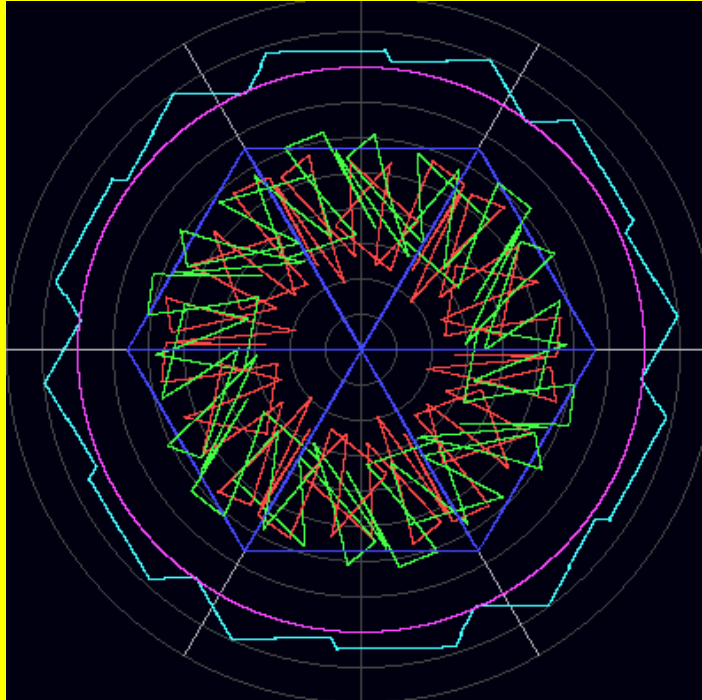
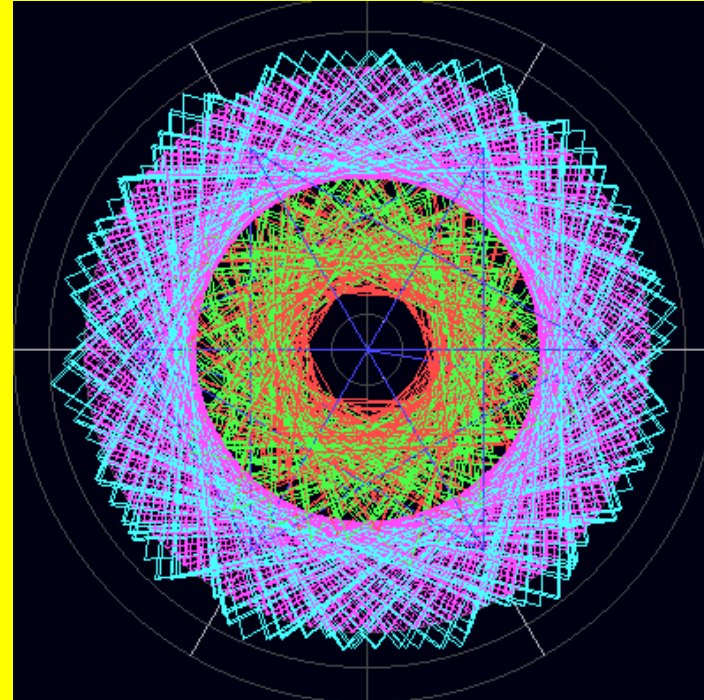


SENSORLESS

F_IE_LD O_RIEN_TE_D C_ON_TR_OL



M
O
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O
R
C
O
N
T
R
O
L



is a **SCIENCE ...**

but also an ART

By ph.dr.eng. **ROBERTO RAFFAETA'** - NEW SYSTEMS

ABSTRACT

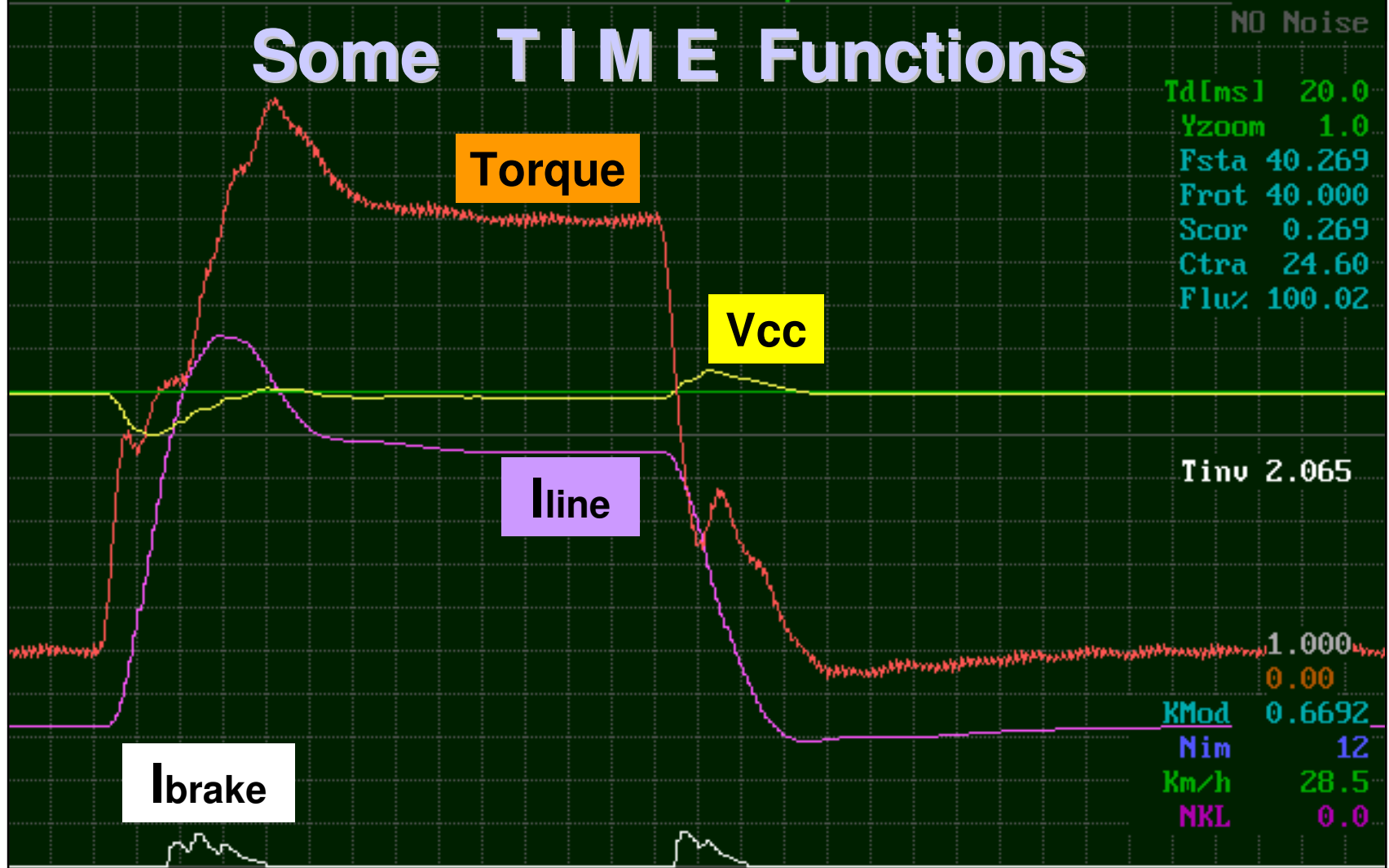
This short presentation will treat of some usual and unusual **CONTROL STRATEGIES** well suited for **SENSORLESS DRIVES** for **SINCRONOUS & ASINCRONOUS MOTORS** ... we will start with some well known **math building block** (easy to implement in **FPGA**) allowing us to construct simple structures well suited for our task **without entering in tedious details** ...

We will see some **SIMULATIONS** to understand some statements better ...
The simulators , which I use normally to verify new solutions and to test some custom controls , are very Spartan , but they contain a function library that have been well tested and optimised for motor control in the last 30 years ...
I started to control a power induction drive developed by two professors of mine in 1971 and afterwards , up to date , I designed several controls for many different drives ranging from 1W to 2 MW.
I want here to thank **Thomas A. Lipo** for the good advice and suggestions he gave to me during the development of a FOC traction power drive in 1989 for Ercole Marelli Trazione.

I think that a **PROBLEM SOLUTION** is good when it is **SIMPLE** and **IT WORKS** ...
The **SOLUTIONS** are of primary importance , not the problems ...

232.25 80.87 1600.0 0.0 1595.6 FB Iq&Id
CtraF ILM Upan IFreM VCM Filtro OK

Some TIME Functions



Td[ms] 20.0
 Yzoom 1.0
 Fsta 40.269
 Frot 40.000
 Scor 0.269
 Ctra 24.60
 Flu% 100.02

Tinv 2.065

1.000
 0.00
 KMod 0.6692
 Nim 12
 Km/h 28.5
 NKL 0.0

Space-Vectors VECTORS

Modulo Gradi

Ustatore
1053.2 60.0
1500.0

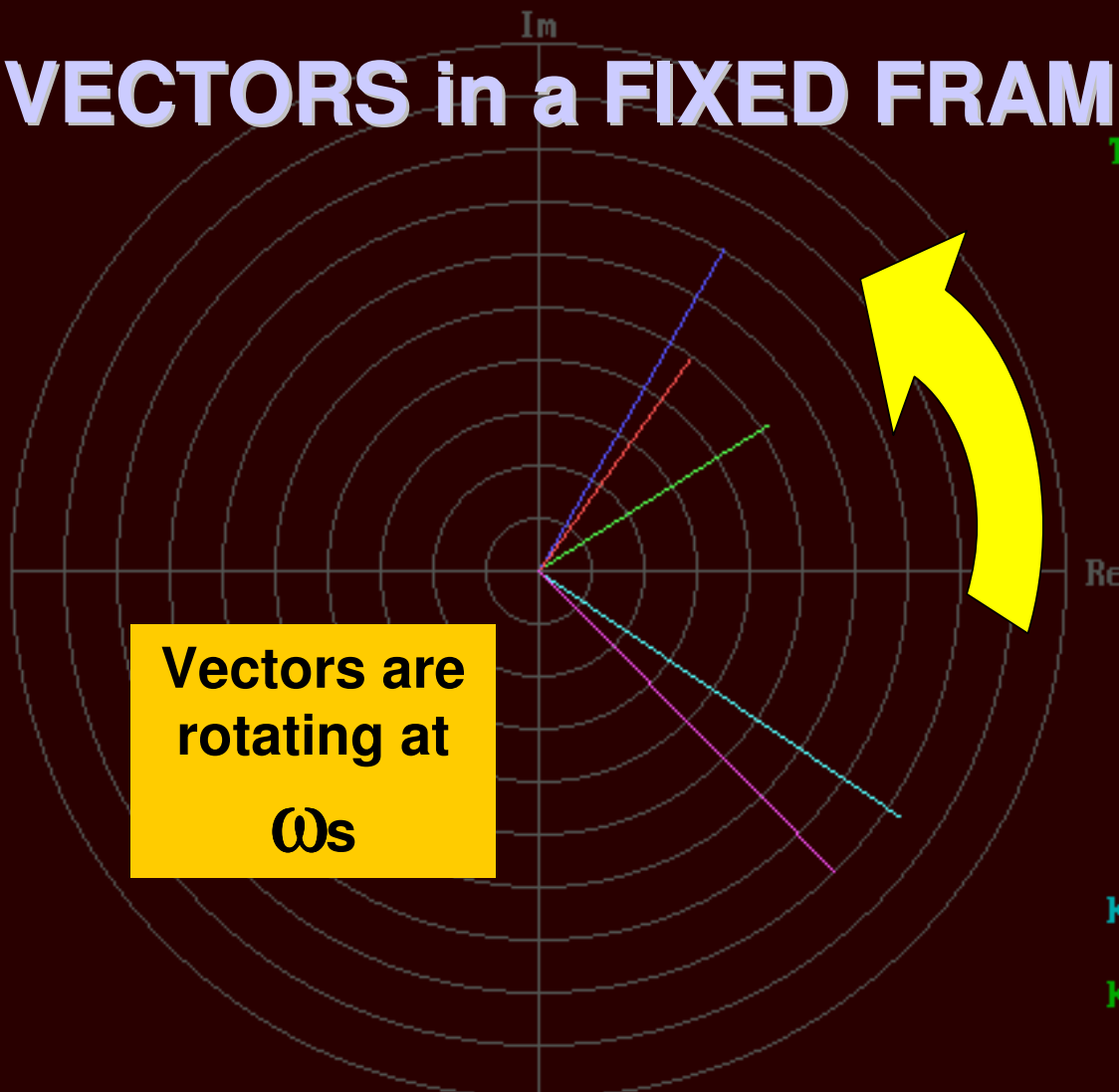
Istatore
205.60 32.5
400.00

Irotore
196.98 54.3
400.00

FlussoS
2.0632 -34.1
2.4925

FlussoR
1.9948 -45.5
2.4925

VECTORS in a FIXED FRAME



FB Iq&Id
Filtro OK
NO Noise

Tc[us] 5
Yzoom 1.0
Fsta 41.077
Frot 40.000
Scor 1.077
Ctrr 99.41
Flu% 100.04

Vectors are rotating at ω_s

KMod 0.7104
Nim 12
Km/h 28.5
NKL 0.0

1600 100.00 1.000 1.000 1.000 0.0 1.000
Upan Cref% GSFil GRInu GRChf KTEST GAIN

NEW SYSTEMS - MEHOPT

Diagramma Re-Im riferito ad ASSI FISSI

== PWM ==

Space-Vectors TRACKS

FB Iq&Id

Modulo Gradi

Filtro OK

Ustatore

NO Noise

0.0 0.0

Istatore

210.28-151.0

Irotore

191.39-129.2

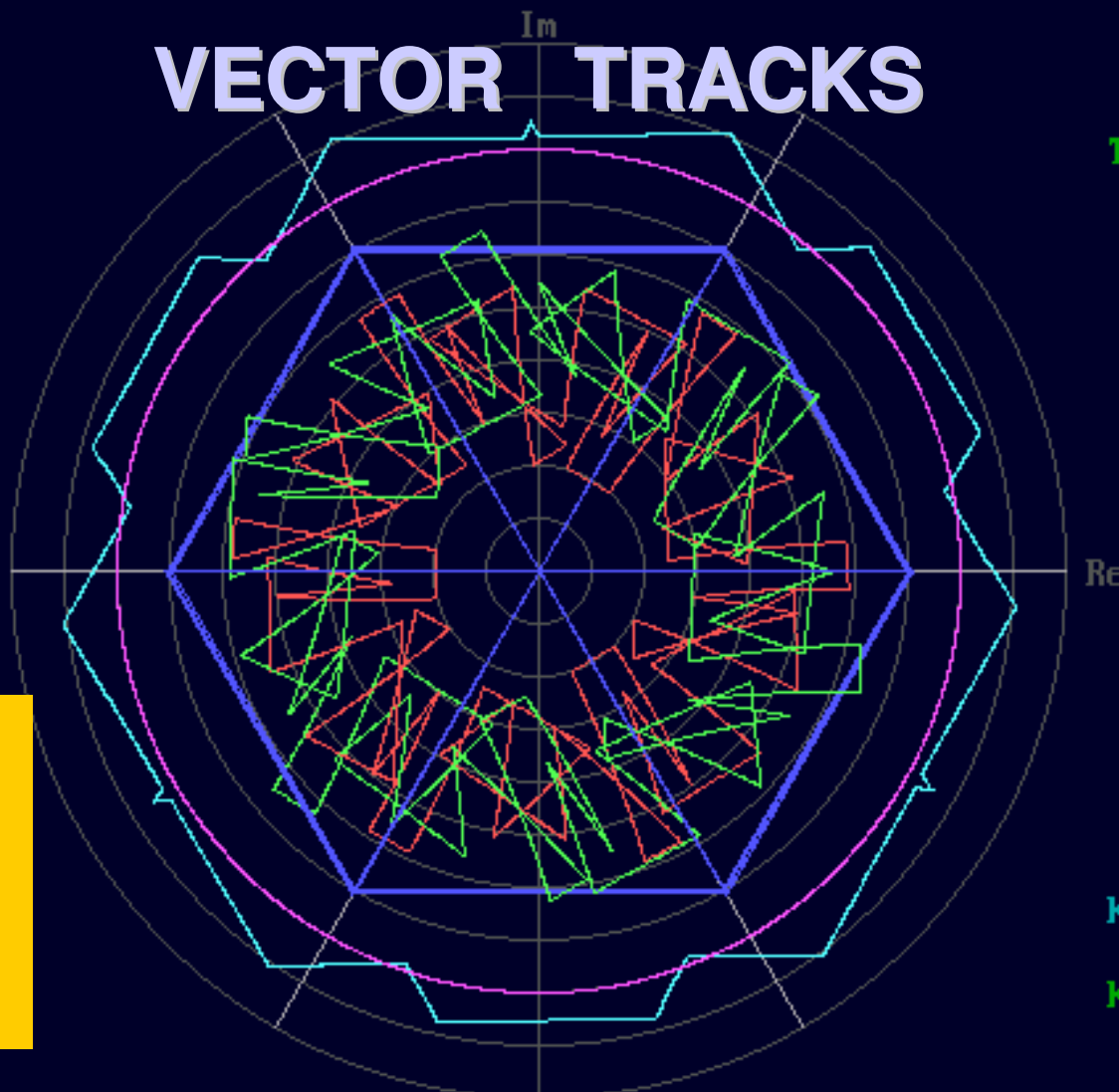
FlussoS

2.1281 151.1

FlussoR

1.9944 140.4

VECTOR TRACKS



Tc[us] 5
 Yzoom 1.0
 Fsta 41.048
 Frot 40.000
 Scor 1.048
 Ctra 99.68
 Flu% 100.02

