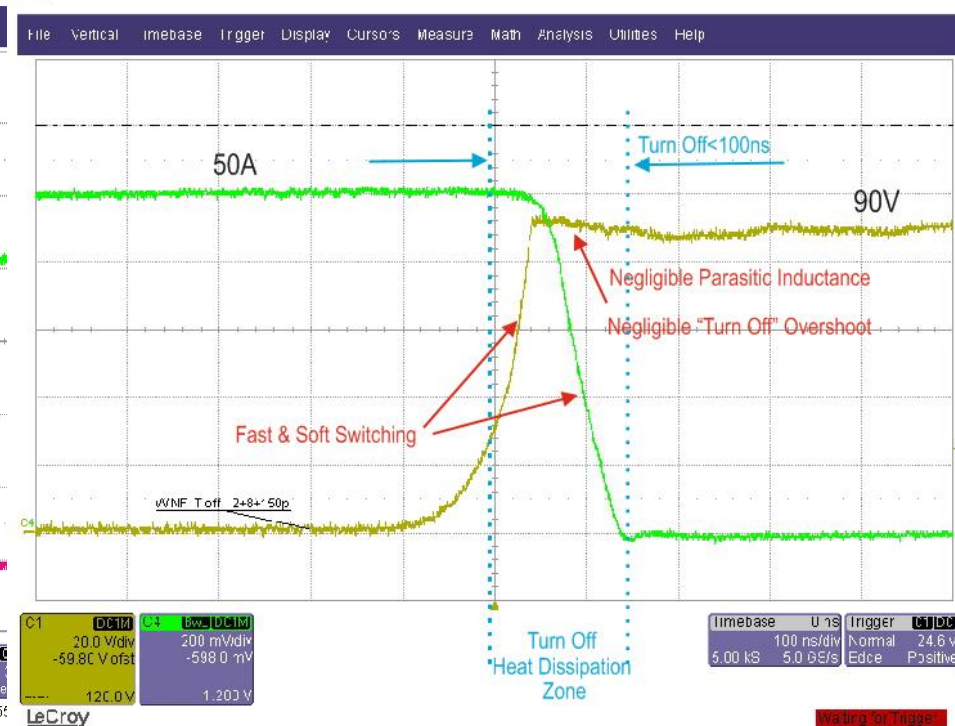
Ultra Hi Current, Ultra Small, Ultra Efficient

