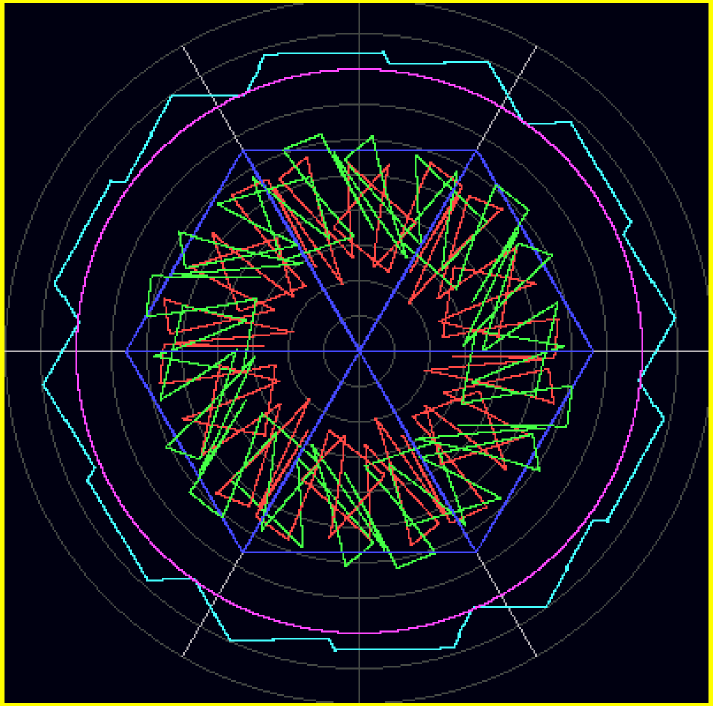
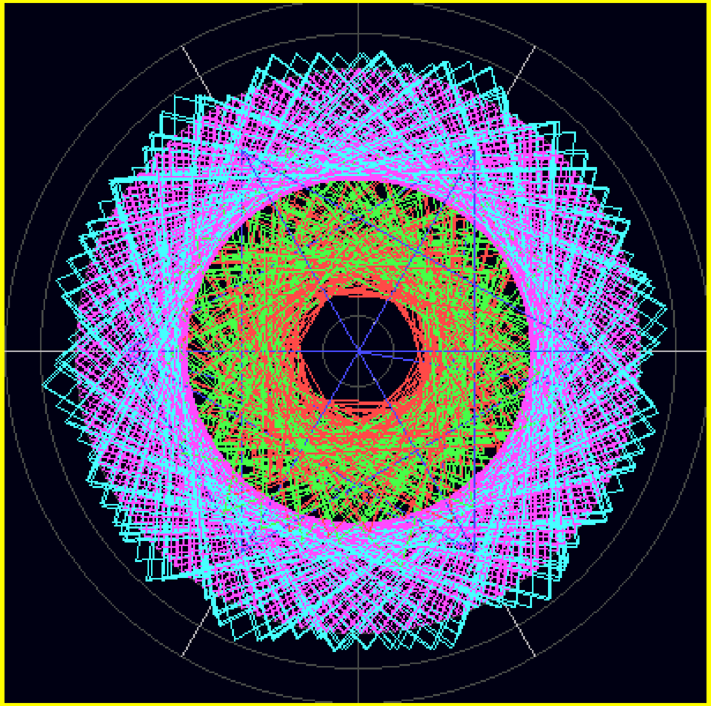
SENSORLESS FIELD ORIENTED CONTROL



MOTOR CONTROL



is a SCIENCE ... *but also an* ***A R T***

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

A B S T R A C T

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 …

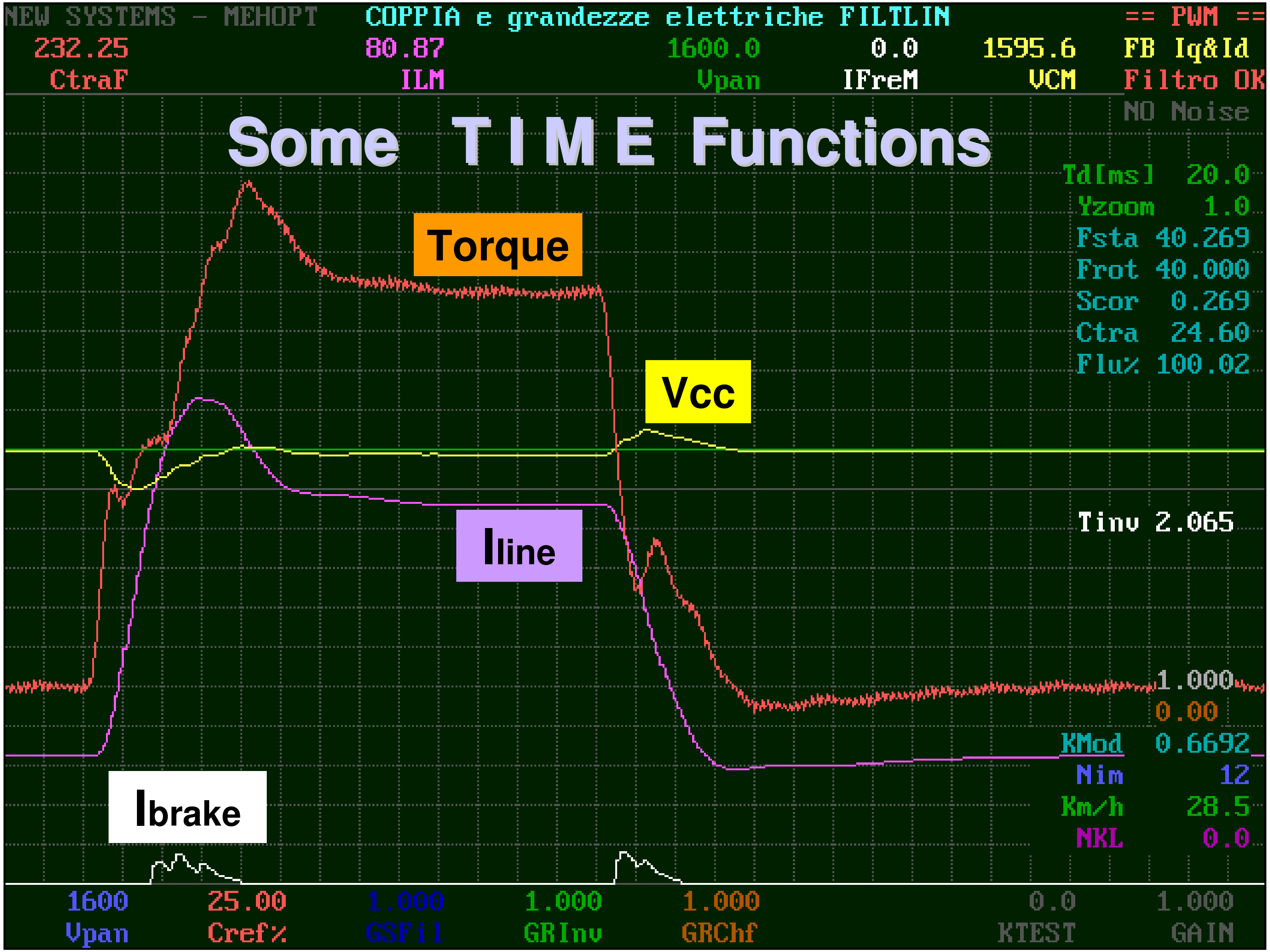
The simulators , which I use normally to verify new solutions and to test some custom controls , are very Spartan , but they contain a function library that have been well tested and optimised for motor control in the last 30 years …