KMod 0.7103
 Nim 12
 Km/h 28.5
 NKL 0.0

Same
 vectors
 of the
 previous
 dia

1600

100.00

1.000

1.000

1.000

0.0

1.000

Upan

Cref%

GSfil

GRInv

GRChf

KTEST

GAIN

NEW SYSTEMS - MEHOPT

Diagramma Re-Im riferito a ANGOLO U_s

== PWM ==

Space-Vectors TRACKS

FB Iq&Id

Modulo Gradi

Filtro OK

Ustatore
1058.8 97.1

NO Noise

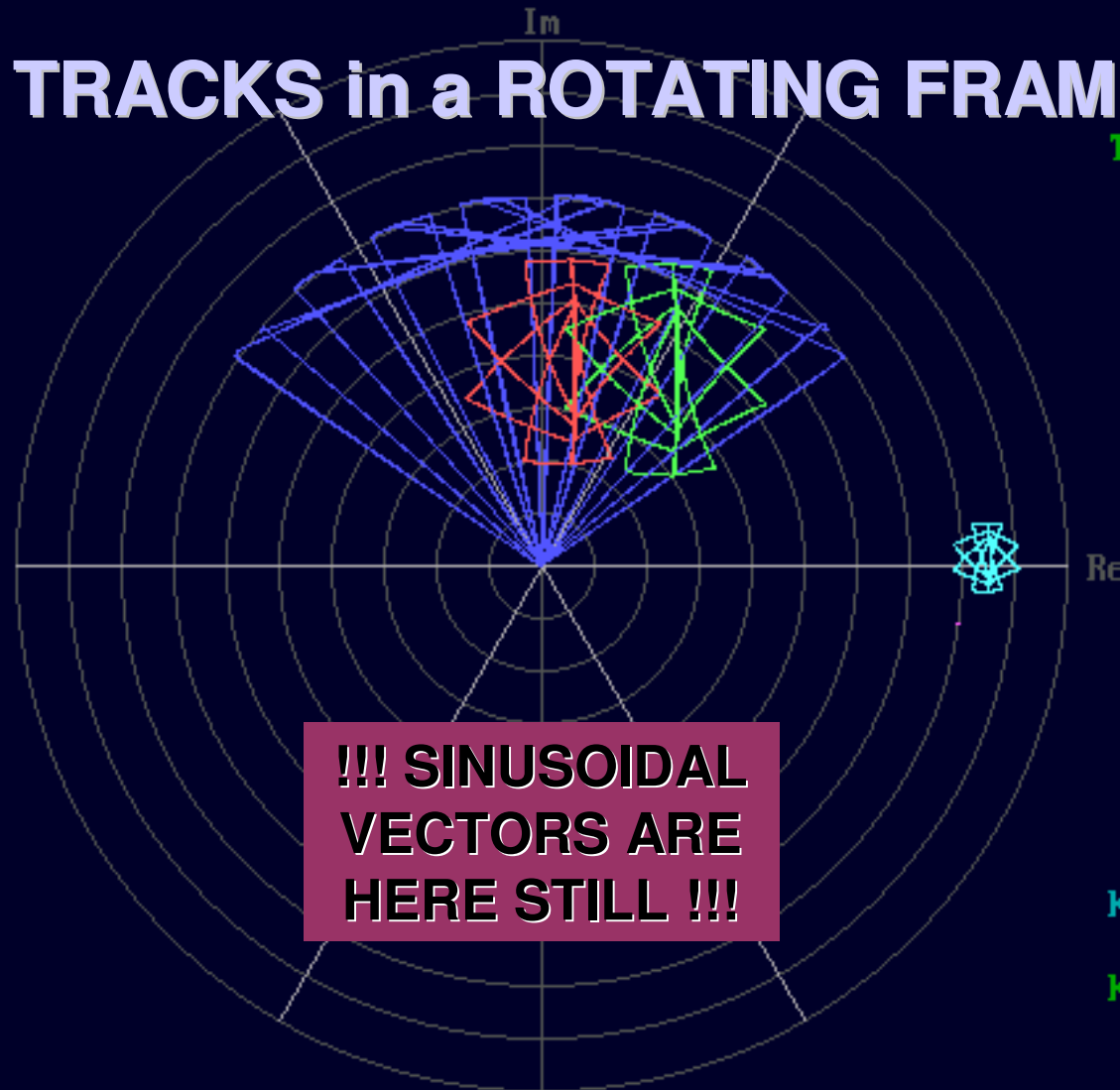
Istatore
163.25 44.6

Irotore
126.34 72.3

FlussoS
2.1527 -0.8

FlussoR
1.9942 -7.8

TRACKS in a ROTATING FRAME



Tc[us] 5
 Yzoom 1.0
 Fsta 41.048
 Frot 40.000
 Scor 1.048
 Ctra 100.28
 Flu% 100.01

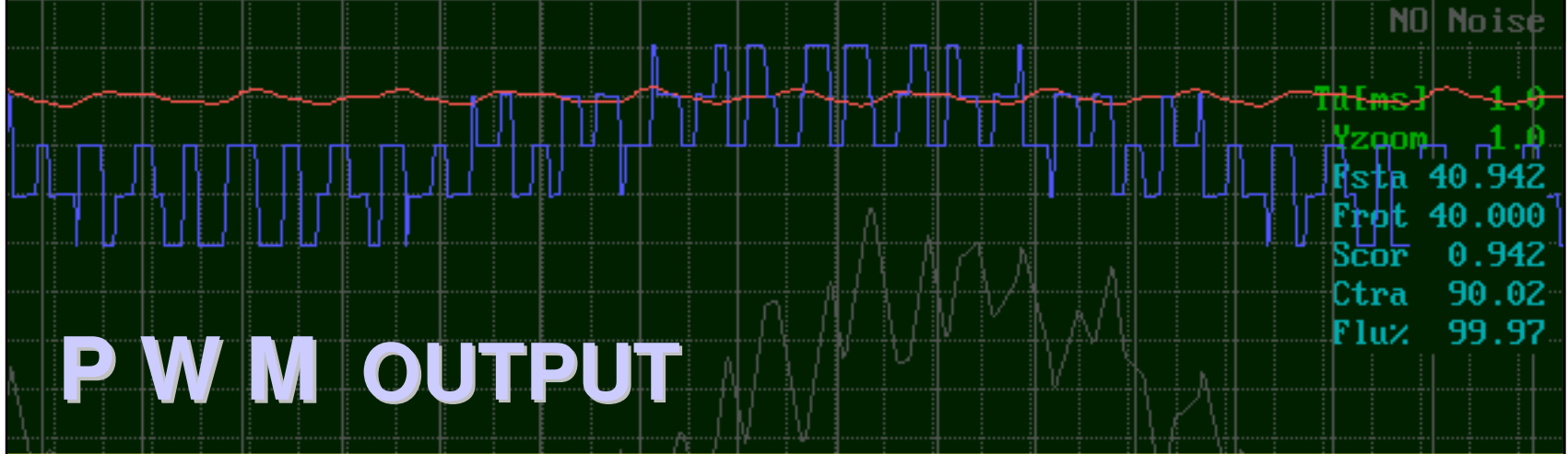
KMod 0.7103
 Nim 12
 Km/h 28.5
 NKL 0.0

1600 100.00 1.000 1.000 1.000 0.0 1.000
 Upan Cref% GSFil GRInu GRChf KTEST GAIN

NEW SYSTEMS - MEHOPT PWM & Tensione & Coppia & Corrente == PWM ==

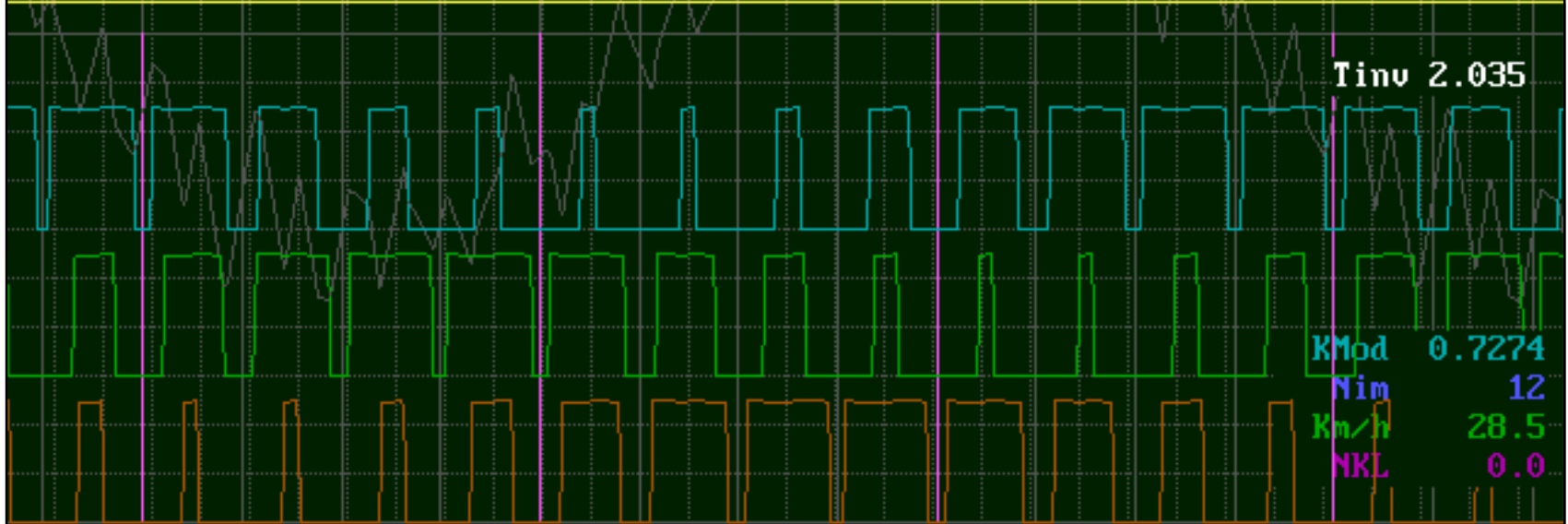
849.82 0 4100 6350 7480.2 -175.21 1532.9 FB Iq&Id
CtraF Pot1 Pot2 Pot3 Ufs1 Is1 VCM Filtro OK

NO Noise



P W M OUTPUT

Td[ms] 1.0
Yzoom 1.0
Fsta 40.942
Frot 40.000
Scor 0.942
Ctra 90.02
Flu% 99.97



Tinv 2.035

KMod 0.7274
Nim 12
Km/h 28.5
NKL 0.0

1550 90.00 1.000 1.000 1.000 0.0 1.000
Upan Cref% GSFil GRInv GRChf KTEST GAIN

NEW SYSTEMS - MEHOPT

VALORI Istantanei Flur Flus

== PWM ==

1.9029

0.5960

1.9397

0.8916

FB Iq&Id

FluRe

FlurIm

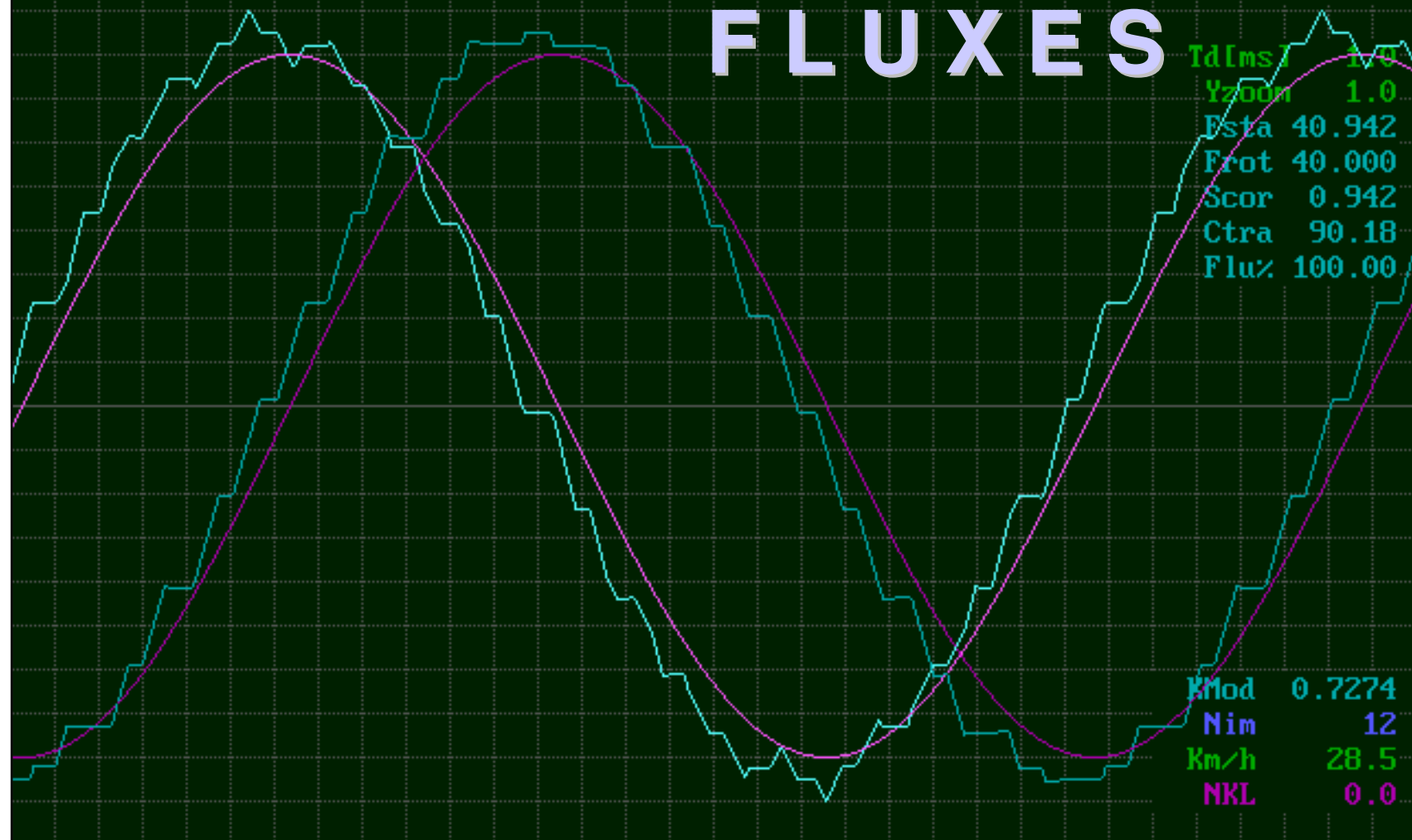
FlusRe

FlusIm

Filtro OK

NO Noise

FLUXES



TdImst 1.0
 Yzoom 1.0
 Fsta 40.942
 Frot 40.000
 Scor 0.942
 Ctra 90.18
 Flu% 100.00

KMod 0.7274
 Nim 12
 Km/h 28.5
 NKL 0.0

1550

90.00

1.000

1.000

1.000

0.0

1.000

Upan

Cref%

GSFll

GRInu

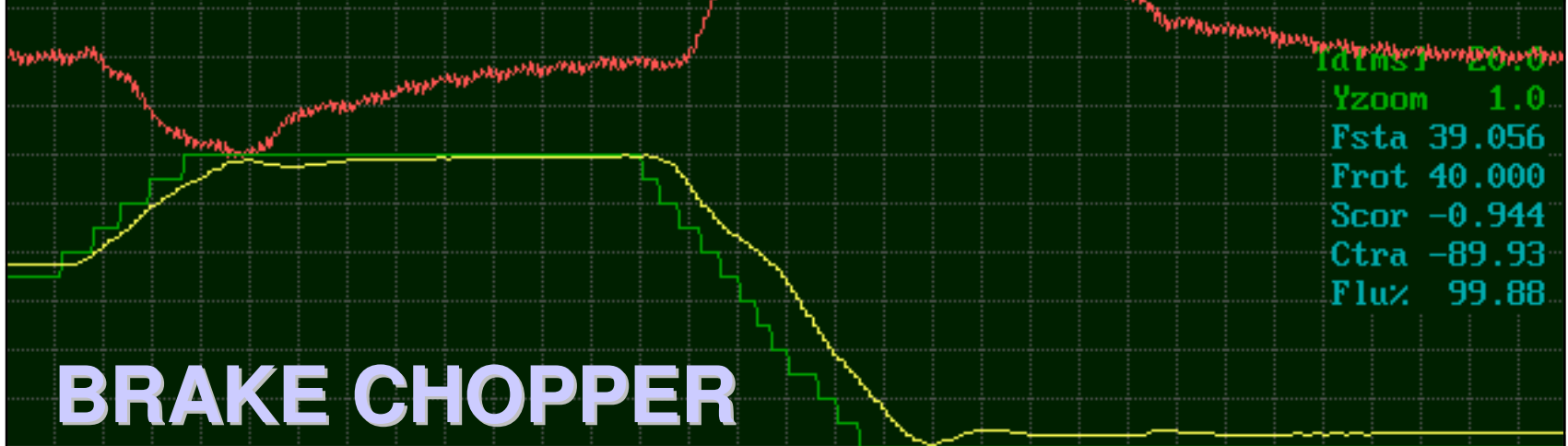
GRChf

KTEST

GAIN

NEW SYSTEMS - MEHOPT Grandezze elettriche FILTLIN in FRENATURA == PWM ==

848.91	-261.26	1500.0	1514.9	0.00	FB Iq&Id
-CtraF	ILM !	Upan	UCM	IFreM	Filtro OK
944.00	500.00	2000.0	2000.0	800.00	NO Noise



BRAKE CHOPPER

IdIMS 20.0
 Yzoom 1.0
 Fsta 39.056
 Frot 40.000
 Scor -0.944
 Ctra -89.93
 Flu% 99.88

KMod 0.6666
 Nim 12
 Km/h 28.5
 NKL 0.0

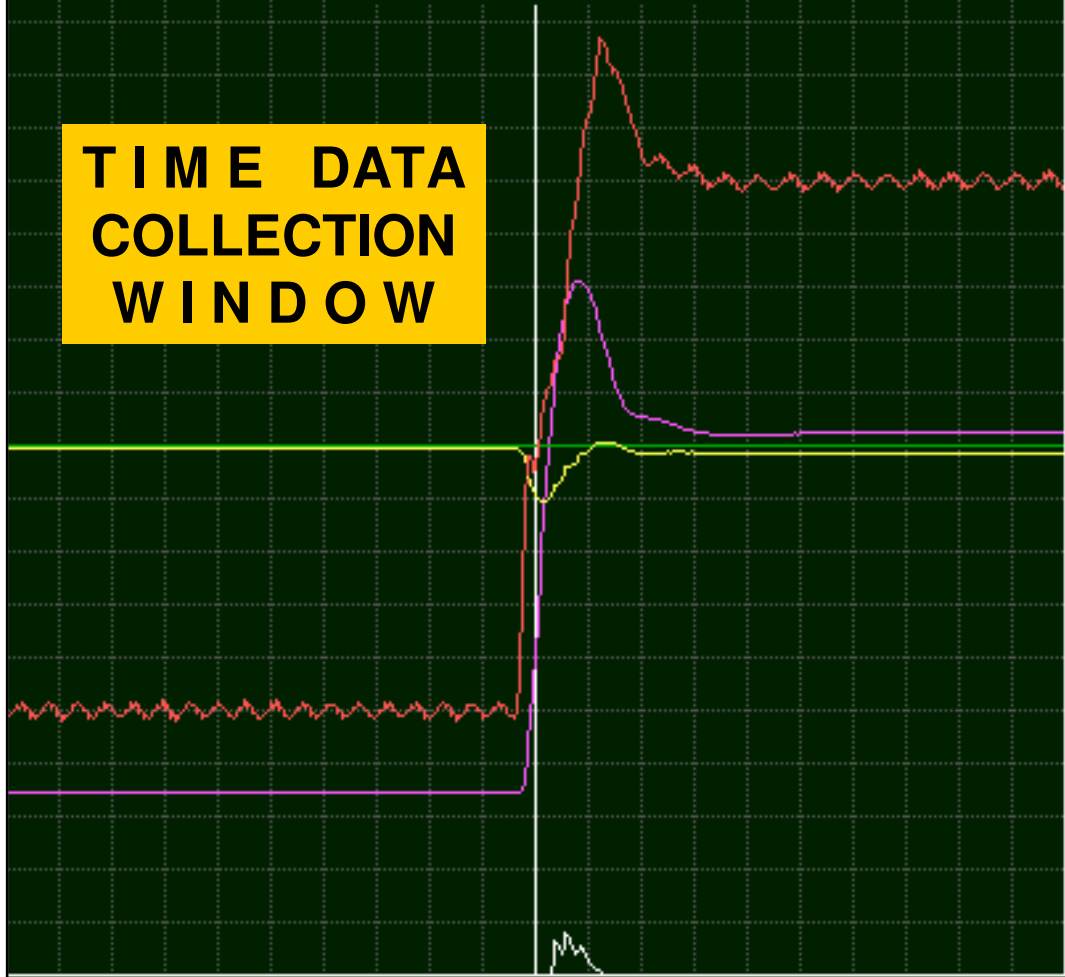
0	-500.00	1000.00	1000.00	0
---	---------	---------	---------	---