Elmo's Fast And Soft Switching Technology results Perfect PWM Process

GOLD TWITTER Turn On



GOLD TWITTER Turn Off

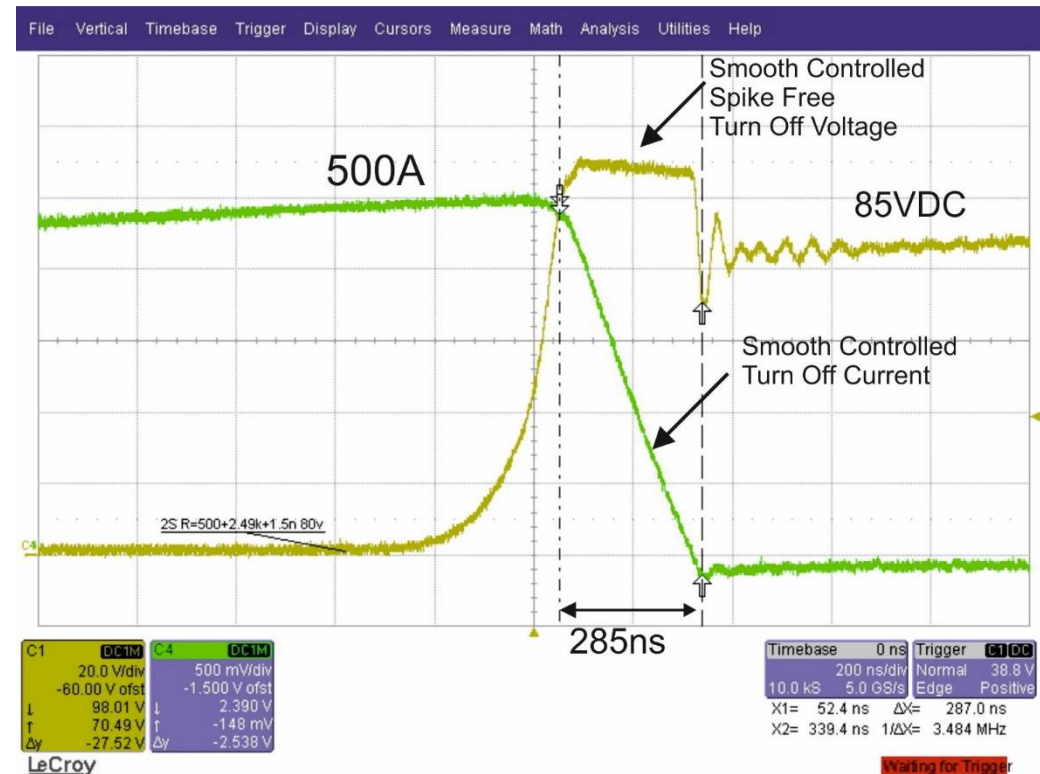


Ultra Hi Efficiency, FASST

Perfect PWM Control results:

- Best Servo performance due to:
 - Very high linearity
 - Negligible dead bands
 - Fast response time
- Ultra high efficiency.
- Negligible, almost NON, EMI
- Utmost reliability due to significantly lower stress on power switches
- Ultra small package than can be mounted “anywhere” in the machine.

GOLD DRUM 550A, 100VDC, Turn Off at 500A



Drive's Power Dissipation

What is the electrical output power?

The power output of the drive is of a 3 phases sinusoidal generator and is calculated by:

$$Power\ Output_{Drive} = \sqrt{3} * \frac{I_{Out_Amplitude}}{\sqrt{2}} * \frac{V_{DC_Bus}}{\sqrt{2}}$$

Power Dissipation, 80/80

At 80A current output @ 72VDC the maximum output power is

$$Output_{Max. Power} = \frac{\sqrt{3}}{2} * 80A * 72V \approx 5000W$$

At those conditions the 80/80 dissipates only 55W

$$Efficiency = \frac{55W}{5000W} = 98.9\%(@80A!)$$

GOLD Twitter Power Dissipation

The charts show power conversion efficiency of
98.9% - 99.5%

When dealing with electrical output power in the range of
≈5000W, those are excellent results.

Servo performance Vs Heat Dissipation

The servo sample rate, motor PWM frequency and loops bandwidth in Elmo products are optimized by default to achieve the best performances and overall system efficiency.

In specific cases, common to high dynamics systems, requiring tight tracking performances, very low positioning errors or high dynamic response to commands and external disturbances, the servo system performances can be further improved by increasing the loops bandwidth.

Servo performance Vs Heat Dissipation

This can be achieved in most cases by fine tuning the specific servo loops using our Tuning Wizard, and can also be aided by reducing the servo sample time (increasing servo sample rate) thus reducing the system phase lag.

But, What it has to do with the drive's heat dissipation?

Heat dissipation depends also on the PWM switching.

In Elmo Drives the PWM can be change by the user,
Understanding the link of PWM-Performance- Efficiency

Servo performance Vs Heat Dissipation

In Elmo Drives the PWM can be determined by the user,

Clarifying the link of

PWM frequency – Servo Performance- Efficiency

will help to select the best suitable PWM frequency

Ts =100us, what is it?

The Ts is the sampling time of the internal computation cycle process.

The current loop , the commutation and the power stage PWM are processed at the Ts.

In the GOLD Twitter the default TS is 100us,
And thus the PWM frequency of each FET is $1/T_s = 10\text{KHz}$