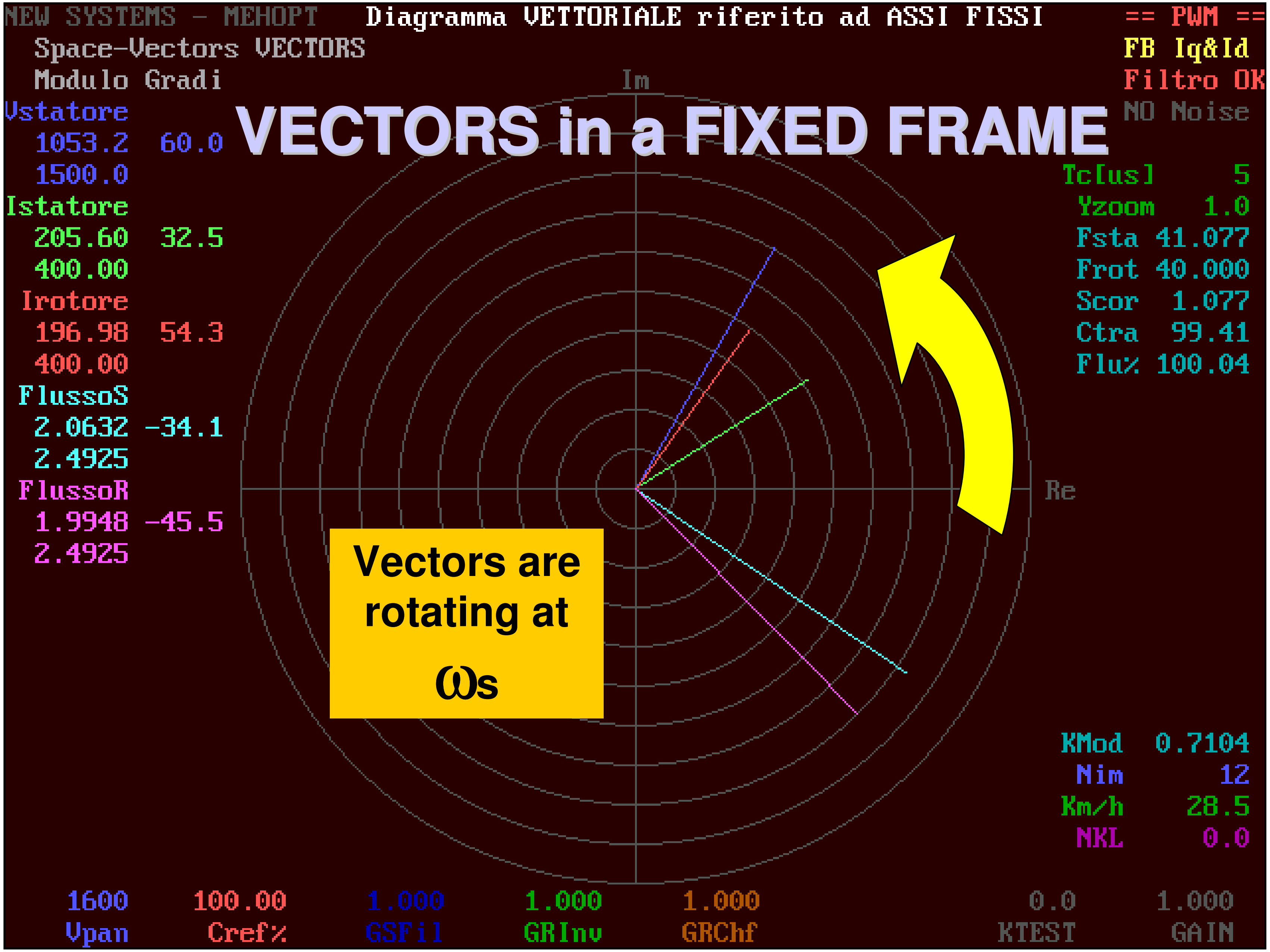
I started to control a power induction drive developed by two professors of mine in 1971 and afterwards , up to date , I designed several controls for many different drives ranging from 1W to 2 MW.

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.