1500	-90.00	1.000	1.000	1.000	0.0	1.000
Upan	Cref%	GSFll	GRInu	GRChf	KTEST	GAIN

699.87 255.91 1500.0 0.0 1485.9 FB Iq&Id
CtraF ILM Upan IFreM VCM Filtro OK

Collecting 200.000 points for FFT on Ilin
Time window = 1 s

TIME DATA
COLLECTION
WINDOW



TIME
DATA

Td[ms] 50.0
Yzoom 1.0
Fsta 40.808
Frot 40.000
Scor 0.808
Ctra 74.14
Flu% 100.02

Tinv 2.045

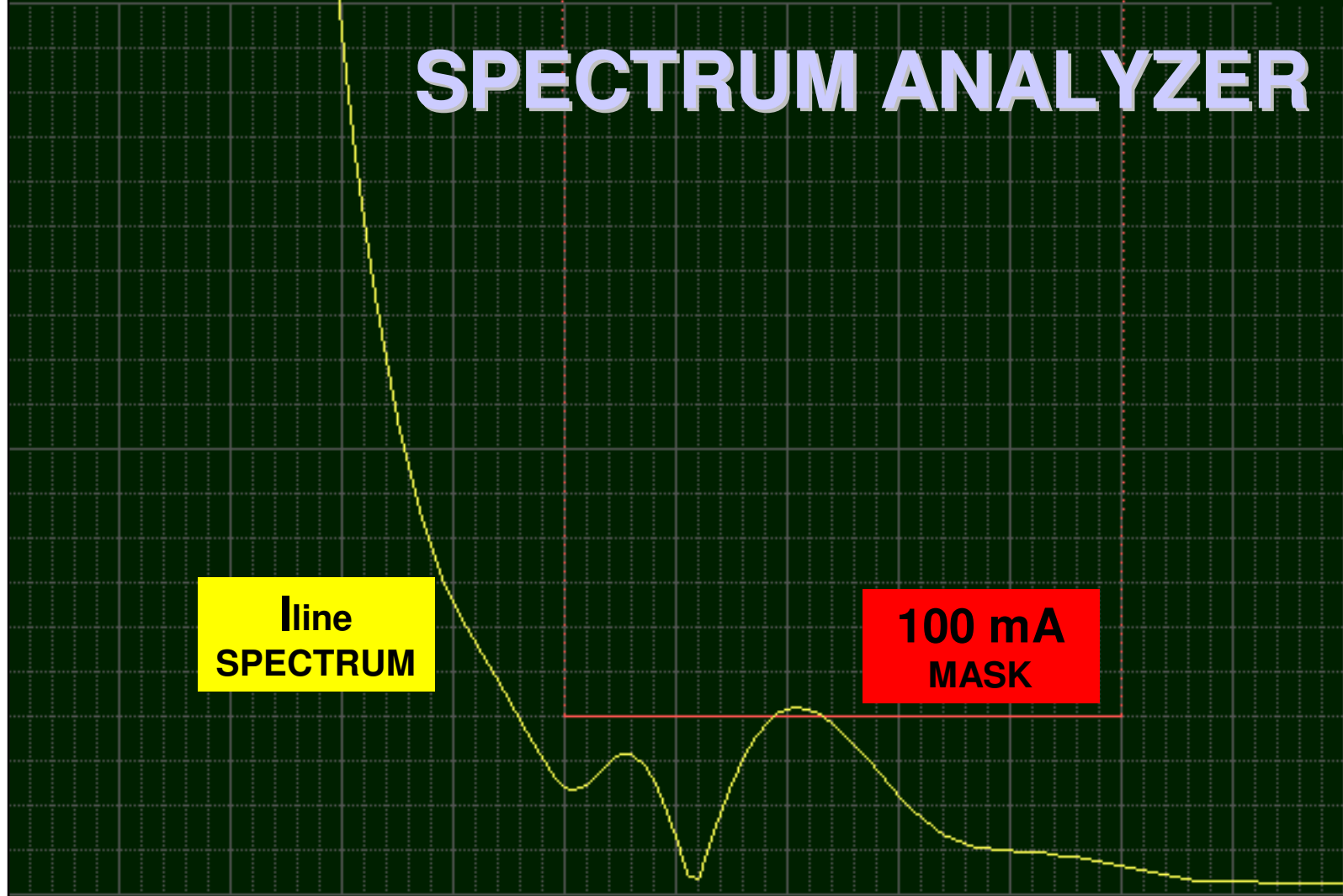
1.000
0.00
KMod 0.7427
Nim 12
Km/h 28.5
NKL 0.0

1500 75.00 1.000 1.000 1.000 0.0 1.000
Upan Cref% GSFil GRInv GRChf KTEST GAIN

MEHOPT FFT 4000 punti, HANNING Window, BT=1s ILin Max =33.083 @ 3 Hz
Fsta = 40.808 Cref = 75.00 Nim = 12 KMod = 0.74269

NO Noise

SPECTRUM ANALYZER



Iline
SPECTRUM

100 mA
MASK

ILin
.25
Arms

Hz 20 30 40 50 60 70 80 90 100 110
[<]/[>] Hz Range [↑]/[↓] Y Gain [M]/[C] Mem/Clear [Esc]o[Inviol] EXIT

MEHOPT FFT 4000 punti,HANNING Window,BT=1s Ctra Max = 202.5 @ 986 Hz
Fsta = 41.046 Cref = 100.00 Nim = 12 KMod = 0.75890

NO Noise

T SPECTRUM ANALYZER

TORQUE HARMONICS SPECTRUM

15°
615.7 Hz
126.3 Nm

24°
981.1 Hz
202.5 Nm

Ctra
125
NmPk

Hz 600 650 700 750 800 850 900 950 1000 1050
[<]/[>] Hz Range [↑]/[↓] Y Gain [M]/[C] Mem/Clear [Esc]o[Inviol] EXIT

FFT on 1000 real points of ILx - SIMULATOR TAFO By FIREMA (NEW-SYSTEMS)
Window for data -> HANNING

MEMORY SPECTRUM ANALYZER

10.0 1 Ver.Div -> 500mA
mA are in RMS value !

Max 2278mA @ 15Hz
Min 15mA @ 80Hz

5.0 Axes are both LINEAR !

PROGRAMMABLE
LIMIT
MASK

0Hz 10 20 30 40 50 60 70 80Hz 1 Hor.Div -> 2Hz

[R] Redo FFT [M] Memory [A] Admit. or *** Any other key to EXIT ***

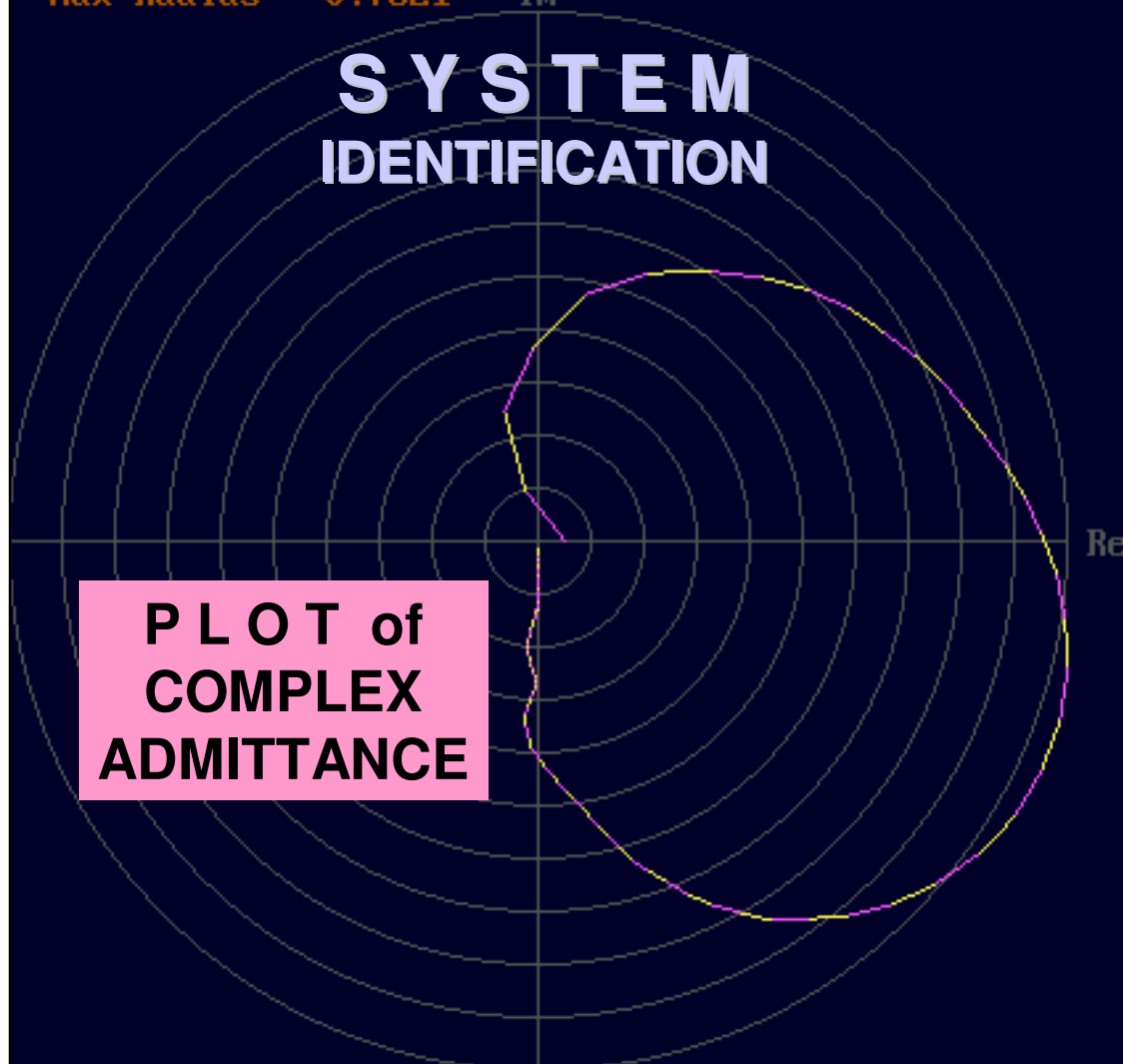
COMPLEX ADMITTANCE CALCULATION

Values are in Siemens units

Max Radius = 0.7821 Im

SYSTEM IDENTIFICATION

PLOT of
COMPLEX
ADMITTANCE

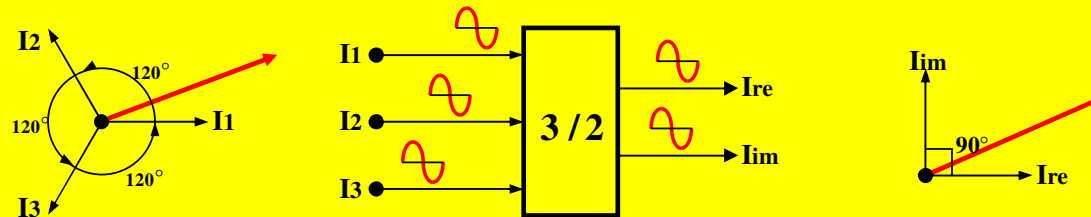


Hz	Real	Imag
0	0.0404	0.0000
1	-0.0210	0.0751
2	-0.0514	0.1926
3	-0.0071	0.2870
4	0.0719	0.3621
5	0.1630	0.3933
6	0.2567	0.3998
7	0.3332	0.3922
8	0.4008	0.3721
9	0.4612	0.3440
10	0.5139	0.3099
11	0.5583	0.2731
12	0.5965	0.2341
13	0.6304	0.1952
14	0.6611	0.1544
15	0.6909	0.1114
16	0.7186	0.0641
17	0.7448	0.0107
18	0.7659	-0.0489
19	0.7793	-0.1167
20	0.7821	-0.1893
21	0.7704	-0.2656
22	0.7447	-0.3403
23	0.7024	-0.4083
24	0.6489	-0.4666
25	0.5872	-0.5100

[+]/[-] Hz scroll

[F] for FILE SAVE or *** Any other key to EXIT ***

CLARKE TRANSFORM



DIRECT $3/2$ $X_{re} = X_1$ $X_{im} = \sqrt{3}/3 (X_3 - X_2)$
INVERSE $2/3$ $X_1 = X_{re}$ $X_2 = -(\sqrt{3}/2 X_{im} + 1/2 X_{re})$ $X_3 = -(X_1 + X_2)$

With this simple direct transform we can convert a 3 phase vector in a 2 phase orthogonal reference where it is simpler to perform any calculation because the vector has only two orthogonal components (Re & Im)

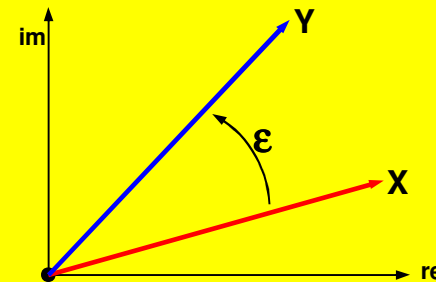
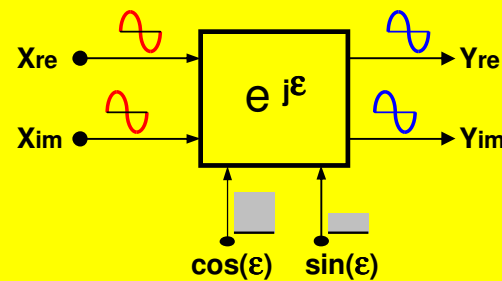
In the 2 phase reference we will perform all the vectorial operations we need ...

At the end we can return in the 3 phase reference with the inverse transform

P A R K TRANSFORM

The PARK transform allows us to perform a lot of operations on our vectors in a fixed or rotating reference

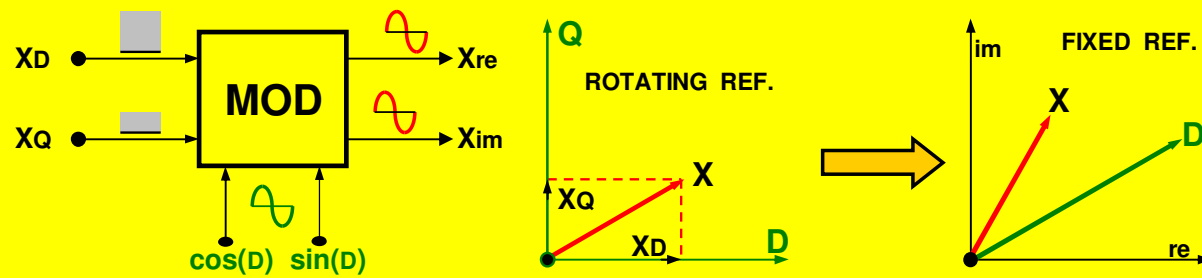
DEPHASING a VECTOR



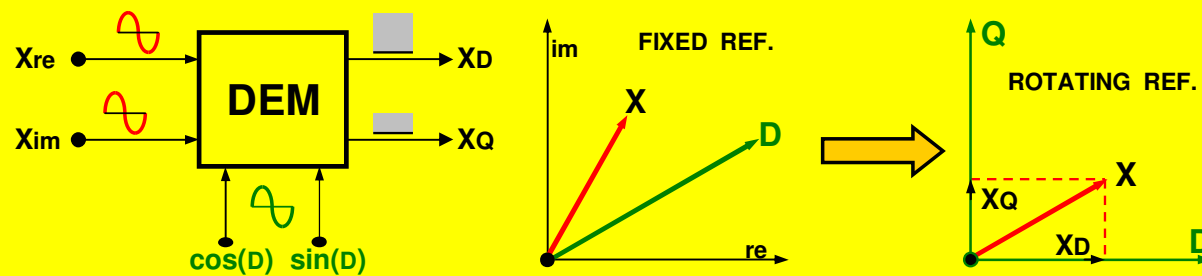
$$\begin{aligned}
 Y &= X e^{j\epsilon} & Y_{re} &= X_{re} \cos(\epsilon) - X_{im} \sin(\epsilon) & Y_{im} &= X_{im} \cos(\epsilon) + X_{re} \sin(\epsilon) \\
 X &= Y / e^{j\epsilon} & X_{re} &= Y_{re} \cos(\epsilon) + Y_{im} \sin(\epsilon) & X_{im} &= Y_{im} \cos(\epsilon) - Y_{re} \sin(\epsilon)
 \end{aligned}$$