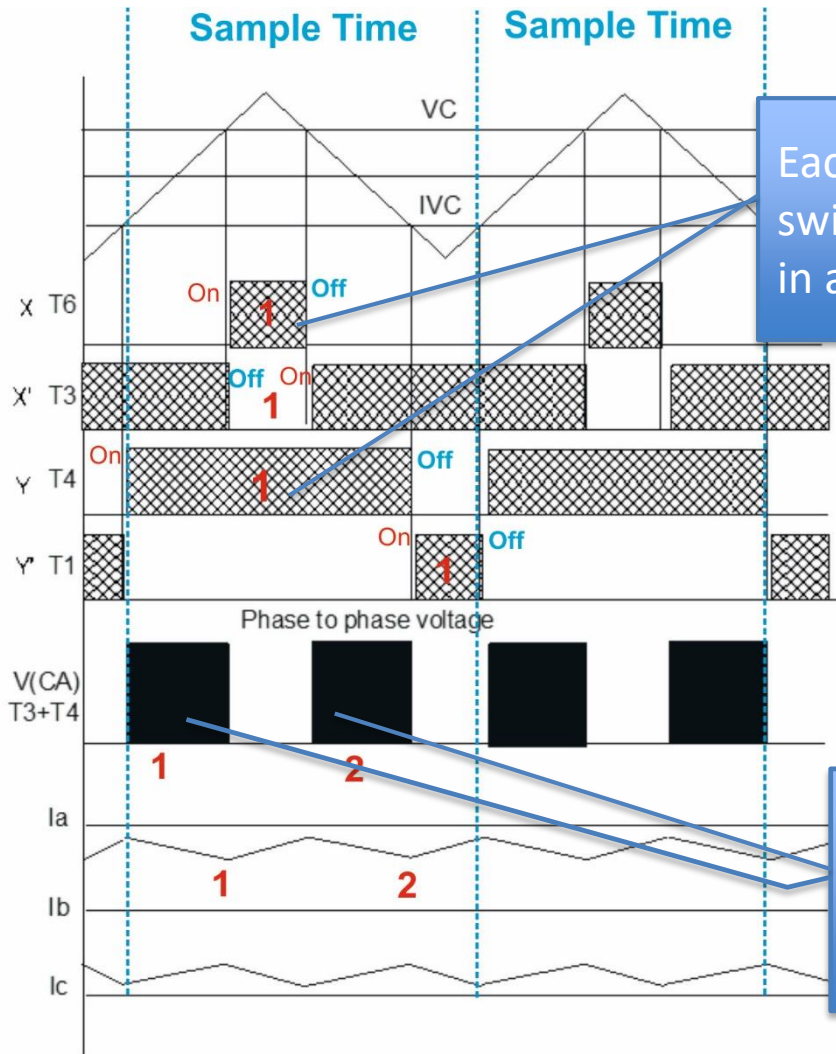
While the load (Motor's windings) are switched at X2 frequency of 20KHz

How Come?

Load PWM Frequency X2

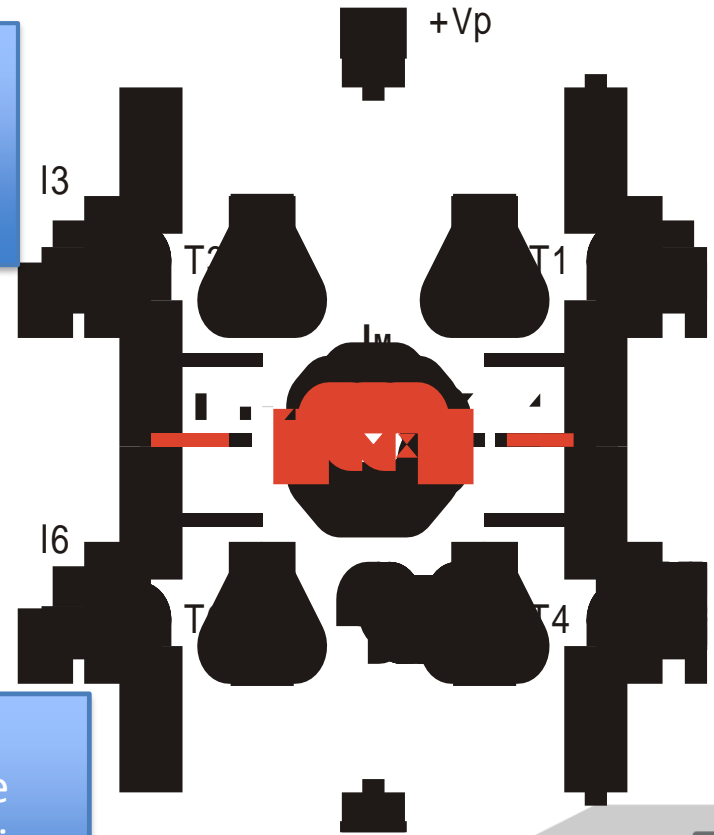
Elmo's advance unipolar PWM switching results Load PWM that is Double than the Sample rate frequency , for $T_s = 100\mu s$ (10KHz)

the load frequency is **20KHz**



Each FET is switched once in a sample

The Motor's windings are switched twice in a sample



PWM & Ts & Servo performance

In all Elmo GOLD Drives the Ts is programmable and can be set between 50us to 150 us

What is the use of changing the Ts?