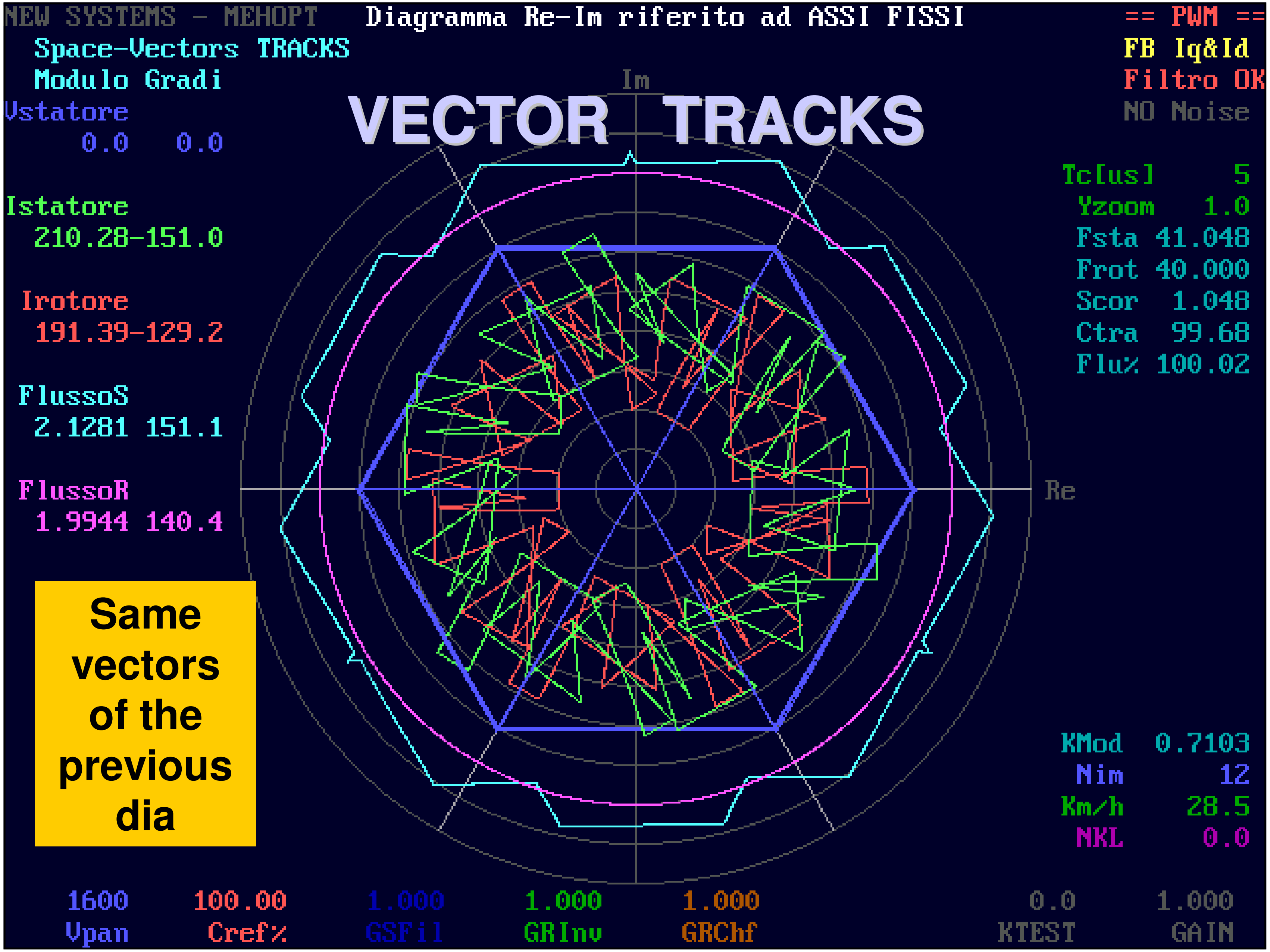
I think that a PROBLEM SOLUTION is good when it is SIMPLE and IT WORKS …

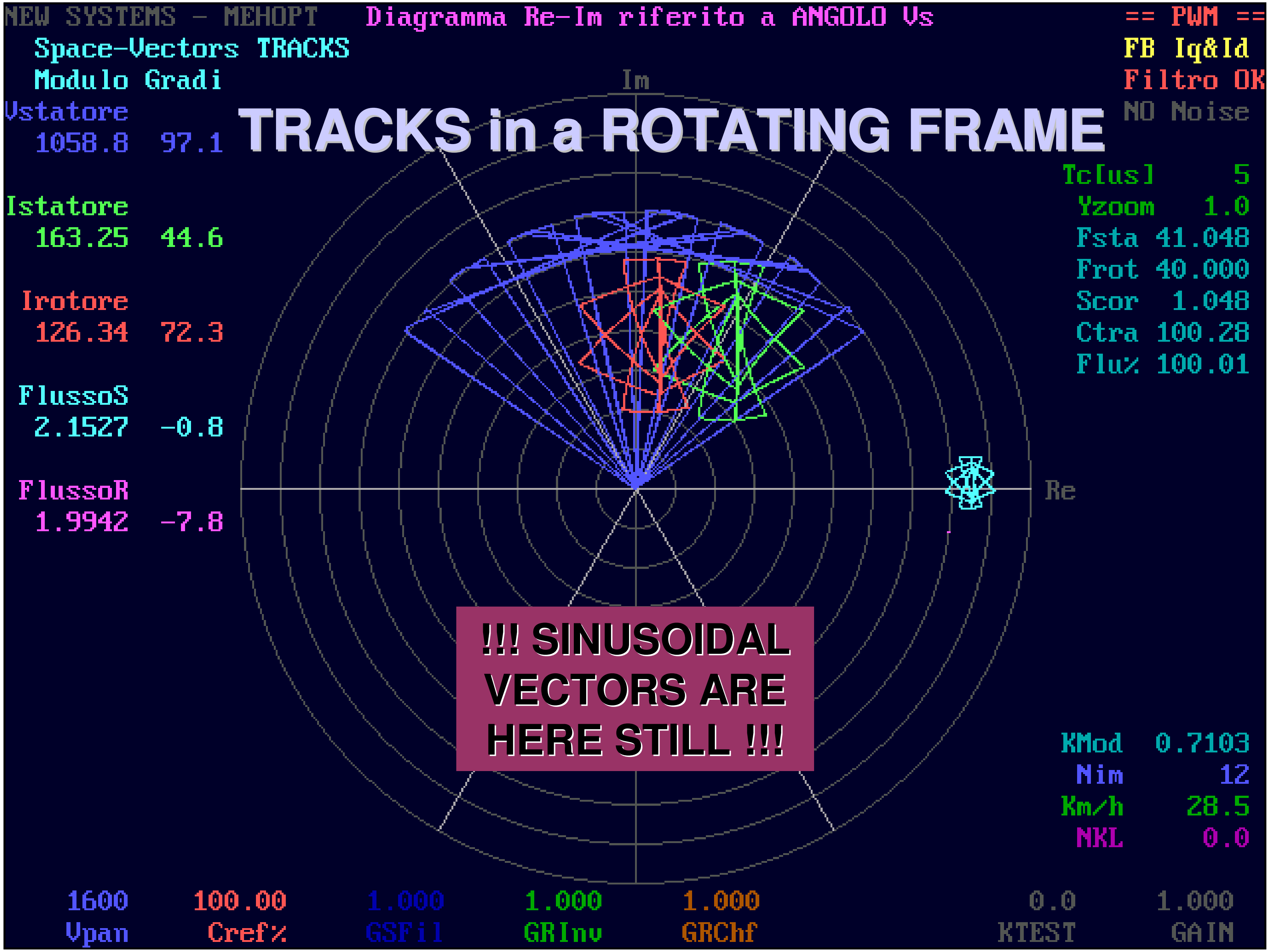
The SOLUTIONS are of primary importance , not the problems …