Passing in the most **useful** REFERENCE

SINCHRONOUS MODULATION



SINCHRONOUS DEMODULATION



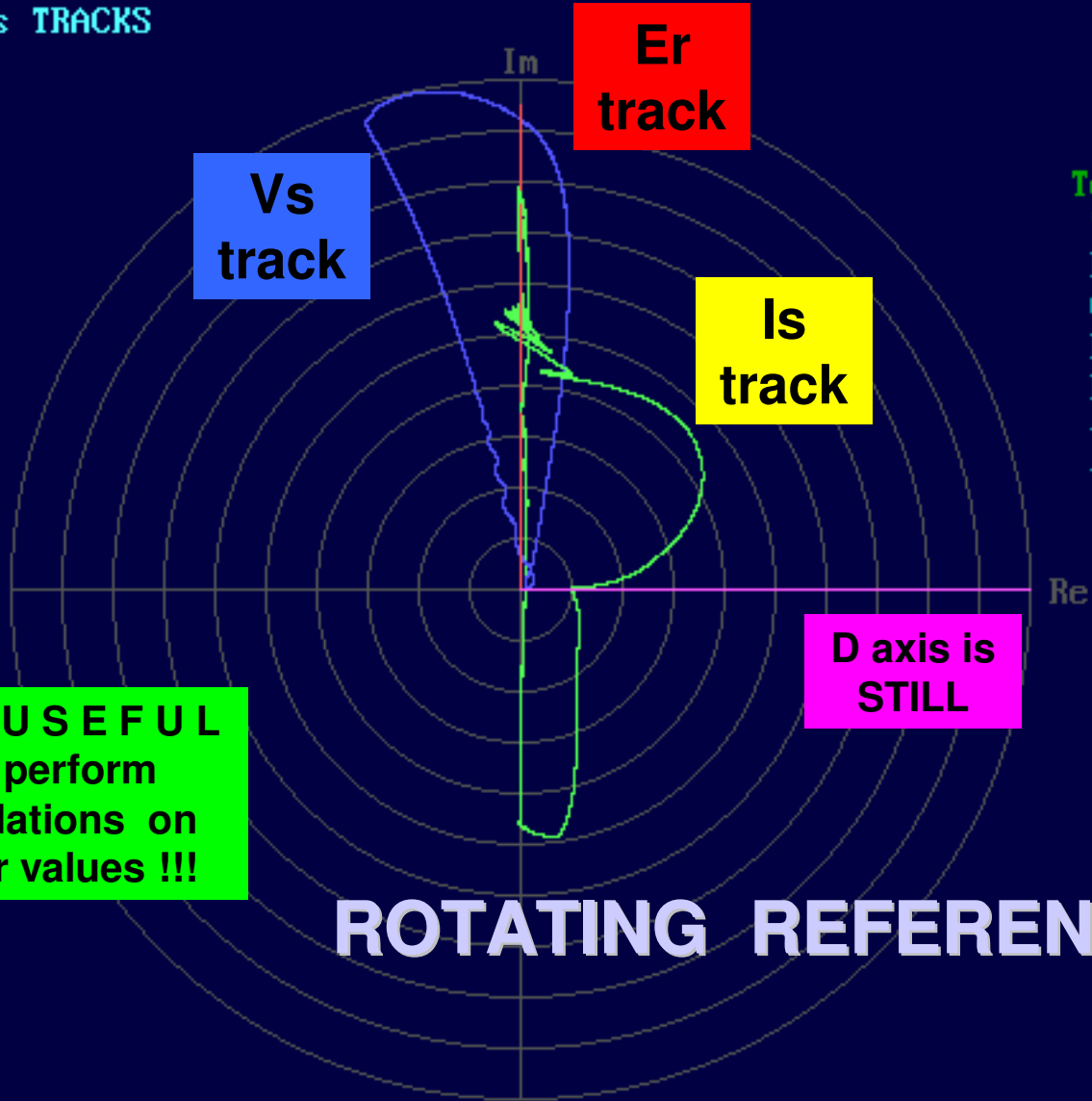
Ing. RAFFAETA' IC10 TRACCE vettori riferiti ad asse D - S I N -

Space-Vectors TRACKS - ideal -

Modulo Gradi NO Round

Flur	
1.00000	0.0
1.00000	
Er	
7.6200	90.0
8.0000	
Is	
1.9241	89.8
5.4971	
Us	
7.9053	98.7
8.0000	

Tc[us]	50
Yzoom	1.0
Frot	500.0
Ctra	7.000
Pmec	21.992
Pele	22.546



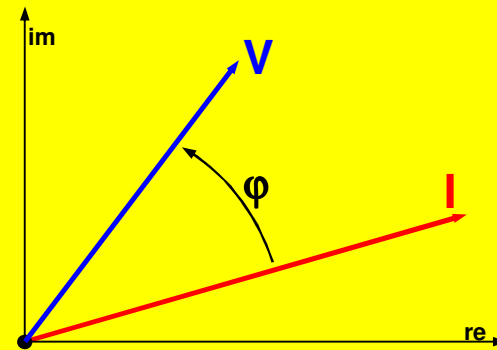
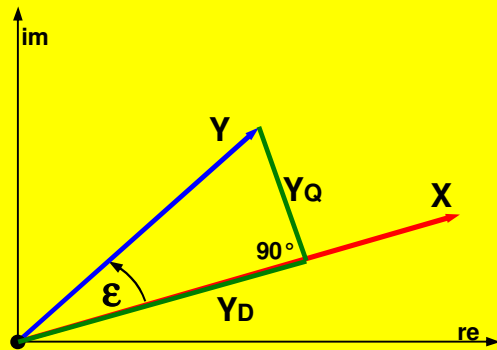
Very USEFUL to perform calculations on scalar values !!!

ROTATING REFERENCE

500	0.00	0.5000	1.0000	1.00	1.00	1.000	1.000
FreSet	Cref%	Gstab	GainR	Caric	ModFF	KTEST	GAIN

VECTOR COMPONENTS

Often , for many purposes , we have to **PROJECT** a vector to obtain its **COMPONENTS** on another vector ...



$$Y_d = |Y| \cos(\epsilon) \quad Y_q = |Y| \sin(\epsilon)$$

$$Y_d = (X_{re} Y_{re} + X_{im} Y_{im}) / |X|$$

$$Y_q = (X_{im} Y_{re} - X_{re} Y_{im}) / |X|$$

$$P = |V| \cos(\epsilon) \quad Q = |V| \sin(\epsilon)$$

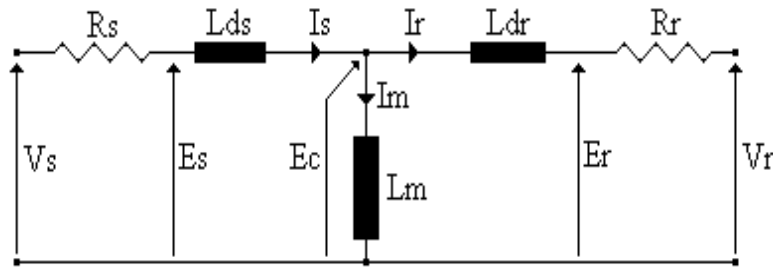
$$P = I_{re} V_{re} + I_{im} V_{im}$$

$$Q = I_{im} V_{re} - I_{re} V_{im}$$

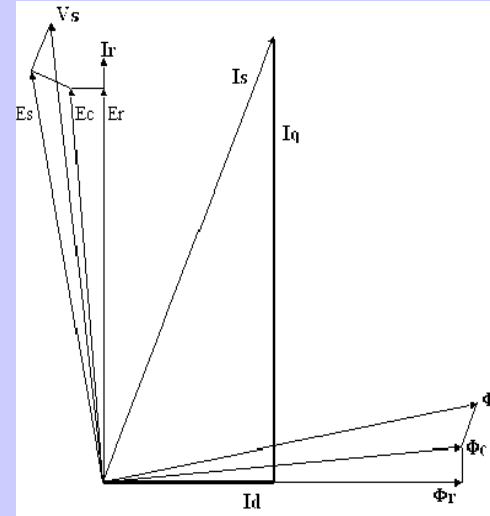
These formulas (all particular case of a Park transform) are very useful to project **I_s** on the **D axis** to obtain **I_d & I_q** or on the **V_s axis** to obtain **P & Q** ; in any case , we obtain a **couple of scalar values** that are the input of our regulators ...

EQUIVALENT CIRCUITS

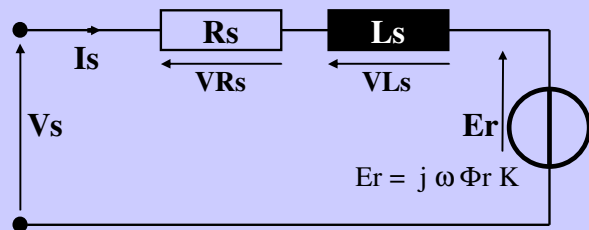
ASYNCRONOUS MOTOR



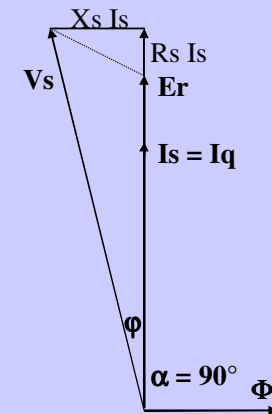
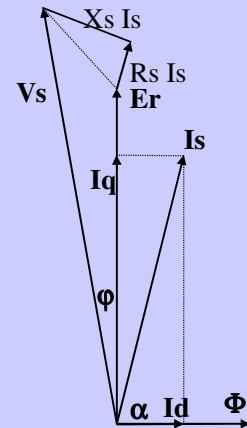
$$E_r = V_r + R_r I_r \quad V_r = j \omega \Phi_r$$



SYNCRONOUS MOTOR



$$E_r = j \omega \Phi_r K_e$$



A GENERAL APPROACH ...

We know V_s because we generate it at every iteration and we also know I_s by measurements ; if we suppose to know the **D direction** (rotor flux), we can calculate all the other values we need ... this task is quite simple if we consider only a **steady-state** condition but it becomes very complex to obtain an exact solution during fast transitory. **Normally the best way is to consider the steady-state solution and compensate it with some well suited added dynamics ...**

$$\alpha = \text{atn}(I_q / I_d)$$

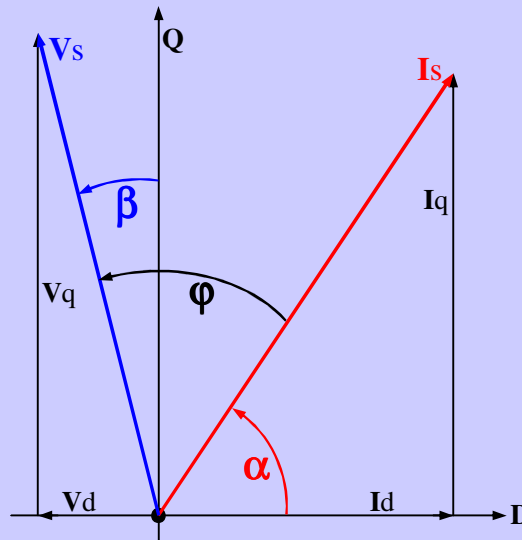
$$\beta = \text{atn}(-V_d/V_q)$$

$$\varphi = \beta + 90^\circ - \alpha$$

$$A = 3 / 2 |V_s| |I_s|$$

$$P = A \cos(\varphi)$$

$$Q = A \sin(\varphi)$$



Now we will consider a general approach valid for a generic motor but then we have to consider two separate solutions for synchronous or asynchronous , but ... with little differences

The main problem of any **SENSORLESS FOC** drive is to know :

Which is the actual **angle** of the **D axis** ??? (Rotor Flux direction)

WHERE IS THE ROTOR FLUX ???

At present time there are **lot of solutions** to this problem , but we will try to find out some solutions **related to the performance** that we need for the **specific application**.

If we have not a **D REFERENCE** , we can use a **VIRTUAL** one and helped from model consistency we can correct our model parameters or commands until the **VIRTUAL D REFERENCE** will overlap the real **ACTUAL D REFERENCE** correctly.

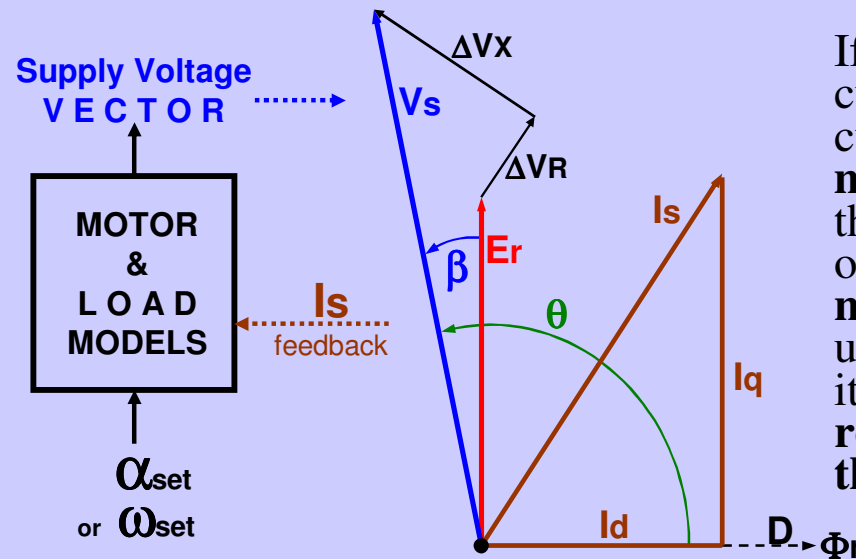
This method **works well** and it is quite **easy to implement in FPGA** , it is also **self convergent** and **robust** and can be **adapted** to the desired performances of the drive ...

With **little differences** it works on **INDUCTION** or **PMSM** ...

BASIC CONSIDERATIONS

A **motor model** calculates V_s and so we **know** , in function of I_{dset} & I_{qset} , ω_{set} , α_{set} , ... V_d , V_q , β , θ , ... , and so we can **derive the D virtual direction angle**.

Measuring I_s , after few calculations , we obtain the **I_s components on D & Q** that we define as **I_{dm} & I_{qm}** (from real and true measurement)



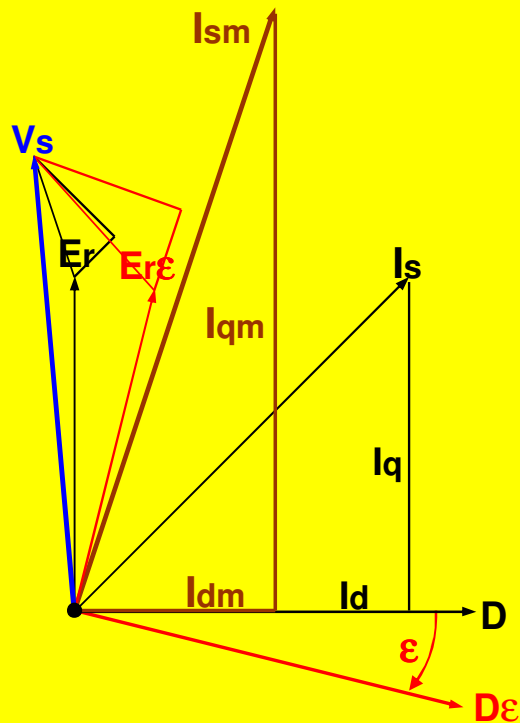
If we compare the measured currents **I_{dm} & I_{qm}** with the currents **I_d & I_q** used by our **motor model** , we can correct these in order to obtain in output of the motor model a **new vector V_s** which will give us in a **very short time** (few iterations) a **coincidence of the real measured current with the one used in the model**.

At the equilibrium point the **motor currents and the model currents are the same** ... but we don't know if the model parameters and the torque reflects the reality ...

In any case , this method is autoconvergent and the practical results are sufficient for a lot of practical applications ; precision and dynamic depend only on the regulators we decide to use ... the system is optimally decoupled ...

MOTOR is SELF-REACTIVE

The autoconvergence of this sensorless strategy is greatly helped by the motor characteristic impedance, and this is true for any motor type



Let us suppose that the **LOAD is increasing**
ROTOR begins to **DECELERATE**

Rotor Direction **LAGS** from our Virtual D

E_r **LAGS** with the same angle ϵ

$V_s - E_r$ start to increase on the impedance

I_s leads and augments its modulus

I_{qm} becomes **greater** than our model I_q

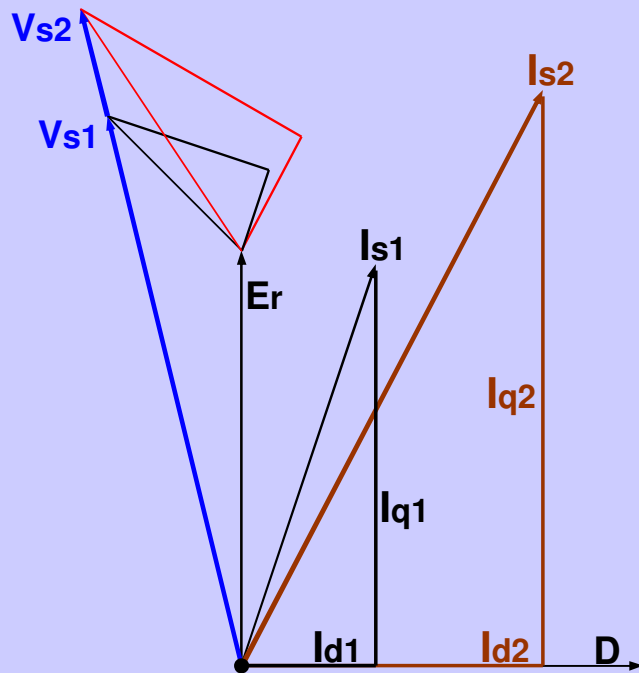
So we **increase I_{qset}** in our **model** and the resulting V_s gives to the motor a **greater torque** that **accelerates the rotor** in order to obtain a coincidence of the rotor direction with our virtual D reference; at this point we **have restored a new equilibrium point** with new correct I_d & I_q

We have used a **ROTOR D REFERENCE**
and a **CONSTANT ROTOR FLUX !!!**

This choice will adjust any **rotor parameter detuning** in $R_r, L_r, \Phi_r, \omega_r, T_t \dots$
but if we pay attention to the **stator parameters** we will see good news ...

STATOR CONSIDERATIONS

Even if the motor model is related to rotor flux (as it is obvious in PMSM) also **parametric detuning in the stator is well controlled.**



The supply voltage is the main stator controlled variable.

If we suppose that (for a stator parametric detuning) V_{s1} pass to V_{s2} , we will obtain new measured I_{q2} & I_{d2} that are very different from the I_{q1} & I_{d1} of the model.

Only to understand , we have exaggerate a lot in increasing V_s !!!

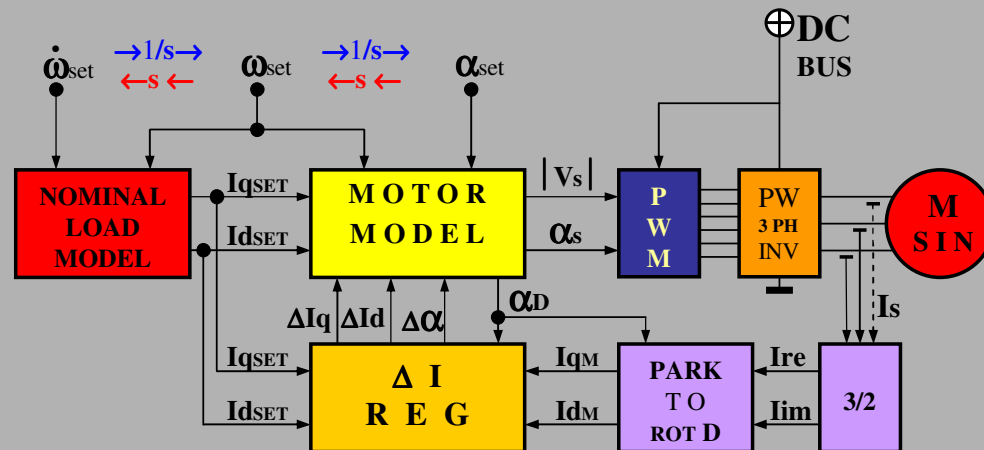
The flux and and torque have a great apparent increase ... the controllers restore the system up to the coincidence of the model I_s with the measured I_s , and at this point also stator parametric detuning is well reduced ... R_s , L_s , Φ_s ...