The Ts has influence on the servo performance. Decreasing the TS increases the Bandwidth.

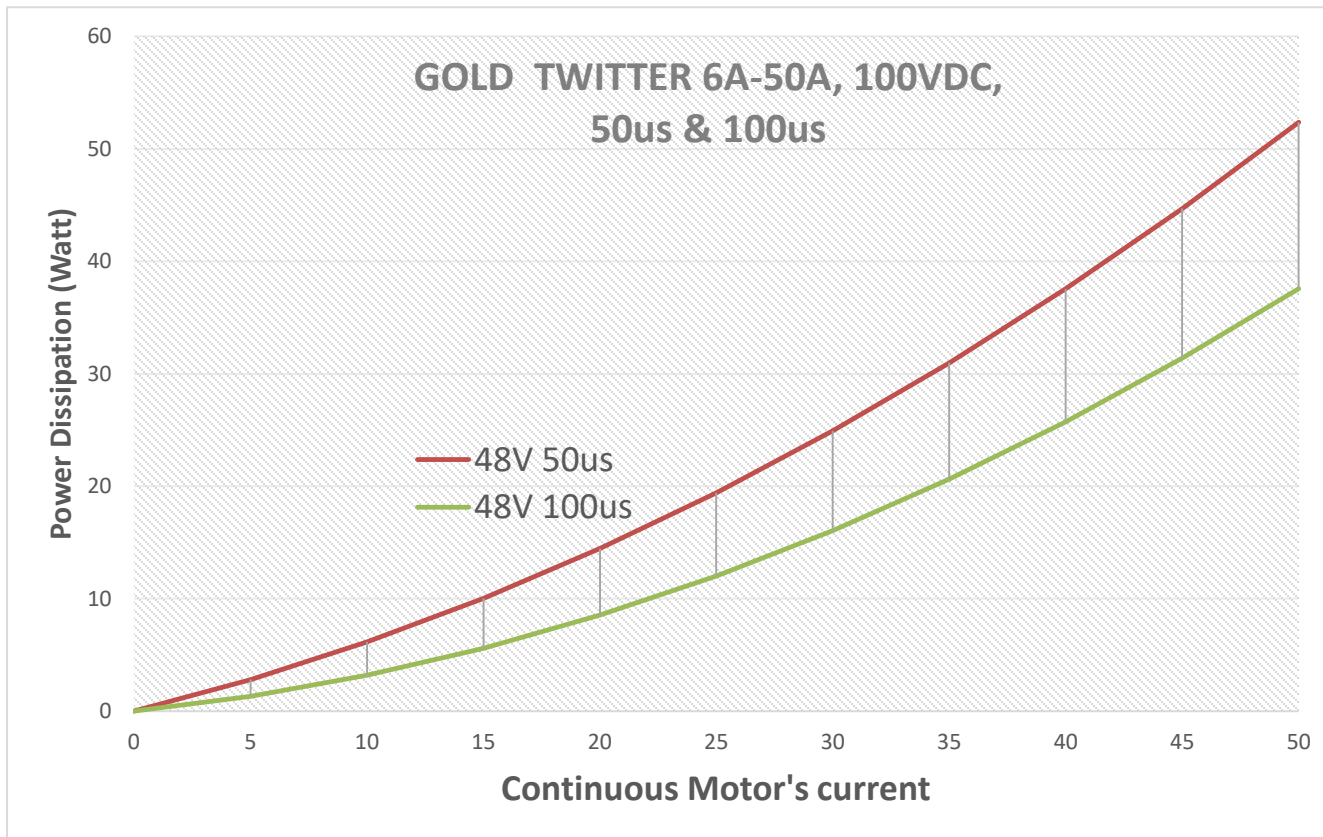
PWM & Ts & Servo performance

So, why not set always to 50us for widest Bandwidth?

1. In most of the cases the results of $T_s=100\mu s$ are more than required.
2. In many cases simply increasing the PWM frequency (increasing theoretically the bandwidth) is not contributing anything to reach the control goals.