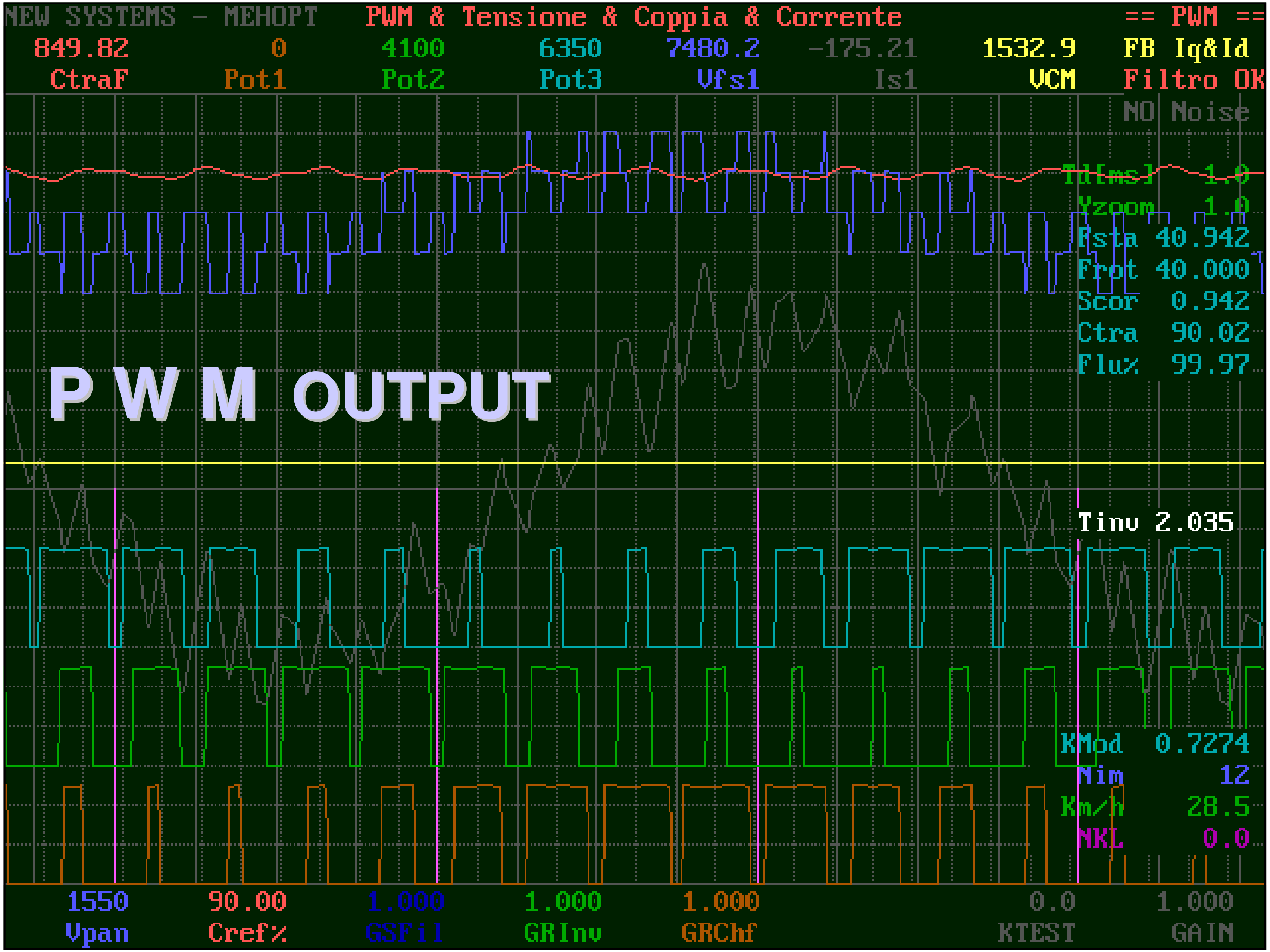

NEW SYSTEMS - MEHOPT
COPPIA e grandezze elettriche FILTLIN
== PWM ==
232.25 CtraF
80.87 ILM
1600.0 Vpan
0.0 IFreM
1595.6 VCM
FB Iq&Id
Filtro OK
NO Noise
Some T I M E Functions
Torque
Vcc
Iline
Ibrake
Td[ms] 20.0
Yzoom 1.0
Fsta 40.269
Frot 40.000
Scor 0.269
Ctra 24.60
Flu% 100.02
Tinv 2.065
1.000
0.00
KMod 0.6692
Nim 12
Km/h 28.5
NKL 0.0
1600 Vpan
25.00 Cref%
1.000 GSFil
1.000 GRInv
1.000 GRChf
0.0 KTEST
1.000 GAIN