The rotor & stator detuning is so **well reduced** ... but a decrease in L_m (saturation) can produce a **loss of flux & torque** (we work at **constant current**) , especially at very **low speed** or at **starting phase** ... it is possible to compensate these effects.

TYPICAL SENSORLESS

This structure is very general one and is also well suited also for POSITIONING purposes ... normally we use a projection of I_s on the **D axis** (rotor flux), but sometimes , for special applications it is better to project I_s on V_s axis , thus obtaining the active & reactive powers P & Q and use energetic methods ...

To reach a **good global dynamic and stability**, we must not stress the complex conjugate poles of the system in any way ... the **position and speed** sets must be previously **well and properly filtered** to reach the final goal to achieve a smooth action.



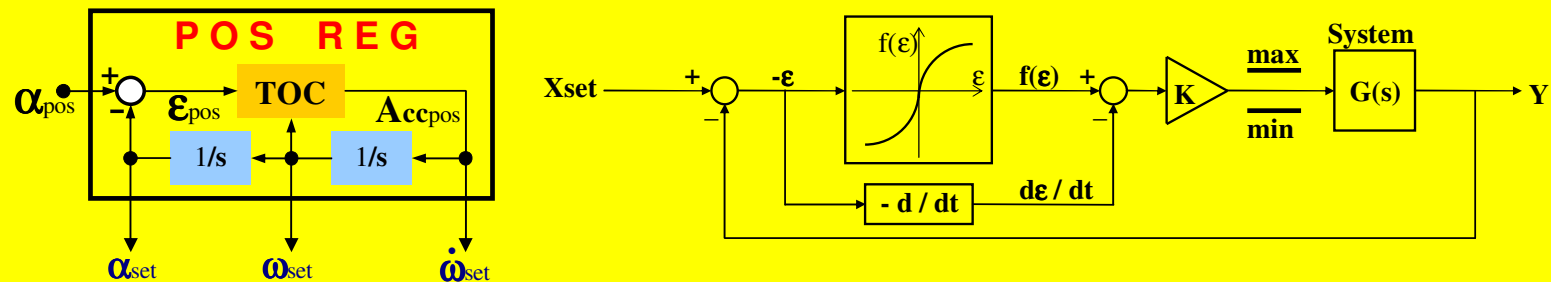
For the regulation block on ΔI , we can use the strategy we prefer , but **we have to consider all the dynamic characteristic of the PWM & MOTOR we use ...**

In order to obtain a good dynamic and stability , we have to consider that the I_q (Torque) regulator can be generally fast but we must pay attention to the I_d (Flux) regulator and use this feedback action in a light and smooth way ... some filtered functions of ΔI_d are sometimes used to perform a dumping on the whole drive ...

Time Optimal Control

For accurate positioning we advise you to use the **TOC strategy** that has a **lot of useful advantages** and **it is simpler to implement in FPGA than other old strategies ...**

General Optimal Control tends to minimize a “cost function” and it is generally complex , but if we want only to optimise the **SETTLING TIME** , it becomes **very simple** and reflects the fundamental dynamic law $\omega^2 = 2 \text{ Acc } \alpha$, and so , **the tracks in the phase plane of such a system are pure arcs of a parabola.**



TOC strategy gives us directly POSITION , SPEED , ACCELERATION sets that the motor regulator requires and has many advantages over a classic PID regulator.

- 1) **Very fast and perfectly controlled positioning without any overshoot**
- 2) **The best stability with null error at the positioning end**
- 3) **Absolute tracking on ramps also with no explicit integrative actions**
- 4) **Energetic optimisation of the PW driver and of the motor during positioning**
- 5) **TOC is simple , precise and robust in all the operative conditions**

Ing. RAFFAETA' DEMOPOS2 Posizioni Angolari in funzione del Tempo

0.00 -0.00 -0.0002
PosVol PosAct PosErr
500.00 500.00 10.0000

Pos Set

T O C POSITIONING

Act Pos

Td[ms] 100
Yzoom 1.0
Fset 0.000
Aset -0.00
Cnom 0.00
Inom 1.00
PVol 0.0
PErr -0.0

Pos Error !!! AMPLIFIED !!!

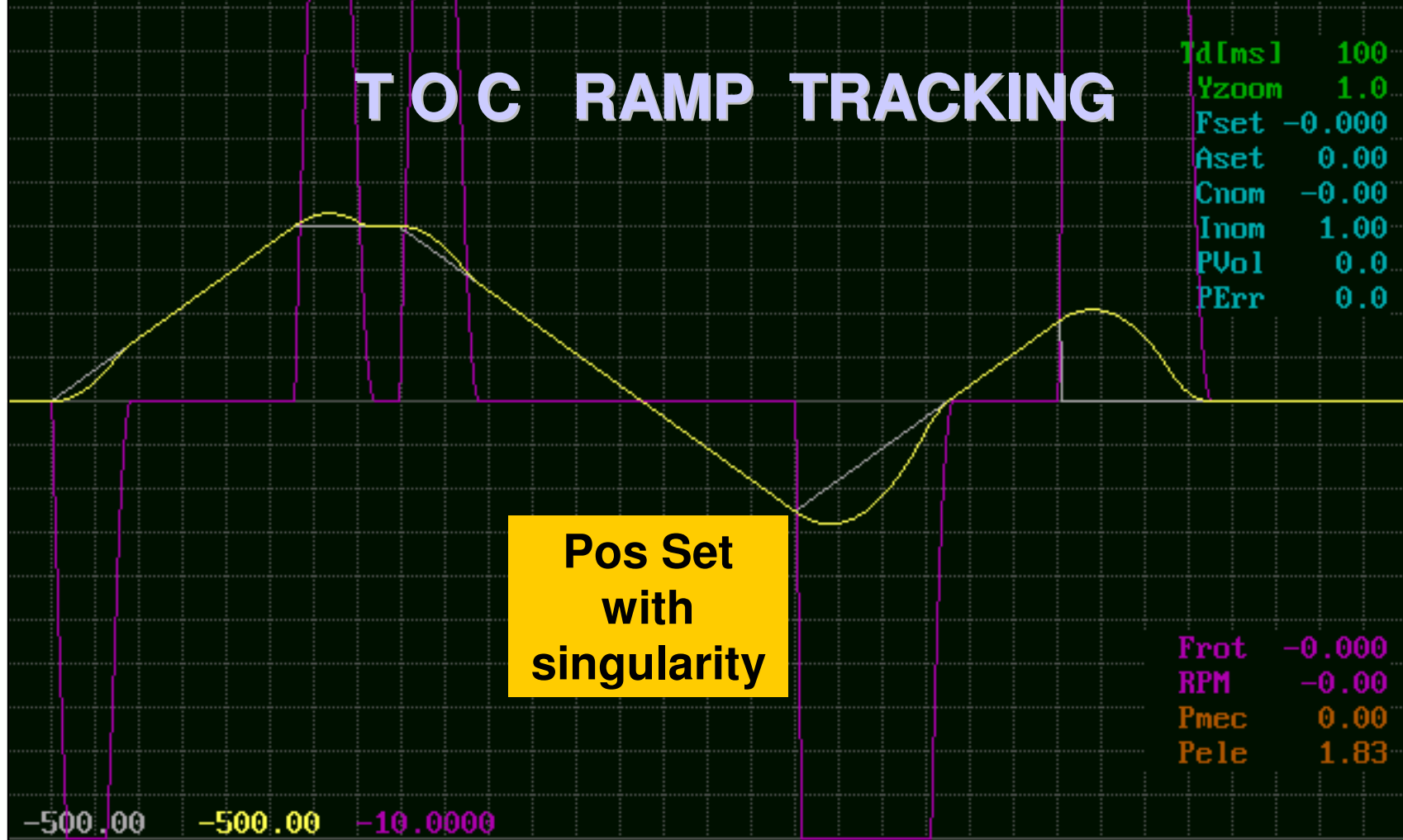
Frot 0.001
RPM 0.01
Pmec 0.00
Pele 1.83

-500.00 -500.00 -10.0000
65.0 1.000 1.00 1.00 0.000 0.000
Fmax Ramp KCres KCdin KTEST GAIN

0.00	0.00	0.0010
PosVol	PosAct	PosErr
500.00	500.00	10.0000

T O C RAMP TRACKING

Td[ms]	100
Yzoom	1.0
Fset	-0.000
Aset	0.00
Cnom	-0.00
Inom	1.00
PVol	0.0
PErr	0.0



Frot	-0.000
RPM	-0.00
Pmec	0.00
Pele	1.83

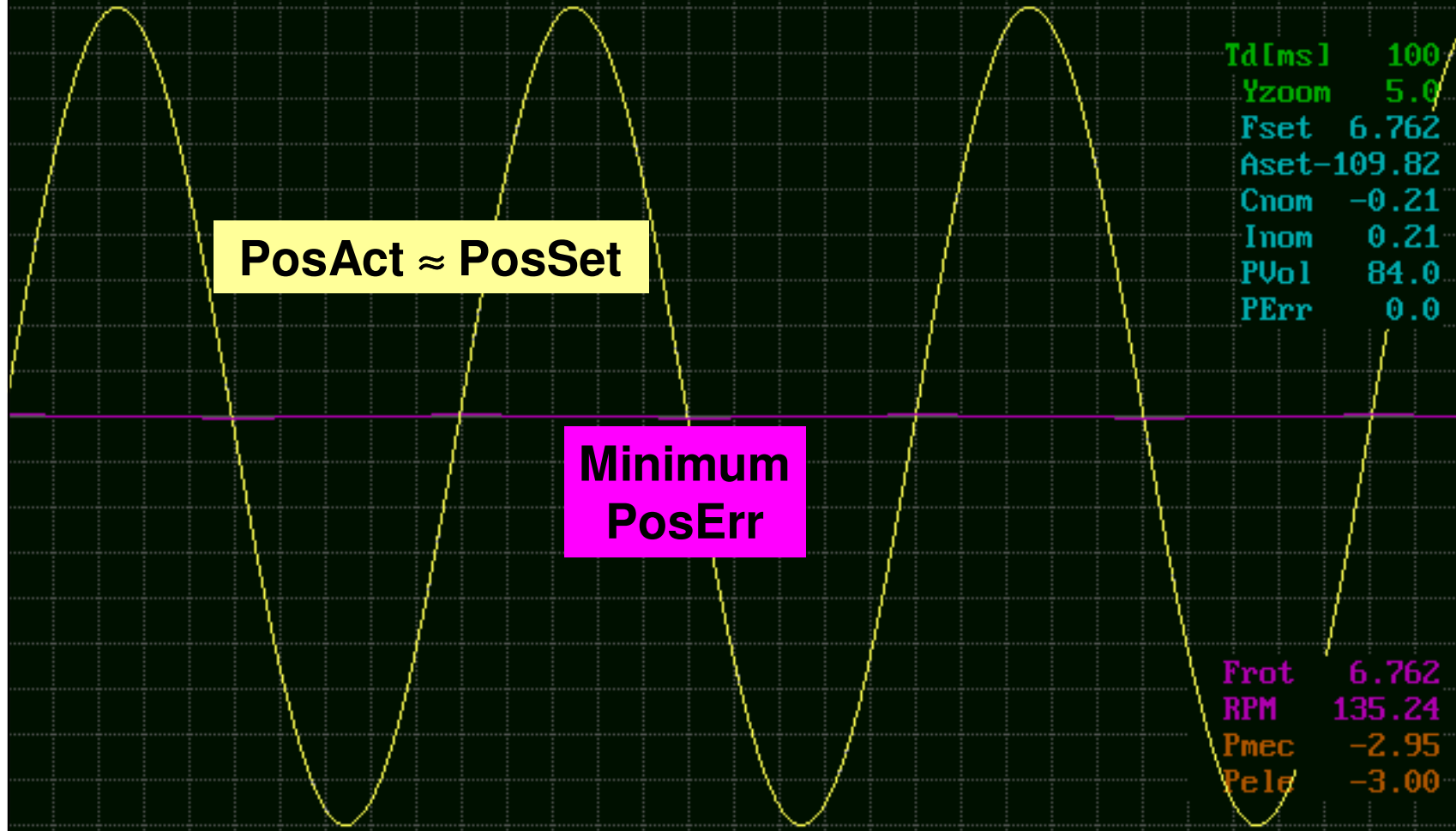
-500.00	-500.00	-10.0000	65.0	1.000	1.00	1.00	0.000	0.000
Fmax	Ramp	KCres	KCdin	KTEST	GAIN			

Ing. RAFFAETA' DEMOPOS2 Posizioni Angolari in funzione del Tempo

83.95 83.96 0.013
PosVol PosAct PosErr
100.000 100.000 10.0000

TOC SINE TRACKING

Sin+/-90°



Td[ms] 100
Yzoom 5.0
Fset 6.762
Aset -109.82
Cnom -0.21
Inom 0.21
PVol 84.0
PErr 0.0

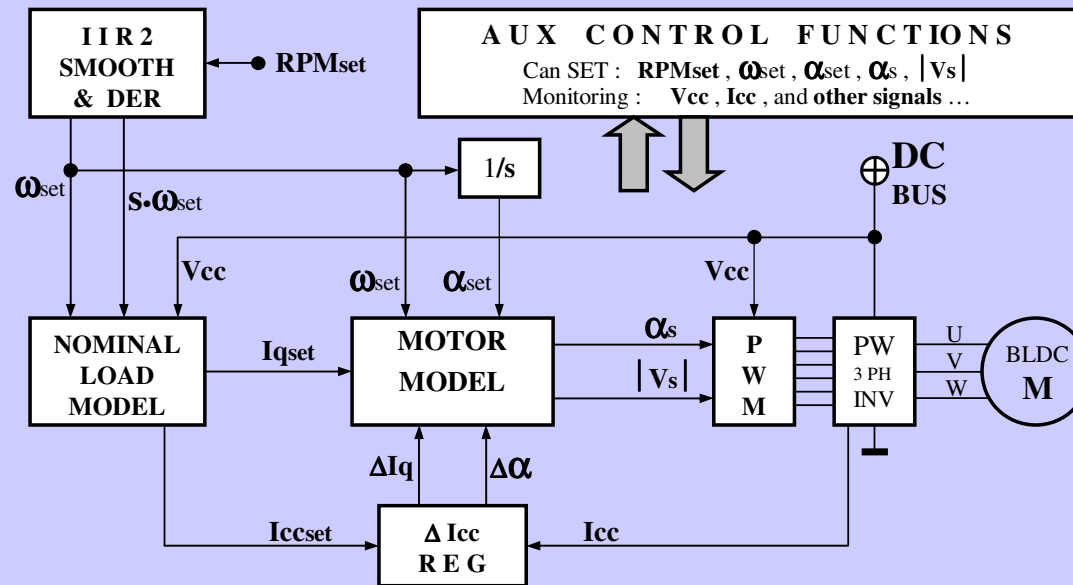
Frot 6.762
RPM 135.24
Pmec -2.95
Pelc -3.00

-100.000 -100.000 -10.0000

65.0 1.000 1.00 1.00 0.000 0.000
Fmax Ramp KCres KCdin KTEST GAIN

SIMPLIFIED SENSORLESS

For speed-only control in low cost and medium performance drives, we can simplify our system ...



This is an example of a complete drive we have used for a low-cost but **high-speed BLCD** motor ; the only feedback is **Icc** (DC bus current) which is a scalar value and that it is easy to measure. This motor is **unstable** (in open loop condition) in the region of the medium speeds. The ΔI_{cc} regulator can **stabilize the system** in any operating condition and optimise the **Id nulling** also for **large load variations**.

Ing. RAFFAETA' IC10 TRACCE vettori riferiti ad asse D

Space-Vectors TRACKS

Modulo Gradi

Flur

1.00000 0.0

Er

7.6200 90.0

Is

1.9239 89.8

Us

7.9053 98.7

- S I N -

- ideal -

NO Round

Tc[us] 500

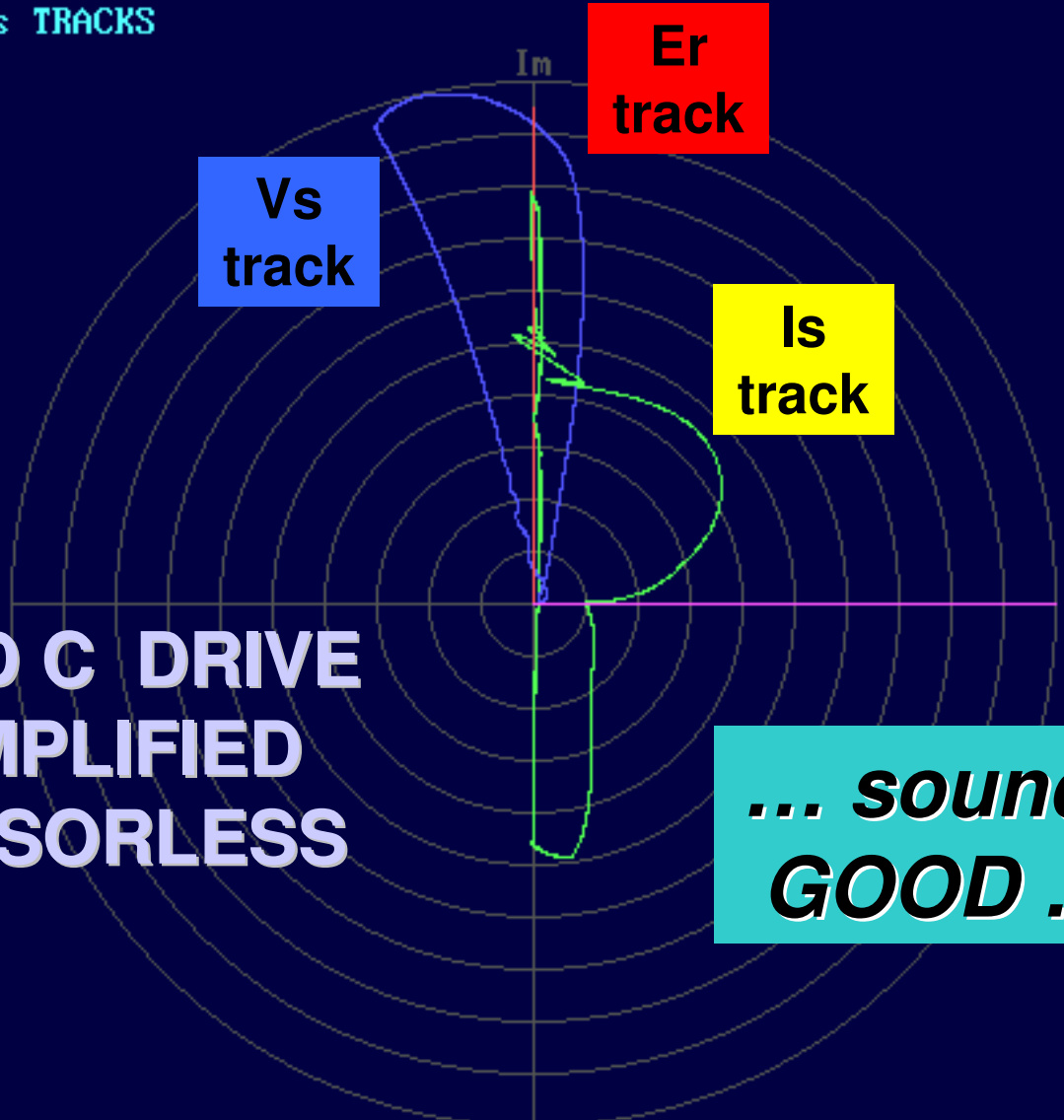
Yzoom 1.0

Frot 500.0

Ctra 7.000

Pmec 21.991

Pele 22.545



Vs track

Er track

Is track

**B L D C DRIVE
SIMPLIFIED
SENSORLESS**

*... sounds
GOOD ...*

500
FreSet

0.00
Cref%

1.0000
Gstab

1.0000
GainR

1.00
Caric

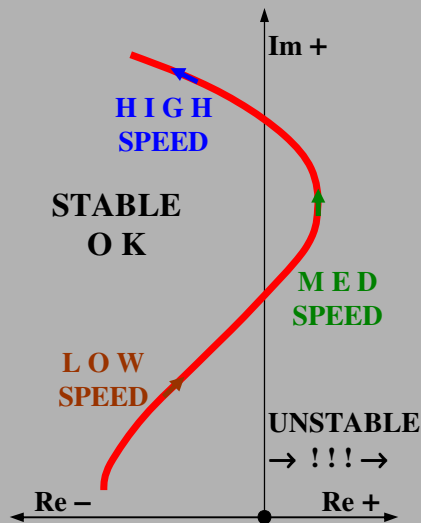
1.00
ModFF

1.000
KTEST

1.000
GAIN

OPEN LOOP DRIVES

For speed control in very low-cost and low dynamic performance drives , we can use only a simplified motor model and act in feed-forward mode on the motor ...
Normally it works well ... , but in rare cases something wrong appears ...