PWM & Ts & Servo performance

3. Increasing the PWM frequency has also drawbacks:
 - The heat dissipation is increased by 20% - 30%



Iout	Ts	Power losses W
5	50	2.8
5	100	1.3
10	50	6.1
10	100	3.2
15	50	10.0
15	100	5.6
25	50	19.4
25	100	12.0
50	50	52.4
50	100	37.6

PWM & Ts & Servo performance

- The current loop linearity is degraded.
- In Elmo's drives the degradation is negligible due to the FASST power conversion that overcomes this weakness.
- The max. output voltage is reduces.

PWM & Ts & Servo performance

So, How to reach the required performance

By “controlling” the control

And it is much more than just “manipulating” with Ts

- Using Elmo’s 1:1:1 control topology will increase substantially the BW and the response of the velocity and the position loops without the need to decrease the Ts (increase the PWM frequency).

How come? Isn’t the control theory asking for at least current loop frequency that is double than the velocity/ position?

This was true before the “Era” of advance tuning.

High quality tuning enables very effective

“1:1:1” operation

PWM & Ts & Servo performance

So, How to reach the required performance

- The best way to reach the needs and beyond is by executing a “perfect” tuning that can be “Fast & Easy” accomplished by Elmo’s EASII

PWM & Ts & Servo performance

As Default keep the following:

1. $T_s = 100\mu s$
2. Set “1:1:1” mode.
3. Perform “Fast & Easy” tuning by the EASII.

So, When to change the T_s ?

- In extreme cases that with the above the required results are not yet satisfactory, the T_s can be lowered,
- The “1:1:1” should be kept, and tuning is always the key for best results.

Remark: The minimum T_s for “1:1:1” operation is 60 μs

Multiplying the PWM

The Xp[2] command is a PWM multiplier without changing Ts

Ts= 100us	Fets PWM KHz	Motor's PWM KHz	
Xp[2]=0	10	20	
Xp[2]=1	5	10	Not applicable for Drives ≤ 200V (Except the GDRU & GEAG)
Xp[2]=2	20	40	
Xp[2]=3	30	60	
Xp[2]=4	40	80	

Low inductance

What for the PWM Multiplier?

This is a good remedy for very low inductance motors.

Low inductance creates High current ripple that results:

1. Excessive heating of the motor
2. Excessive heating of the drive
3. Unstable current loop.

What is “Too Low inductance” that will result the above “difficulties”? Drawback?

As a rule of thumb a 30% -40% of the I_c (or the motor's rated continuous current) is fine and increasing the PWM might worsen the situation for not heating too much and not disturbing the control loop.

Low inductance

On the other hand, Increasing the PWM frequency is “spoiling” a bit the:

1. Drive's Power losses are increased.
2. Linearity is reduced.
3. Max Output voltage/ Max speed is reduced.
4. Motor's Power losses are increased
5. Some motors behave “strangely” at high frequency, this is caused by the material quality (magnets, winding, metal parts), parasitic inductance and capacitive coupling...
 - Above 60KHz “some” motors might not behave as an inductive load.

Too Low inductance

So, when multiply the PWM?

Only in cases of “Too Low Inductance” to reduce the current ripple

The Maximum current ripple is:

$$I_{Max\ Ripple(peak2peak)} = \frac{V_{DC}}{3 * L_{Phase2Phase} * f_{PWM\ on\ the\ motor}}$$

Increase the PWM frequency only if I_{max_ripple} is higher than 30% - 40% of Drive's I_c or of Motor's rated current.

Servo Motors Efficiency

The typical/ Average efficiency of a servo motor is
 $\approx 85\%$

The basic equation of the servo motor is:

$$V_{ph_rms} = \sqrt{(E_{ph_rms} + I_{ph_rms} * R_{ph})^2 + (2\pi * f_e * L_{ph} * I_{ph_rms})^2}$$

The “Pure Rotation” is only E_{ph_rms} ($K_e * RPM$),
all the rest are parasitic effects

The $I_{ph_rms} * R_{ph}$ is the resistive internal voltage drop due
to the internal resistance of the copper windings.

Servo Motors Efficiency

The heat losses due to the internal resistance is given by:.

$$I_{ph_rms}^2 * R_{ph}$$

Additional losses are caused by the Eddy currents, “rotating” mechanical losses (bearings, friction, cogging, internal fan’s air turbulence , etc..)

Servo Motors Efficiency

The $2 \cdot p \cdot f_e \cdot L_{ph} \cdot I_{ph_rms}$ (=wL voltage losses) is the Phase- Neutral voltage drop due to the internal inductance that is “rotating” at the electrical commutation frequency. The wL is Only voltage drop, No power dissipation.