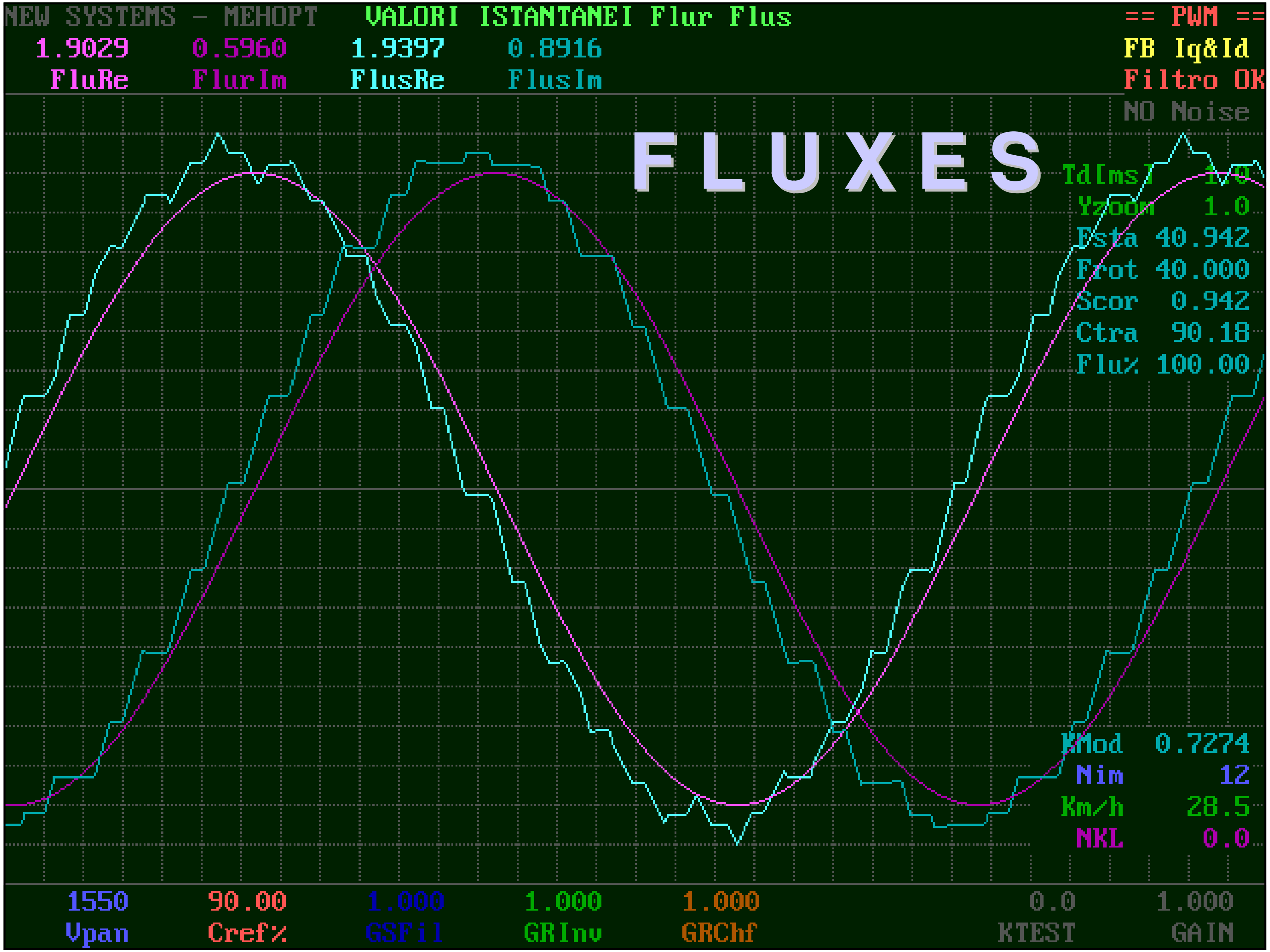


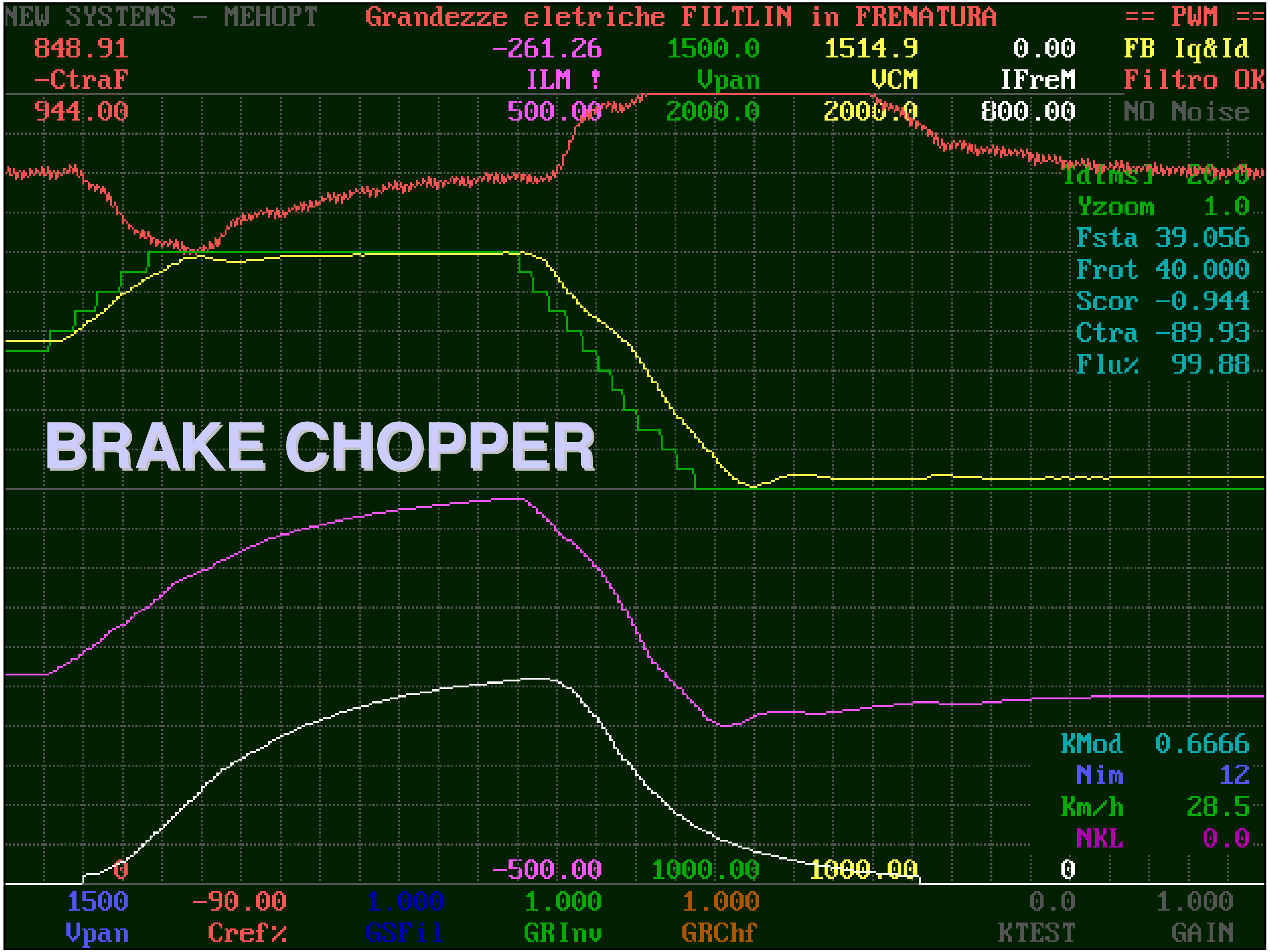
NEW SYSTEMS - MEHOPT
Diagramma VETTORIALE riferito ad ASSI FISSI
== PWM ==
Space-Vectors VECTORS
FB Iq&Id
Modulo Gradi
Filtro OK
NO Noise
VECTORS in a FIXED FRAME
Vstatore
1053.2 60.0
1500.0
Istatore
205.60 32.5
400.00
Irotore
196.98 54.3
400.00
FlussoS
2.0632 -34.1
2.4925
FlussoR
1.9948 -45.5
2.4925
Im
Re
Tc[us] 5
Yzoom 1.0
Fsta 41.077
Frot 40.000
Scor 1.077
Ctra 99.41
Flu% 100.04
Vectors are rotating at
ωs
KMod 0.7104
Nim 12
Km/h 28.5
NKL 0.0
1600 Vpan
100.00 Cref%
1.000 GSFil
1.000 GRInv
1.000 GRChf
0.0 KTEST
1.000 GAIN