Also in steady-state conditions , all the motors have a transfer function with some complex conjugate pairs.

Some pairs are generally well-damped while other pairs are under-damped and this fact depends from a lot of factors (speed , Tload , moment of inertia J , viscous friction B , ...) and parameters as R & L.

In **rare cases** and for **unusual motors** and in **certain operating conditions**, can happen that a complex conjugate pair assumes a **positive real part** (as in the graph on the left) ; in this case the motor becomes **absolutely instable** (also in open loop) and **stops in a dangerous situation with very high currents**.

If you have any reasonable doubt that your whole system will be unstable or its behaviour is not well damped in open loop , we advise you to use an Icc feedback as we have seen in SIMPLIFIED SENSORLESS.

Ing. RAFFAETA' IC10 TRACCE vettori riferiti ad asse D - S I N -

Space-Vectors TRACKS - ideal -

Modulo Gradi NO Round

Flur
1.00000 0.0
1.00000

Er
0.8217 90.0
8.0000

Is
12.6645 175.8
5.4971

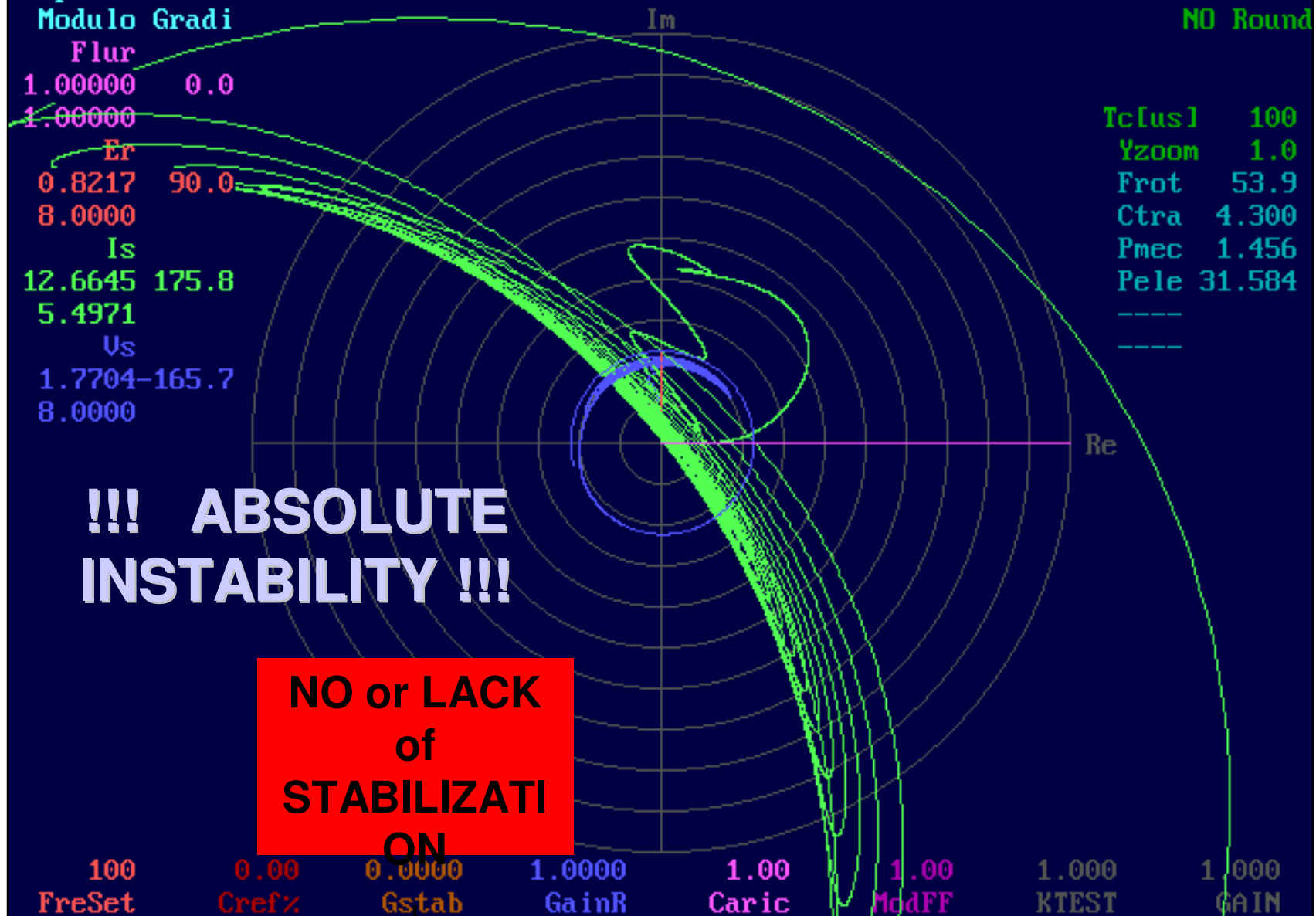
Us
1.7704 -165.7
8.0000

Tc[us] 100
Yzoom 1.0
Frot 53.9
Ctr 4.300
Pmec 1.456
Pele 31.584

**!!! ABSOLUTE
INSTABILITY !!!**

**NO or LACK
of
STABILIZATI
ON**

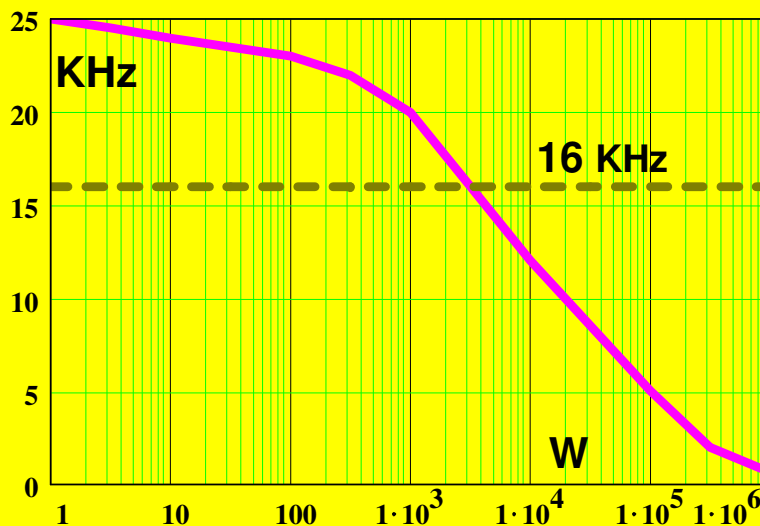
100 0.00 0.0000 1.0000 1.00 1.00 1.000 1.000
FreSet Cref% Gstab GainR Caric ModFF KTEST GAIN



P W M MODULATORS

Considering the power driver , we can divide the drives in three categories :

POWER	KW	FREQUENCY	SWITCHES
LOW	up to 1 KW	16 ÷ 24 KHz	MOSFET (TRANSISTOR)
MEDIUM	1 ÷ 100 KW	2 ÷ 18 KHz	IGBT (MOSFET)
HIGH	over 100 KW	0.4 ÷ 5 KHz	IGBT – GTO



Commutation losses increase with the frequency , so at present state of switch technology , we must reduce the operating frequency of high power modulators ; in these cases is useful to adopt HI-EFF strategies.

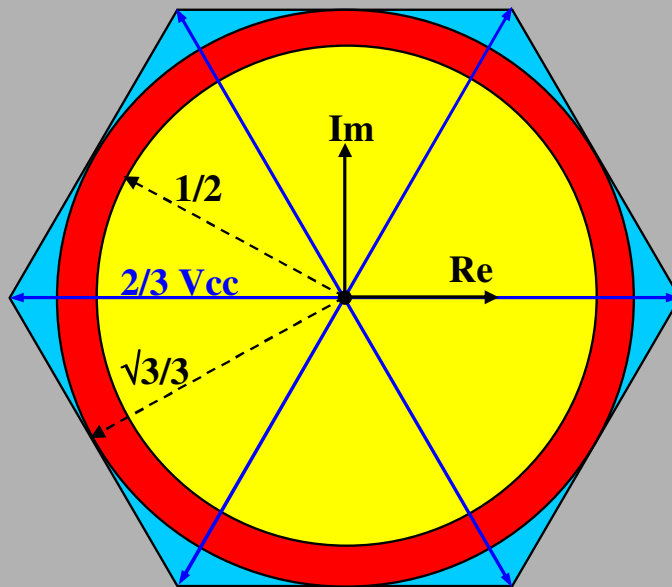
For LOW & MEDIUM power is advisable to operate over 16 KHz in order to work in the not audible range. All we hope to have in the future **high power IGBT** working at higher frequencies with low losses.

High operating frequencies (well handled in F P G A) give us low harmonic contents , short dead-time and minimum Ton & Toff

Modulation STRATEGIES

Considering a monolevel 3 phase modulator we have 8 combinations ; 2 are zero vector , and 6 active vectors ($2/3 V_{cc}$) that define the voltage hexagon.

With the old natural **S I N** modulation we can have unclipped sinusoidal voltages with maximum amplitude of $2/3 V_{cc}$ (yellow region in the figure).



But if we **offset** the 3 inverter potentials with 3 **identical voltages** (also varying in the time), **concatenated voltages** and **phase currents** in the motor **remain identical**.

This fact allows us to have a lot of solutions to obtain **higher unclipped sinusoidal voltages** (red region in the figure)

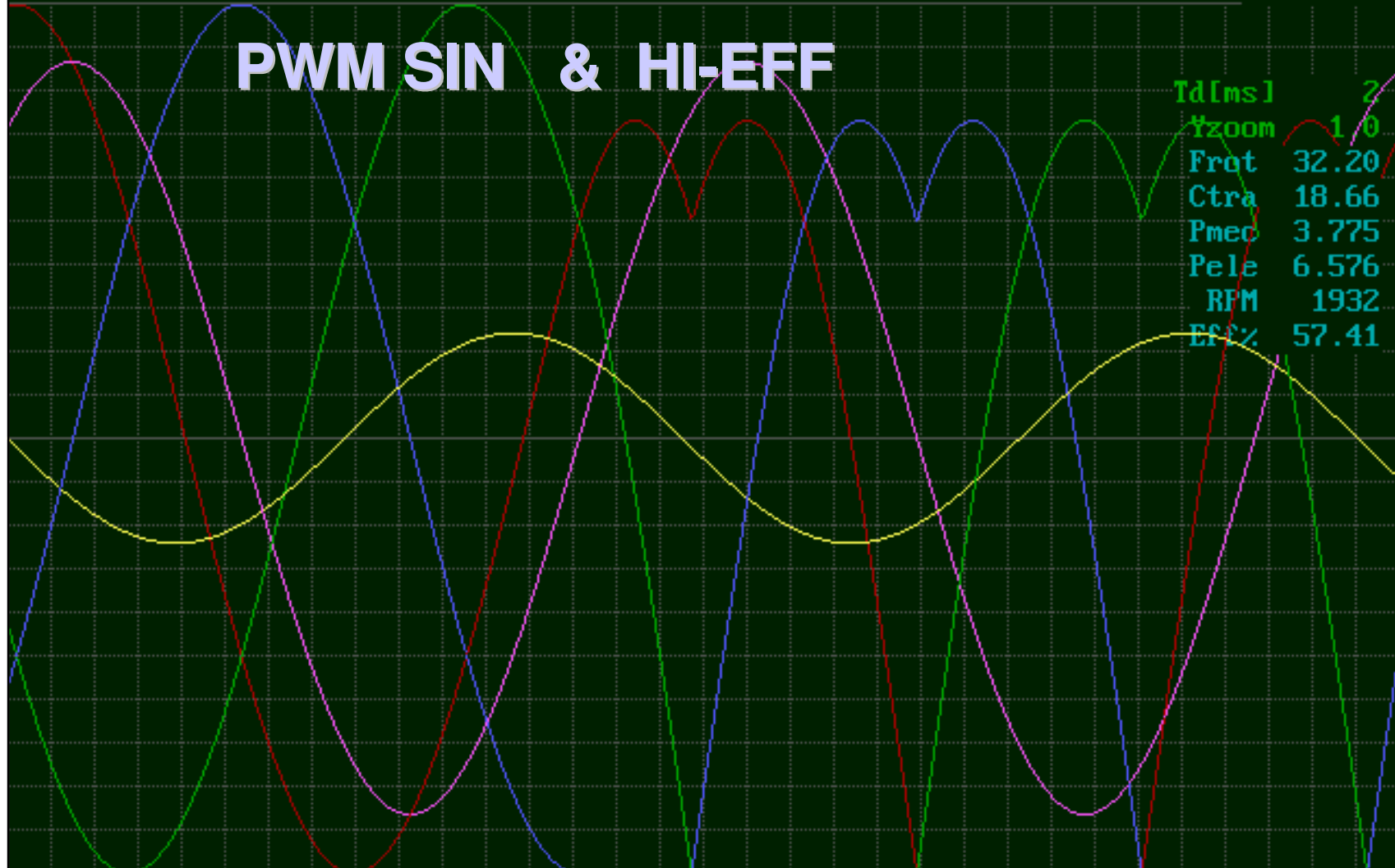
All researchers have their own preferred offset receipt , and personally I prefer **HI-EFF** modulation (I developed in 1995) for the reason that can use all the red region ad above all because reduces the commutation losses by a factor $2/3 \approx 0.667$ (33.3% gain)

In literature you can find many other solutions so to select the best.

The **SPACE VECTOR** modulation is a time weighted average of the basic vectors with $2/3 V_{cc}$ amplitude and can operate in **all the voltage hexagon** (blue region in the figure) ; but also in this case , if we go out of the red circle , we will obtain clipped sinusoids (SATURATION). **!!! The hexagon perimeter is a square wave**

Ing .RAFFAETA' BDPREL MOTOR Supply VOLTAGES and phase CURRENT HI-EFF
 84.061 0.000 24.390 84.061 -0.03480 - ideal -
 Pot1 Pot2 Pot3 Ucon12 Ista2 NO Round

PWM SIN & HI-EFF



Td[ms] 2
 Yzoom 1.0
 Frot 32.20
 Ctra 18.66
 Pmec 3.775
 Pele 6.576
 RPM 1932
 Eff% 57.41

32.20 46.1 1.0000 1.0000 1.00 1.00 1.000 1.000
 FreSet Cref% Gstab GainR Caric ModFF KTEST GAIN

NEW SYSTEMS - HIEFFO

Valori PWM (Offsettati!)