But, high wL can also contribute to increase the servo system losses

Reaching the Speed & torque needs will require higher voltage bus = Higher Losses.

Servo Motors Efficiency

Can the 80/80 really deliver 5000W to a motor?

Yes, the G-TWI drive can deliver 5000W to a motor,

But, the motor's mechanical output will be lower due to the motor's internal power losses and voltage drops caused by the Motor's internal I²R and ωL voltage drops and power losses



Servo Motors Efficiency

Example: Motor: $K_e=42.5V/KRPM$, $T=40NM$, $1000RPM$,

Drive: $VDC=73V$, $I_{motor}= 80A$

Drive's Electrical output power \approx

$$Drive\ Output_{Electrical\ Power} = \frac{\sqrt{3}}{2} * 80A * 73V \approx 5022W$$

$$Motor\ Output_{Mechanical\ Power} = \frac{40NM * 1000RPM}{9.55} = 4188W$$

The heat dissipation efficiency of the motor is $4188/5022 \approx 83\%$

The G-TWI80/80 delivers to the motor 5022 electrical watts, while the motor “produces” only 4188W of mechanical power.

BUS Utilization Efficiency

Long, long time ago....Italy.....

On the way to a customer of 3000 drives & motors

Motor M: "Why your 400W drive is so expensive?"

E: "What are you talking about?"

Motor: "Your PIC-15/200 is too expensive?"

E: "400W? PIC-15/200?"

Motor: "Customer's bus is 170VDC and our motor is 15A"

E: "Motor's data sheet?.....but this is a 48VDC motor?"

Motor M: "That's what we have!"

E: "Maybe higher Ke?"

Motor: "Ah..."

End of story: with the more reasonable KE even the PIC-6/200

Was too strong

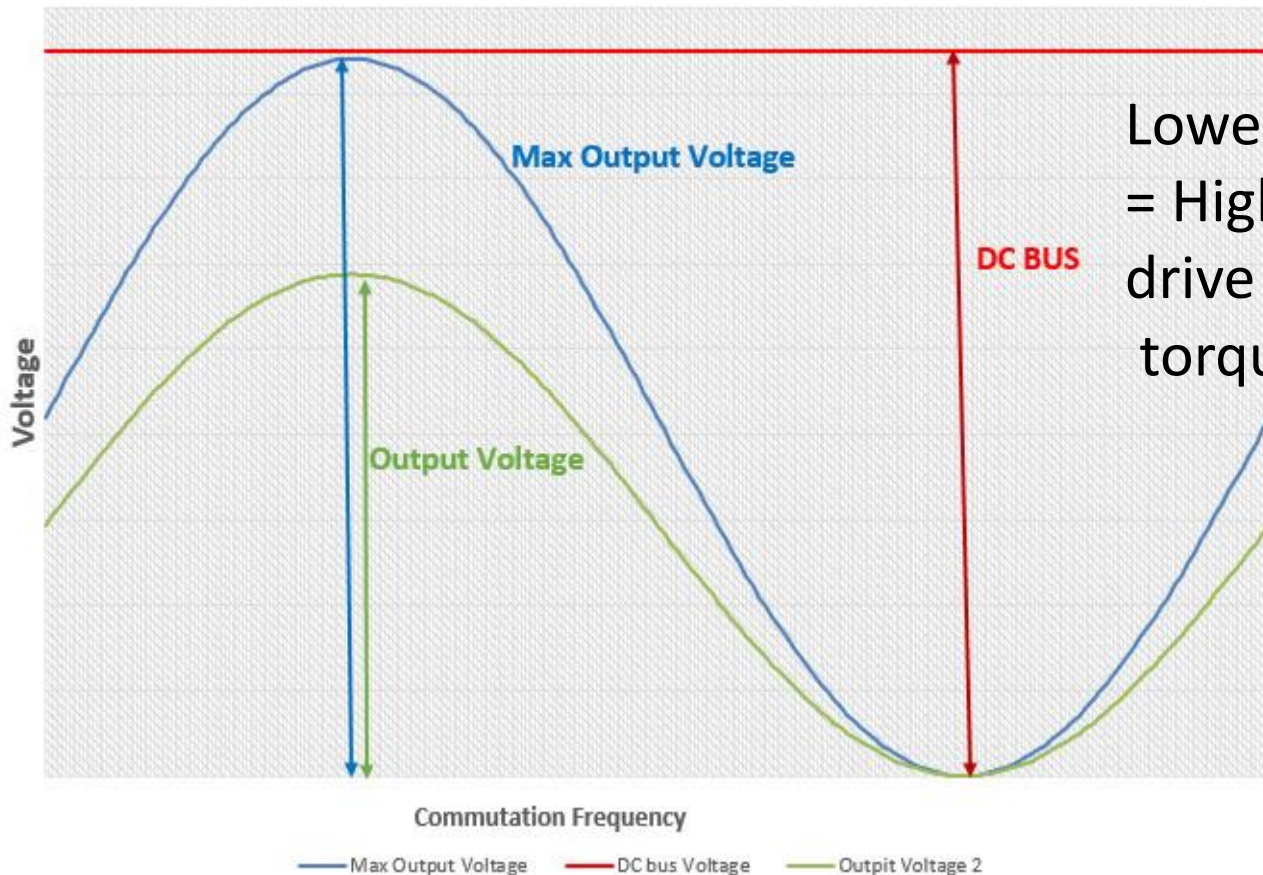
Half the price, half of the losses half of the size.