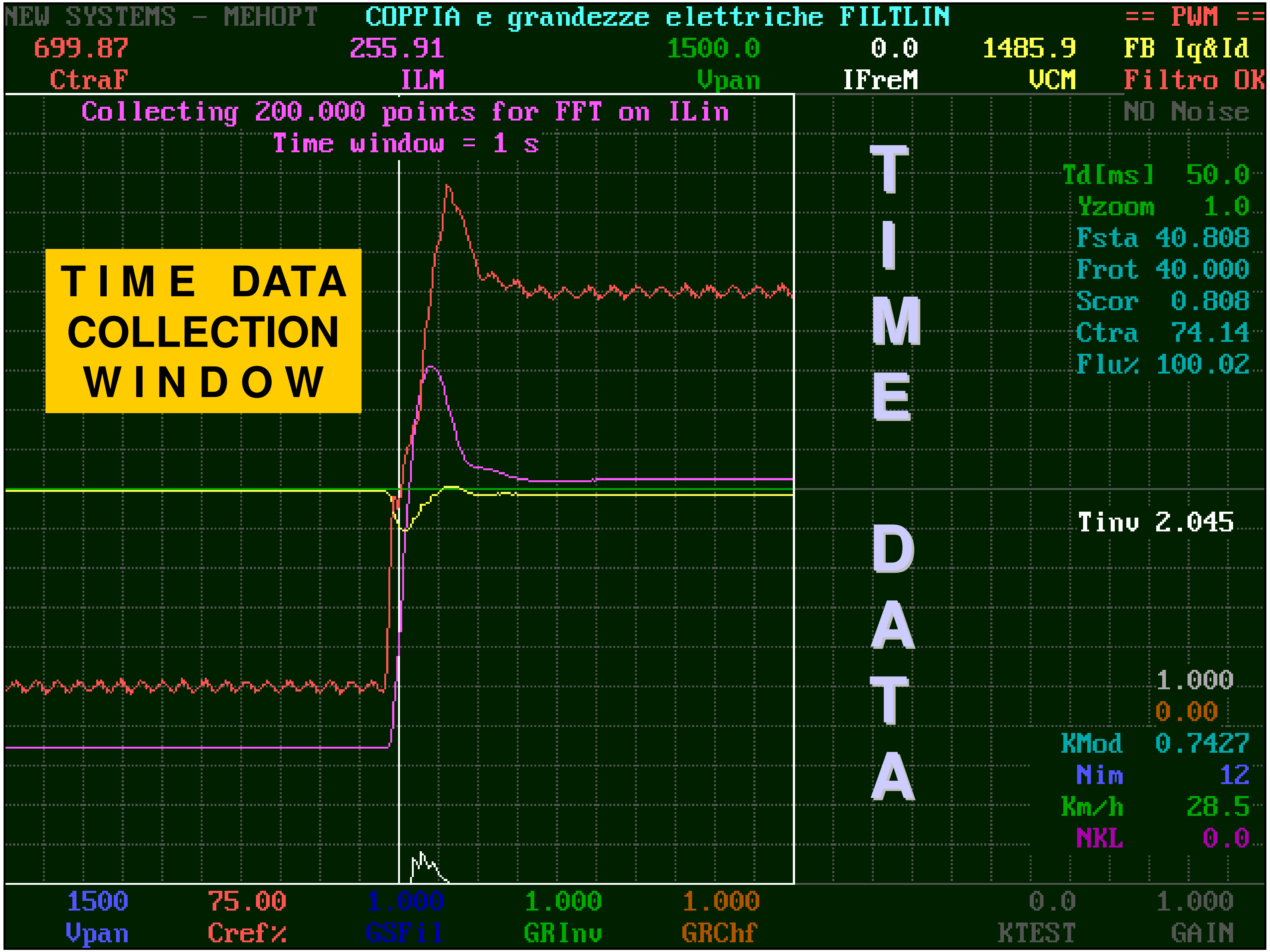

NEW SYSTEMS - MEHOPT
Diagramma Re-Im riferito ad ASSI FISSI
== PWM ==
Space-Vectors TRACKS
Modulo Gradi
FB Iq&Id
Filtro OK
NO Noise
VECTOR TRACKS
Im
Re
Vstatore
0.0 0.0
Istatore
210.28-151.0
Irotore
191.39-129.2
FlussoS
2.1281 151.1
FlussoR
1.9944 140.4
Tc[us] 5
Yzoom 1.0
Fsta 41.048
Frot 40.000
Scor 1.048
Ctra 99.68
Flu% 100.02
KMod 0.7103
Nim 12
Km/h 28.5
NKL 0.0
1600 Vpan
100.00 Cref%
1.000 GSFil
1.000 GRInv
1.000 GRChf
0.0 KTEST
1.000 GAIN
Same vectors of the previous dia