== PWM ==

== FFD ==

CtraF

Pot1

Pot2

Pot3

Ufs1

Is1

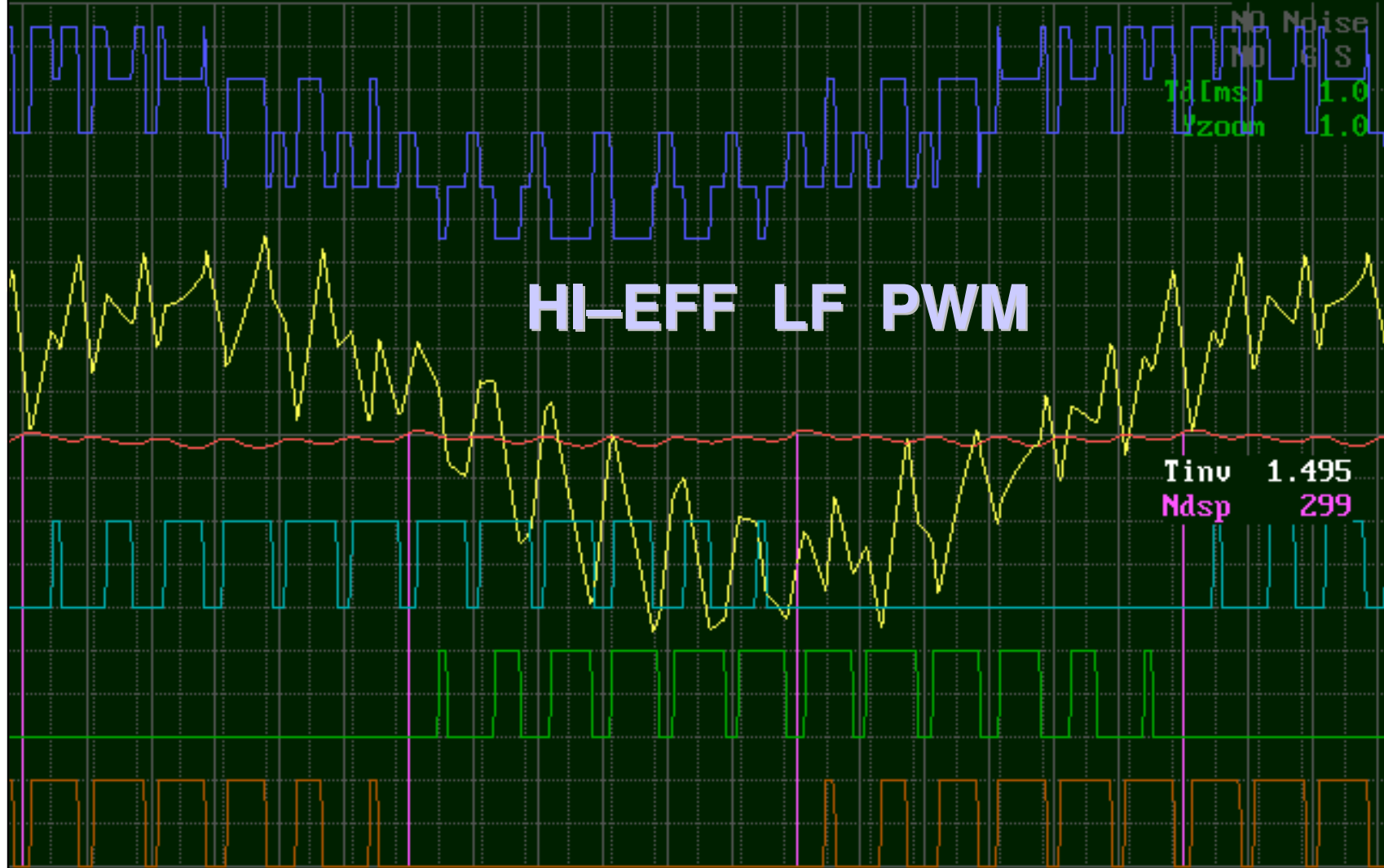
NO Filtro

NO Noise

NO GS

TdLms1 1.0

fzoom 1.0



HI-EFF LF PWM

Tinu 1.495

Mdsp 299

3000

50.00

1.000

1.000

1.000

1.000

0.0

1.000

Upan

Cref%

GSFil

GRInu

GRCho

GRChf

KTEST

GAIN

FIREMA Trasporti - TSRA1

CORRENTE - PWM Pot1 & Tensione

PwmSIN

1697.1

0.0

-152.53

== FFD ==

Pot1

Ufs1

Is1

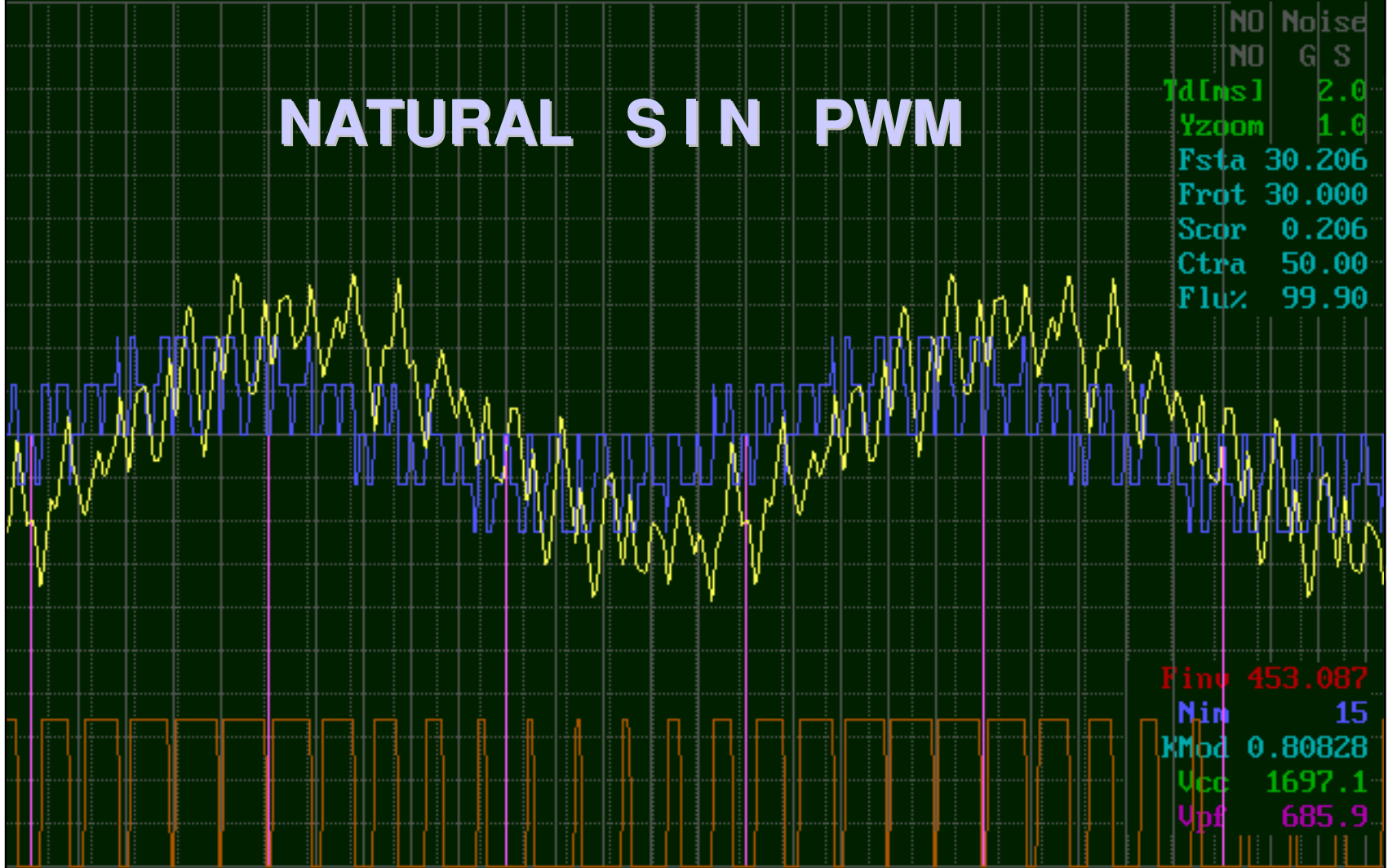
NO Filtro

NO Noise

NO G S

NATURAL SIN PWM

Td[ms] 2.0
 Yzoom 1.0
 Fsta 30.206
 Frot 30.000
 Scor 0.206
 Ctra 50.00
 Flu% 99.90



Finv 453.087
 Nin 15
 KMod 0.80828
 Ucc 1697.1
 Upf 685.9

3000

859.0

1.000

1.000

1.000

1.000

0.0

1.000

Upan

Cref

GSF11

GRInu

GRCho

GRChf

KTEST

GAIN

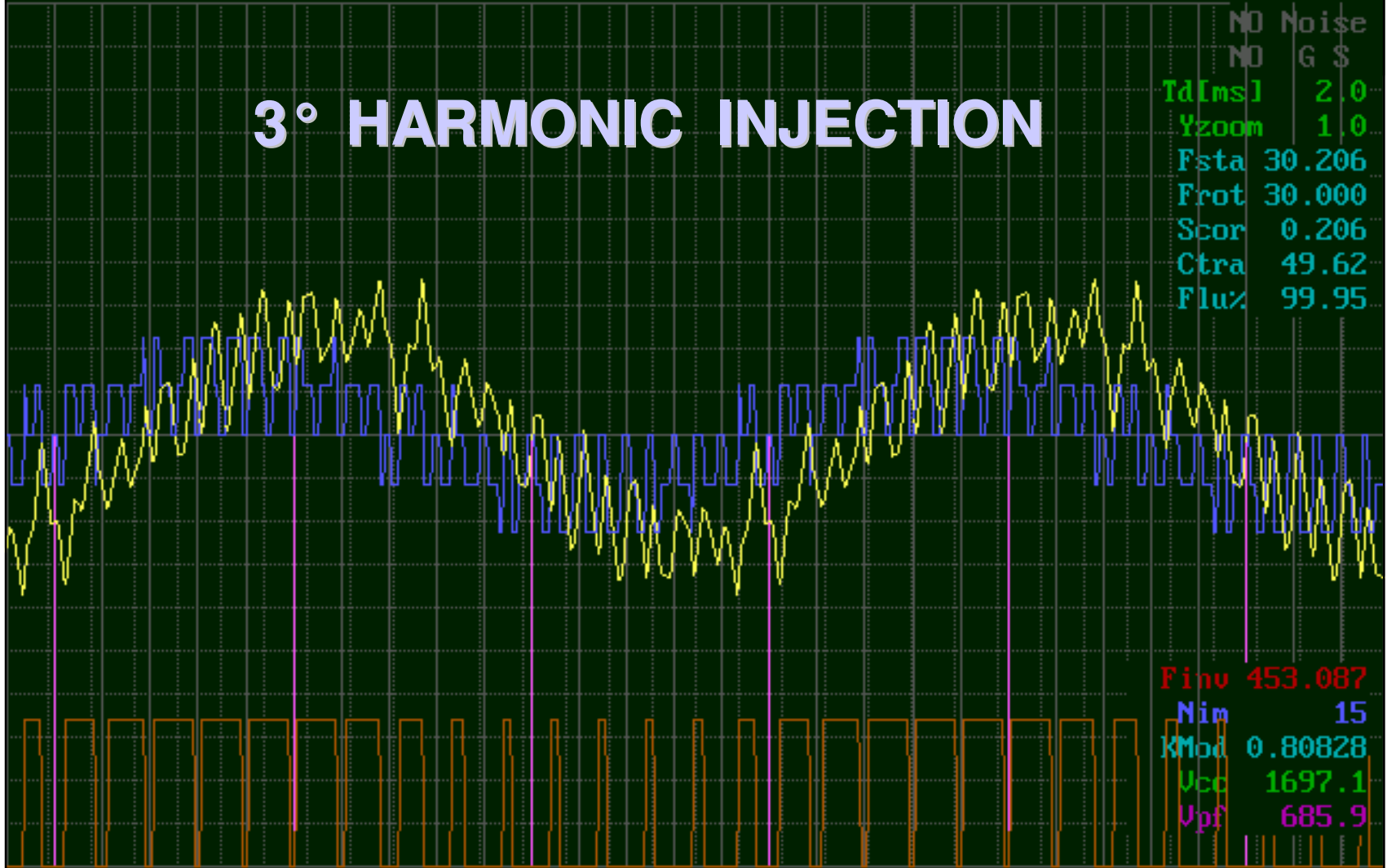
FIREMA Trasporti - TSRA1 CORRENTE - PWM Pot1 & Tensione PwmS3A

0.0 -565.7 -166.19
Pot1 Ufs1 Is1

== FFD ==
NO Filtro
NO Noise
NO G S

3° HARMONIC INJECTION

Td[ms] 2.0
Yzoom 1.0
Fsta 30.206
Frot 30.000
Scor 0.206
Ctra 49.62
Flu% 99.95



Finv 453.087
Nim 15
KMod 0.80828
Ucc 1697.1
Upf 685.9

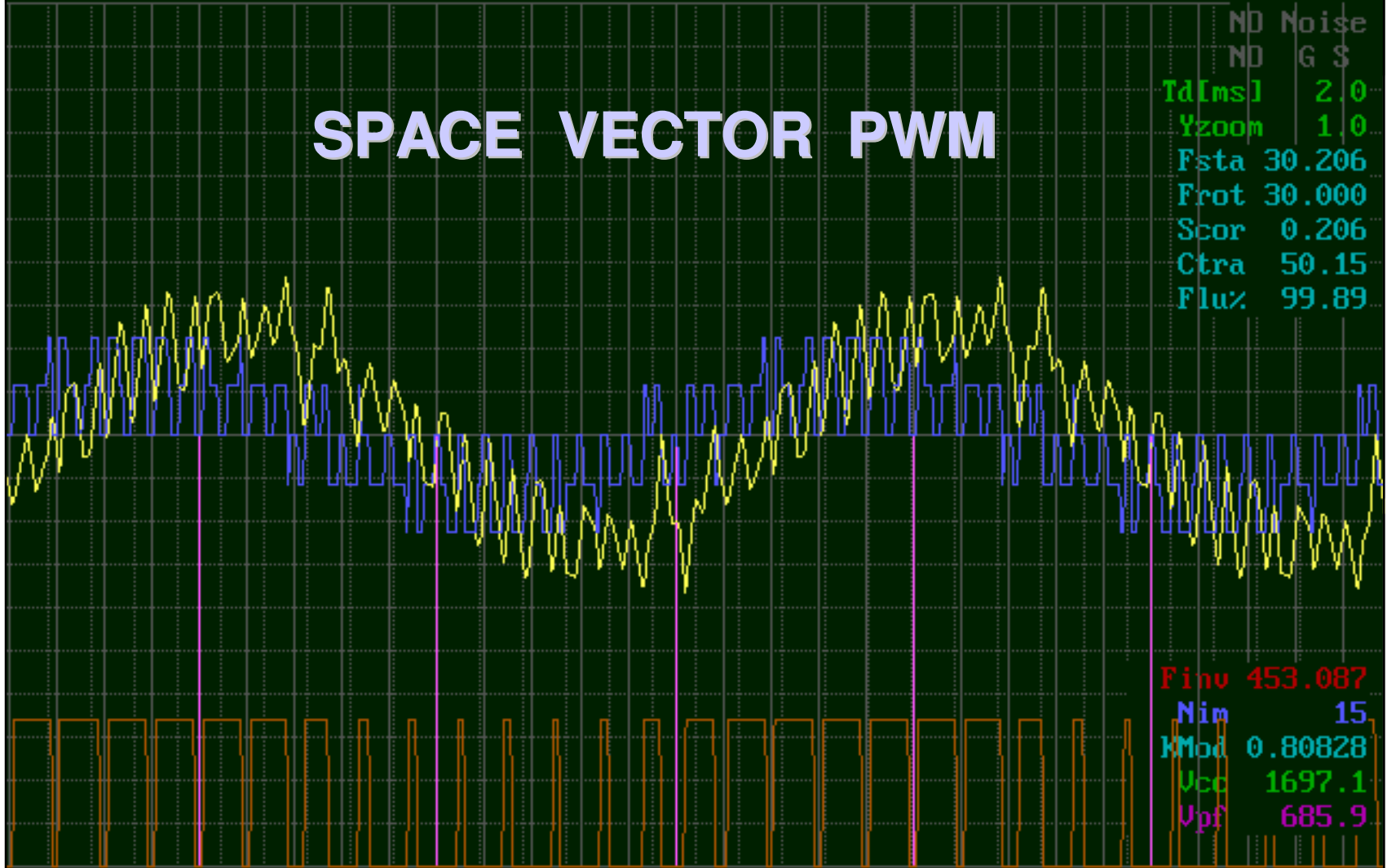
3000 859.0 1.000 1.000 1.000 1.000 0.0 1.000
Upan Cref GSFil GRInu GRCho GRChf KTEST GAIN

FIREMA Trasporti - TSRA1 CORRENTE - PWM Pot1 & Tensione PwmSPU

0.0 -565.7 -90.98
Pot1 Ufs1 Is1

== FFD ==
NO Filtro
NO Noise
NO G S
Td[ms] 2.0
Yzoom 1.0
Fsta 30.206
Frot 30.000
Scor 0.206
Ctra 50.15
Flu% 99.89

SPACE VECTOR PWM



Finv 453.087
Nim 15
KMod 0.80828
Vcc 1697.1
Vpf 685.9

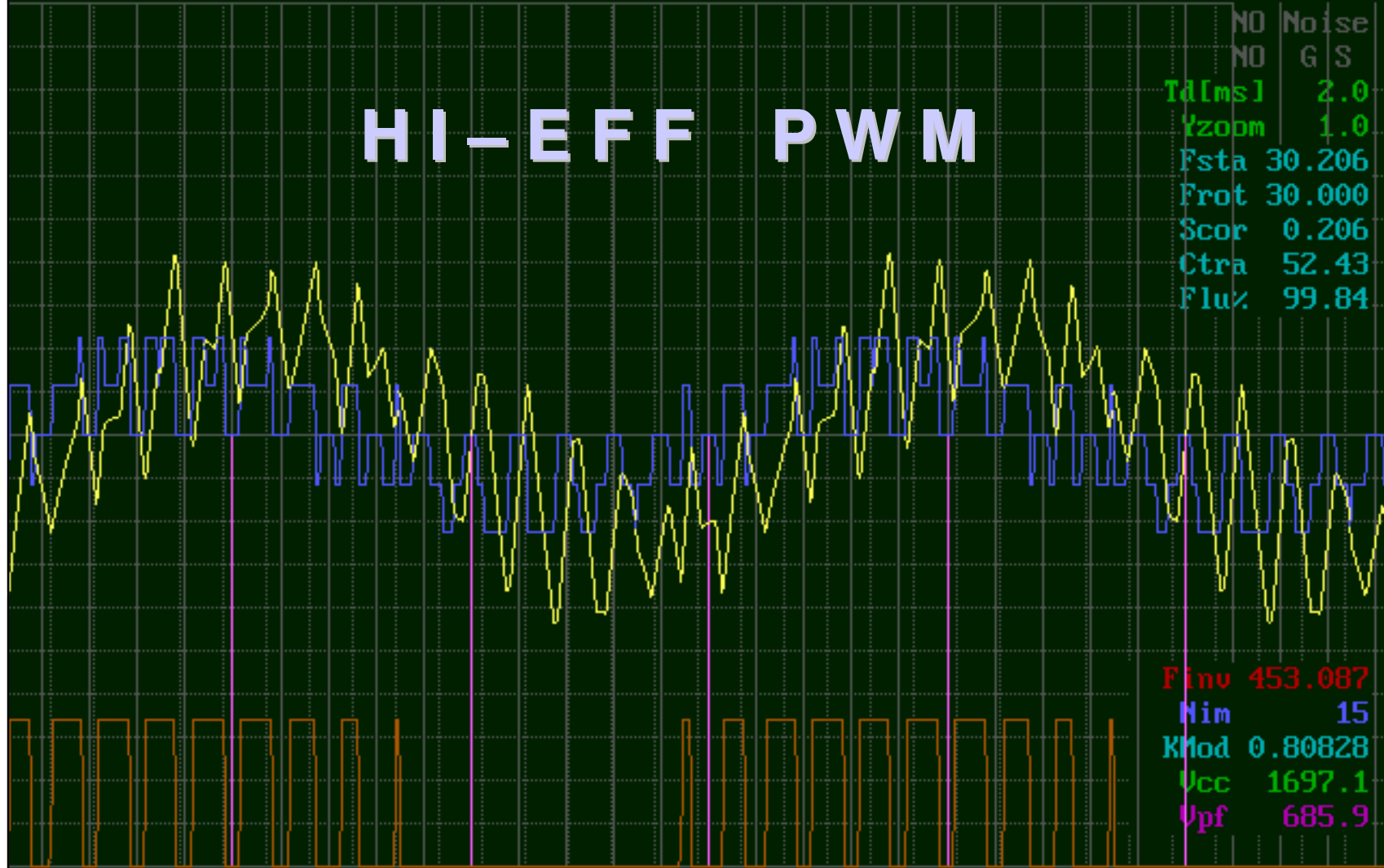
3000 859.0 1.000 1.000 1.000 1.000 0.0 1.000
Upan Cref GSFil GRInu GRCho GRChf KTEST GAIN

FIREMA Trasporti - TSRA1 CORRENTE - PWM Pot1 & Tensione PwmHEF

0.0 == FFD ==
Pot1 Ufs1 Is1 NO Filtro

NO Noise
NO G S
Td[ms] 2.0
Yzoom 1.0
Fsta 30.206
Frot 30.000
Scor 0.206
Ctra 52.43
Flu% 99.84

HI-EFF PWM



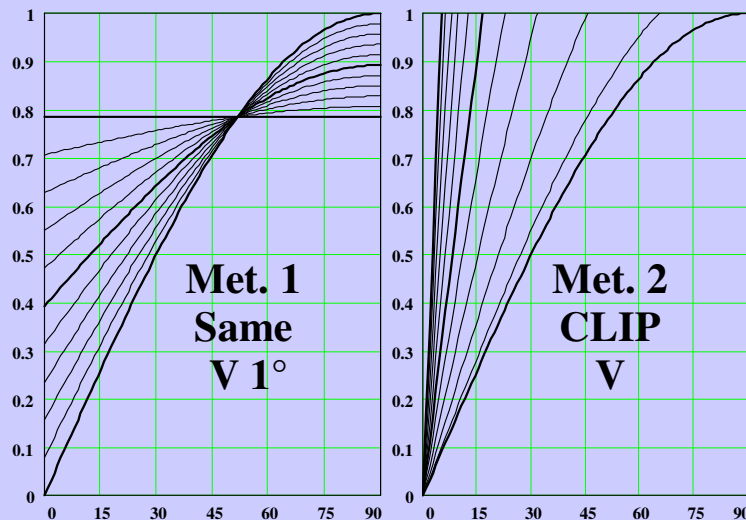
Finv 453.087
Nim 15
KMod 0.80828
Vcc 1697.1
Vpf 685.9

3000 859.0 1.000 1.000 1.000 1.000 0.0 1.000
Upan Cref GSFil GRInu GRCho GRChf KTEST GAIN

Modulation TIPS 'N TRICKS

When the motor speed is high , also voltages are high and so at a certain operating point , and in function of V_{cc} , **SATURATION** appears and we must pass in square wave supply voltage which has a fundamental peak value of $2/\pi \approx 0.637 V_{cc}$.