BUS Utilization Efficiency

Motor's Phase@Phase Voltage Amplitude

DC Bus Voltage

Drive's Sinusoidal Output Voltage



Lower Ph2Ph output voltage
= Higher current of motor &
drive to reach the same
torque @ power needs

BUS Utilization Efficiency

$$\frac{\text{Motor's Phase@Phase Voltage Amplitude}}{\text{DC Bus Voltage}}$$

What does it mean?

How much out of the Voltage Bus is exploit to run the motor?

What it is has to do with efficiency?

If the Voltage Bus is “partially” used, it “spoils” the efficiency of the Servo System by increasing the current of the motor and thus increasing the current of Servo Drive.

How come?

BUS Utilization Efficiency

Matched Motor & Drive

What does it mean?

Motor: 1KW, 3000RPM, 3.2NM Rated, 9.6NM peak.

Ts=100, Xp[2]= 0 (20KHz on the motor)

Max. Continuous Conditions		Motor 1	Motor 2	Motor 3	Motor 1
Rated Torque@Rated Speed		STD Motor Non Matched With Elmo Drive	Matched pair with Elmo Drive	Matched pair with Elmo Drive	Run by "Others" Drive
Minimum Bus Voltage	VDC	161	294	400	120-160
Cont. Heat Dissipation @325VDC	W	38	16	NA	50-70

Rated Torque@Rated Speed					
Cont. Heat Dissipation @560VDC	W	49	31	15	70- 100

The different Drives losses are due to the higher current consumption required to get the same performance of output torque & Output power at the same bus voltage

BUS Utilization Efficiency

Matched Motor & Drive

What does it mean?

Motor: 1KW, 3000RPM, 3.2NM Rated, 9.6NM peak.

Ts=100, Xp[2]= **1 (10KHz on the motor)**

		Motor 1	Motor 2	Motor 3	Motor 1
Rated Torque@Rated Speed Max. Continuous Conditions		STD Motor +Elmo Drive	Matched to Elmo Drive	Matched to Elmo Drive	Run by "Others" Drive
Minimum Bus Voltage	VDC	161	294	400	180 -160
Cont. Heat Dissipation @325VDC	W	26	11	NA	50-70
Cont. Heat Dissipation @325VDC X[2]=0	W	38	16	NA	50-70

Rated Torque@Rated Speed					
Cont. Heat Dissipation @560VDC	W	35	31	10	70-100
Cont. Heat Dissipation @560VDC X[2]=0	W	49	31	15	70- 100

BUS Utilization Efficiency

Operating at a NON optimal BUS utilization results:

- Higher current consumption of Drive – Motor (losses, thicker motor's wires).
- Drives with Higher current rating (bigger size, higher cost).
- Higher power losses (Higher operating temperature-reliability, higher electricity consumption)
- More heat dissipation means (more heat- sinks, fans..)
- bigger electrical cabinet

Those increase substantially the costs of the raw material, the installation costs and increase the operation costs.

Servo System Efficiency

Summary:

The overall efficiency of a Servo System depends on;

- Servo Driver Efficiency
- Servo Motors Efficiency
- Matched Motor & Drive operating envelope