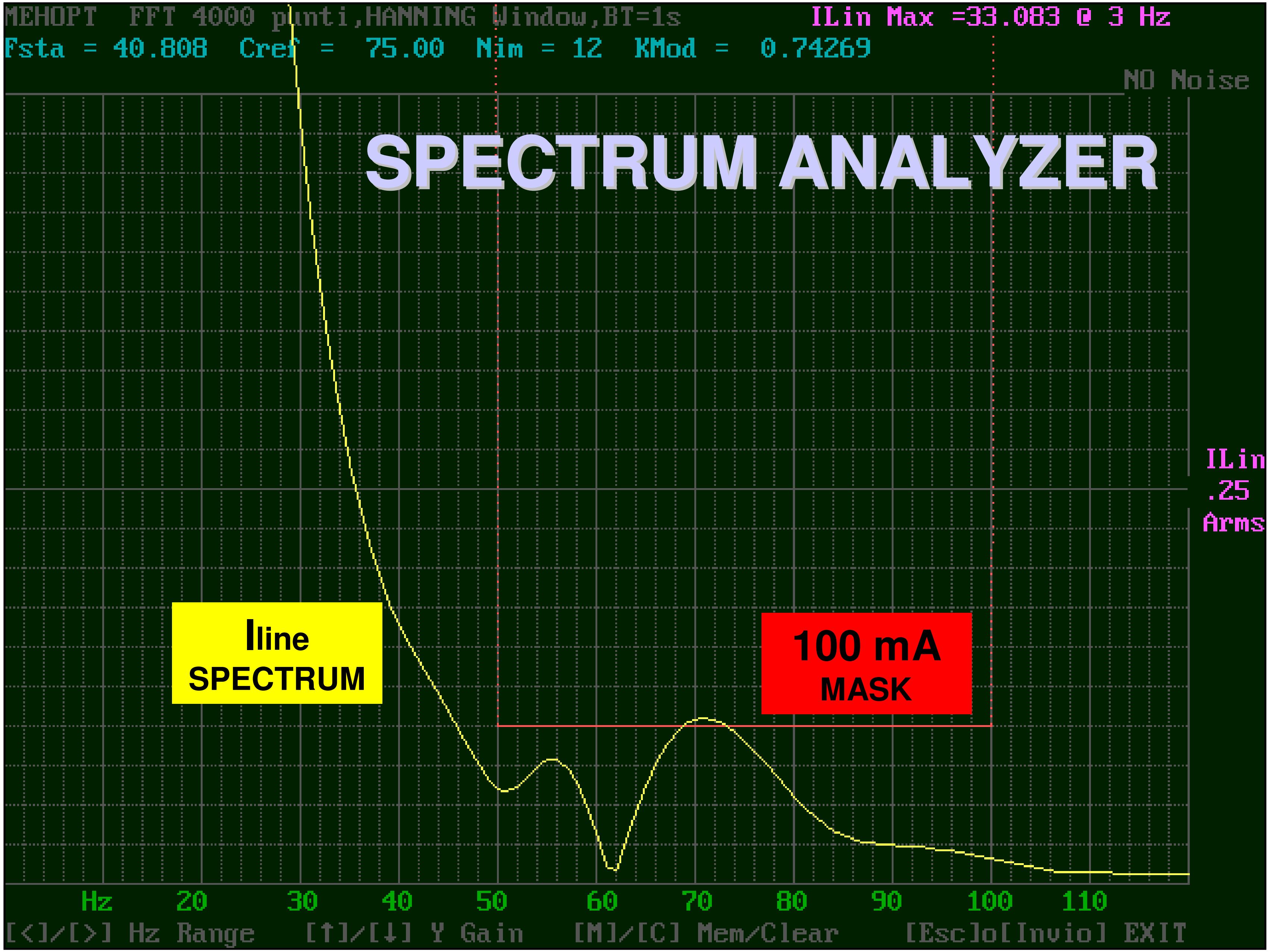

NEW SYSTEMS - MEHOPT
Diagramma Re-Im riferito a ANGOLO Vs
== PWM ==
Space-Vectors TRACKS
FB Iq&Id
Modulo Gradi
Filtro OK
NO Noise
TRACKS in a ROTATING FRAME
Vstatore
1058.8 97.1
Istatore
163.25 44.6
Irotore
126.34 72.3
FlussoS
2.1527 -0.8
FlussoR
1.9942 -7.8
Im
Re
Tc[us] 5
Yzoom 1.0
Fsta 41.048
Frot 40.000
Scor 1.048
Ctra 100.28
Flu% 100.01
!!! SINUSOIDAL VECTORS ARE HERE STILL !!!
KMod 0.7103
Nim 12
Km/h 28.5
NKL 0.0
1600 Vpan
100.00 Cref%
1.000 GSFil
1.000 GRInv
1.000 GRChf
0.0 KTEST
1.000 GAIN