To avoid hard transitory we must SMOOTH this change ...



Method 1 is a **weighted average** of a **sinusoid** with a **square wave** in order to obtain the same fundamental value ; it is **simple to implement** acting on the SIN reference , and I named **SIN-QUA**

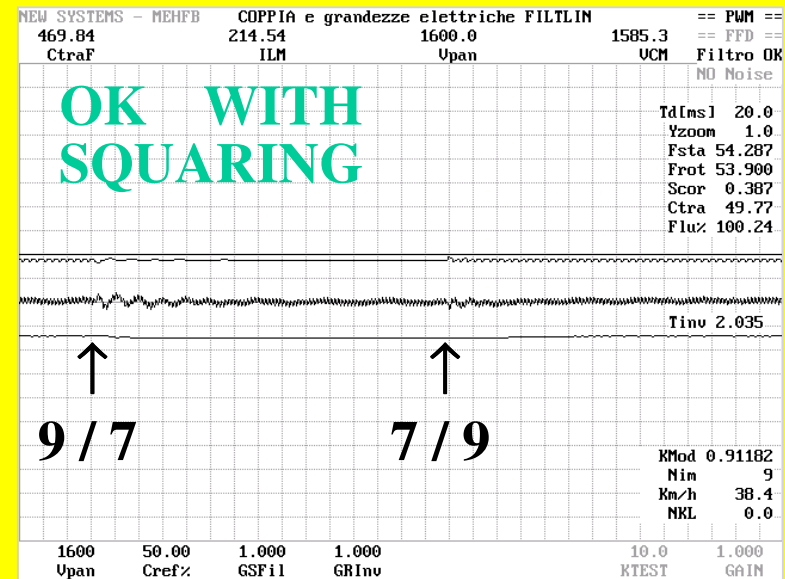
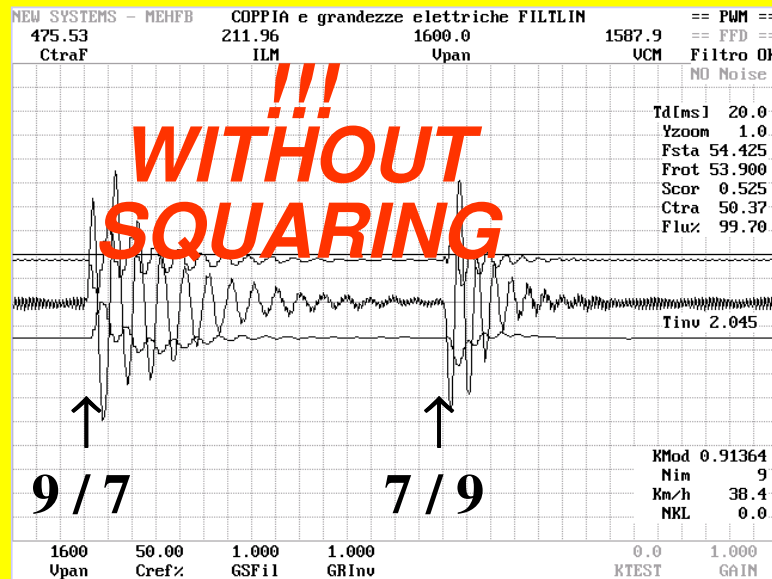
Method 2 is a calculation of a **family of clipped sinusoid** that must have the **desired value** for the **fundamental** ; it **requires a look-up table** because **calculations are too long to be processed in real-time** , and I named **SIN-CLIP**

When the modulation coefficient ($m = K |V_s| / V_{cc}$) is raising to its maximum value , before saturation condition , we have to smoothly pass to the square wave ; the use of method 1 or 2 depend on application requirements and on other factors ...

In square wave condition , we can't control by the means of voltage and we can only pass in field wakening condition and start to advance the voltage vector ...

TRANSITORY LIMITING

Here we have an example of pattern change with & without preventive squaring ...



The simulations have the **same identical characteristics** ; this is the same pattern change in a **LF PWM MODULATOR** from and to **9 & 7 pulses in one period ...**
 This happens because the stator **flux track** is not the same for 9 (pseudocircle) and 7 (hexagon) pulses ; with this simple method we can change **on the fly** and at **any time** the pattern because **SQUARING** brings the **flux track** on a **hexagon smoothly**

MODULATION HARMONICS

The PWM MODULATION generates a lot of HARMONICS whose amplitudes decrease while the modulation frequency increases ... so where it is possible use an high frequency modulator ,... FPGA driven.

VOLTAGE HARMONICS have order $6K \pm 1$ (with some exceptions)

CURRENT HARMONICS have order $6K \pm 1$ (with other exceptions)

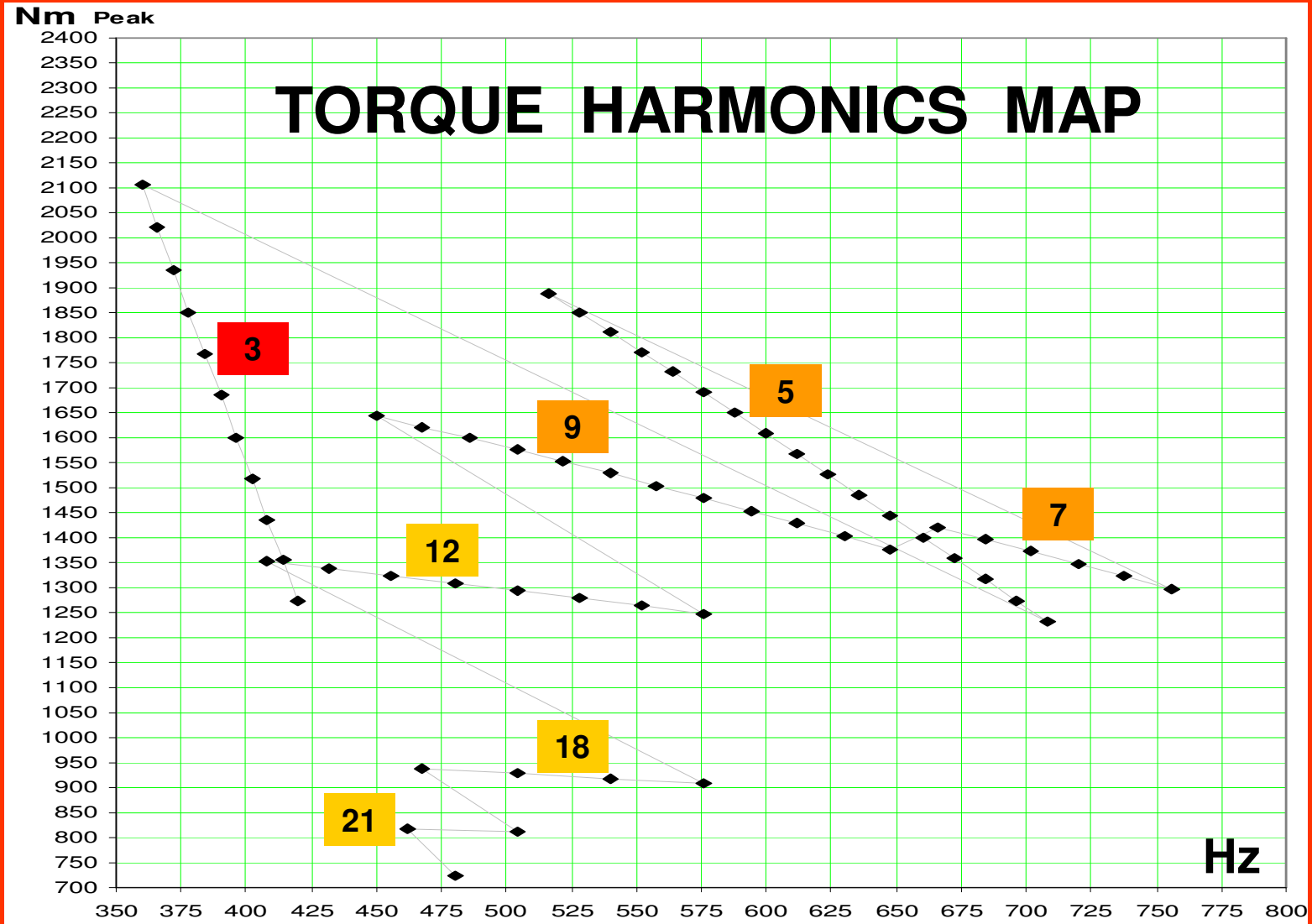
TORQUE & DC BUS HARMONICS have order $6K$ plus NK ...

This is only a **general rule** , with the order K referred to the **stator frequency** ... so the harmonics vary their own frequency in function of the motor speed ... and change their amplitude in function of the modulator frequency ...

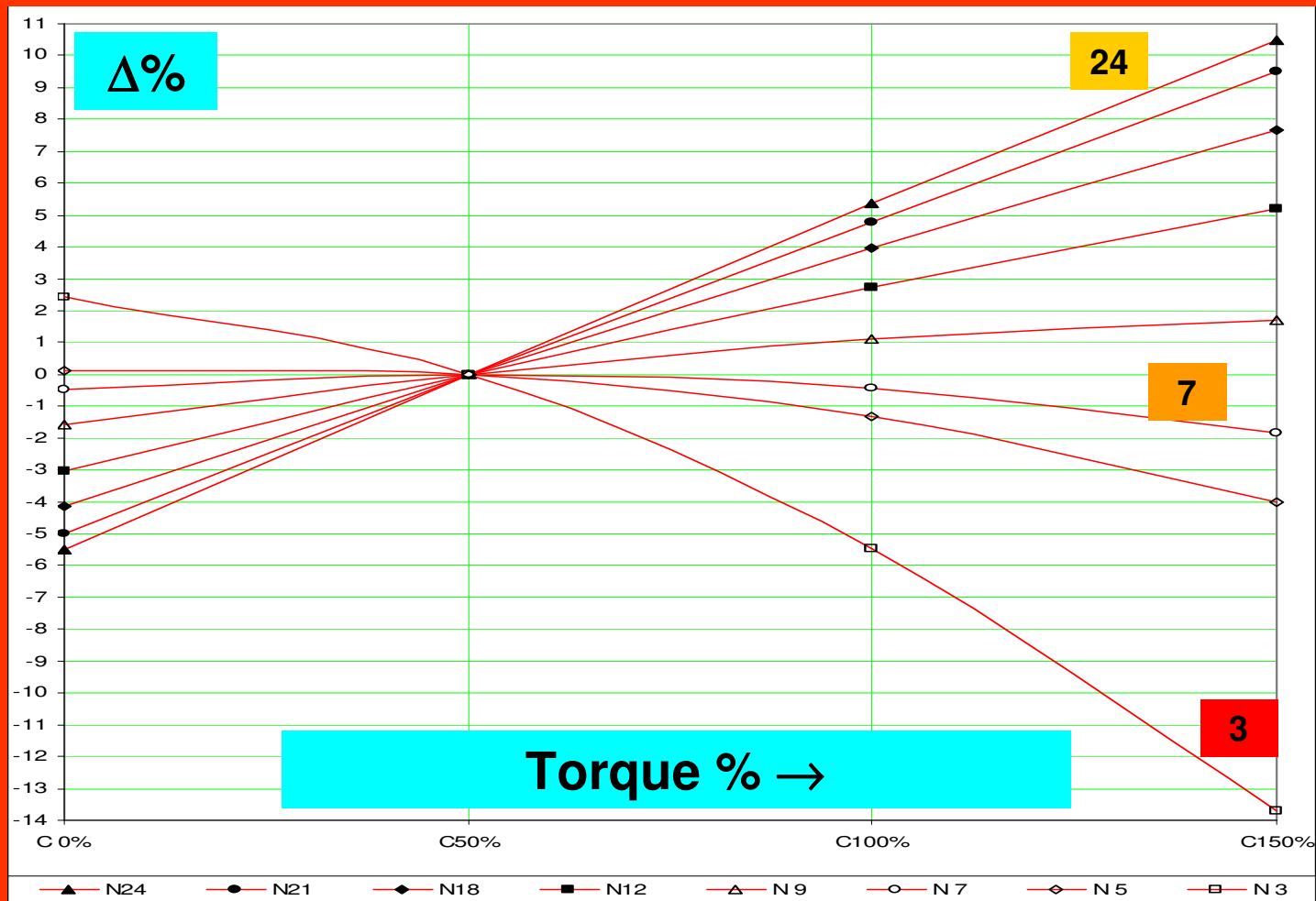
Sometimes it happens that the **DC bus is pre-stabilized by a CHOPPER** ... and in this case every harmonic beat with the chopper frequency generating sum and difference components that scan quickly all the spectrum analyzer range ...

A **reduction of the global harmonic content** (or better a **frequency shift** in a not dangerous range) is generally possible varying the **pulse position** inside a pulse pattern or using (moderate) **spread spectrum techniques**...

To reach a **LOW HARMONIC CONTENT** it is strongly advisable because **line current harmonics can negate an homologation and torque harmonics can destroy motors**

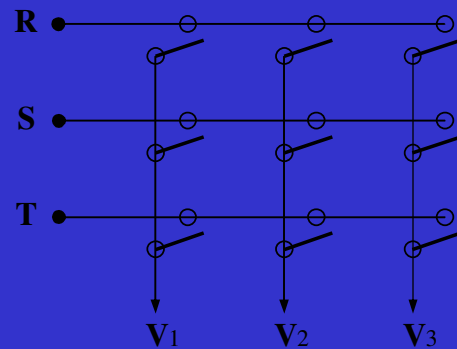


TORQUE HARMONICS VARIATIONS



MATRIX CONVERTER

The future of power drive is a converter without DC bus which can use directly the 3 phase line with very reduced reactive components ...

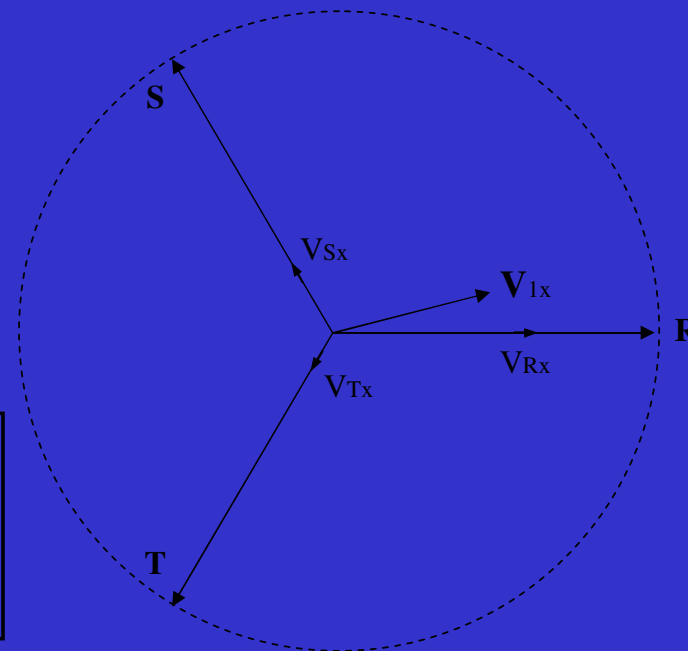


$$V_{1x} = V_{Rx} + V_{Sx} + V_{Tx}$$

$$V_{Rx} = R * tR / tC$$

$$V_{Sx} = S * tS / tC$$

$$V_{Tx} = T * tT / tC$$



Operational theory is just ready , some prototypes are running , but for mass production we have to wait for fully integrated high speed bilateral switches ...

SYSTEM DIAGNOSTICS

Depending on the system requirements we can obtain a lot of useful information from the relation between impressed voltage V_s and the feedback current I_s ...

It is possible using only 2 phase currents to obtain Low level diagnostics but , for more sophisticated diagnostics we need all the 3 phase currents ...

I suggest you should perform a complete system check every time the motor stops and before restarting it ; some tests with **rotor stalled** are a lot simpler than a real-time diagnostic test performed cyclically at fixed times with the running motor ...

In a sensorless drive , which uses a **NOMINAL LOAD MODEL** , is quite **easy** to recognize some system faults like : **Abnormal load , Blocked rotor, Idle running**

For more sophisticated **real-time diagnostics** and **parametric detuning** like R or L variations , **the task is generally hard** and the blocks involved have sometimes the same complexity of the whole drive ..

Many motor or system behaviours may be detected observing the track variations of the current vector in a rotating frame referred to D axis or V_s axis.

At present , the top is the real-time **PREDICTIVE DIAGNOSTIC** that can **observe and predict the system evolution** but with a **large computational effort**

As an example we can observe the **torque ripple pattern** using **DFT** on some harmonics of the rotor frequency and detect anomalous conditions of the ball bearing and alert in advance their fault.

For other tasks we can also use **Injected sign** and **Wavelet transform** ...

NEWSYSTEMS

NOTHING BUT THE BEST



Via VERDI 39
38080 CARISOLO (TN)
ITALY
Phone & Fax : ++39 0 465 502 696
e-mail: newsystems@cr-surfing.net



For your INNOVATIVE SOLUTIONS ...

ph.dr.eng. **ROBERTO RAFFAETA'**