NEW SYSTEMS - MEHOPT
PWM & Tensione & Coppia & Corrente
== PWM ==
849.82 CtraF
0 Pot1
4100 Pot2
6350 Pot3
7480.2 Vfs1
-175.21 Is1
1532.9 VCM
FB Iq&Id
Filtro OK
NO Noise
Td[ms] 1.0
Yzoom 1.0
Fsta 40.942
Frot 40.000
Scor 0.942
Ctra 90.02
Flu% 99.97
P W M OUTPUT
Tinv 2.035
KMod 0.7274
Nim 12
Km/h 28.5
NKL 0.0
1550 Vpan
90.00 Cref%
1.000 GSFil
1.000 GRInv
1.000 GRChf
0.0 KTEST
1.000 GAIN

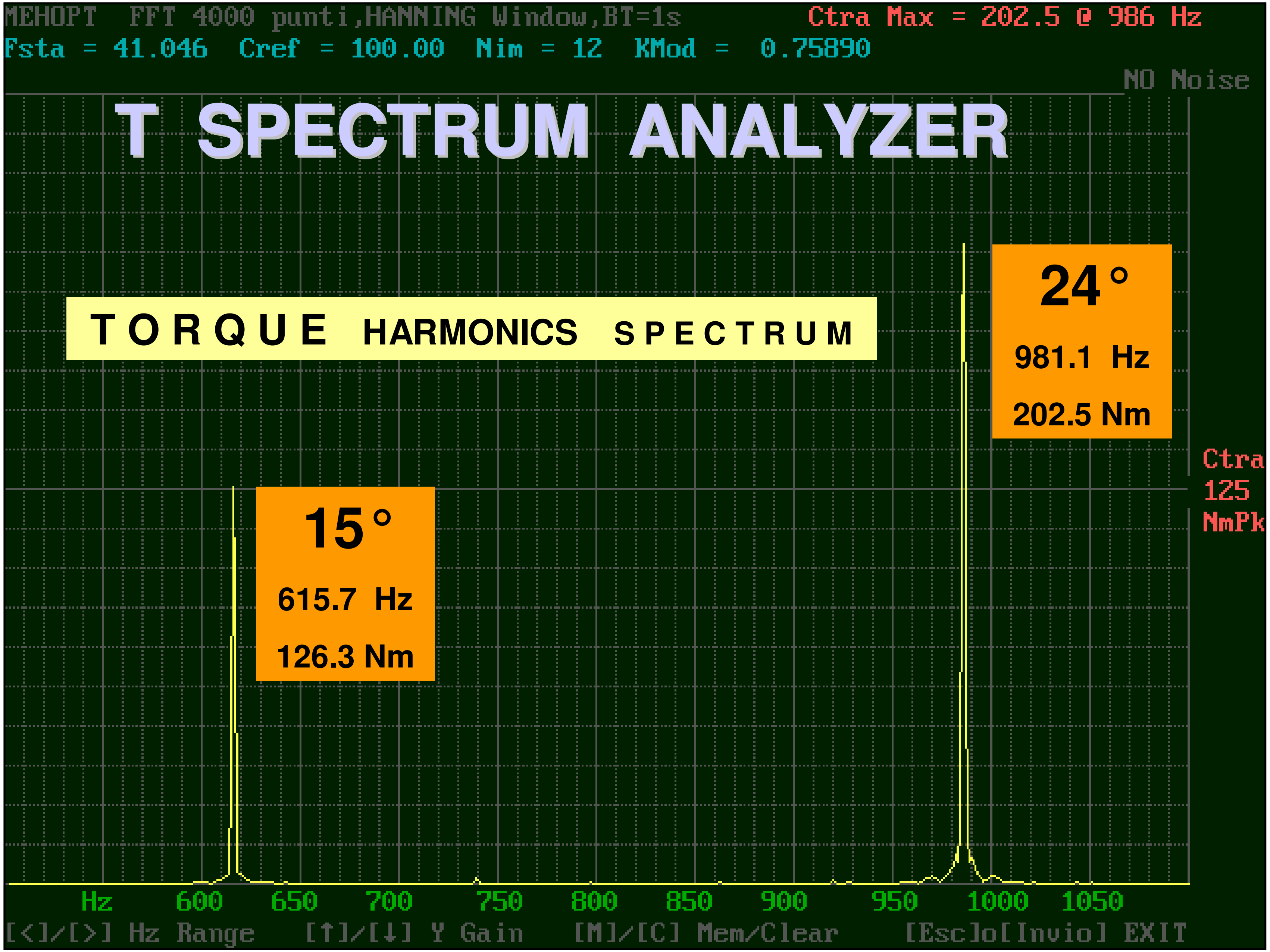

NEW SYSTEMS - MEHOPT VALORI ISTANTANEI Flur Flus
== PWM ==
1.9029 0.5960 1.9397 0.8916
FluRe FlurIm FlusRe FlusIm
FB Iq&Id
Filtro OK
NO Noise
FLUXES
Td[ms] 1.0
Yzoom 1.0
Fsta 40.942
Frot 40.000
Scor 0.942
Ctra 90.18
Flu% 100.00
KMod 0.7274
Nim 12
Km/h 28.5
NKL 0.0
1550 90.00 1.000 1.000 1.000 0.0 1.000
Vpan Cref% GSFil GRInv GRChf KTEST GAIN

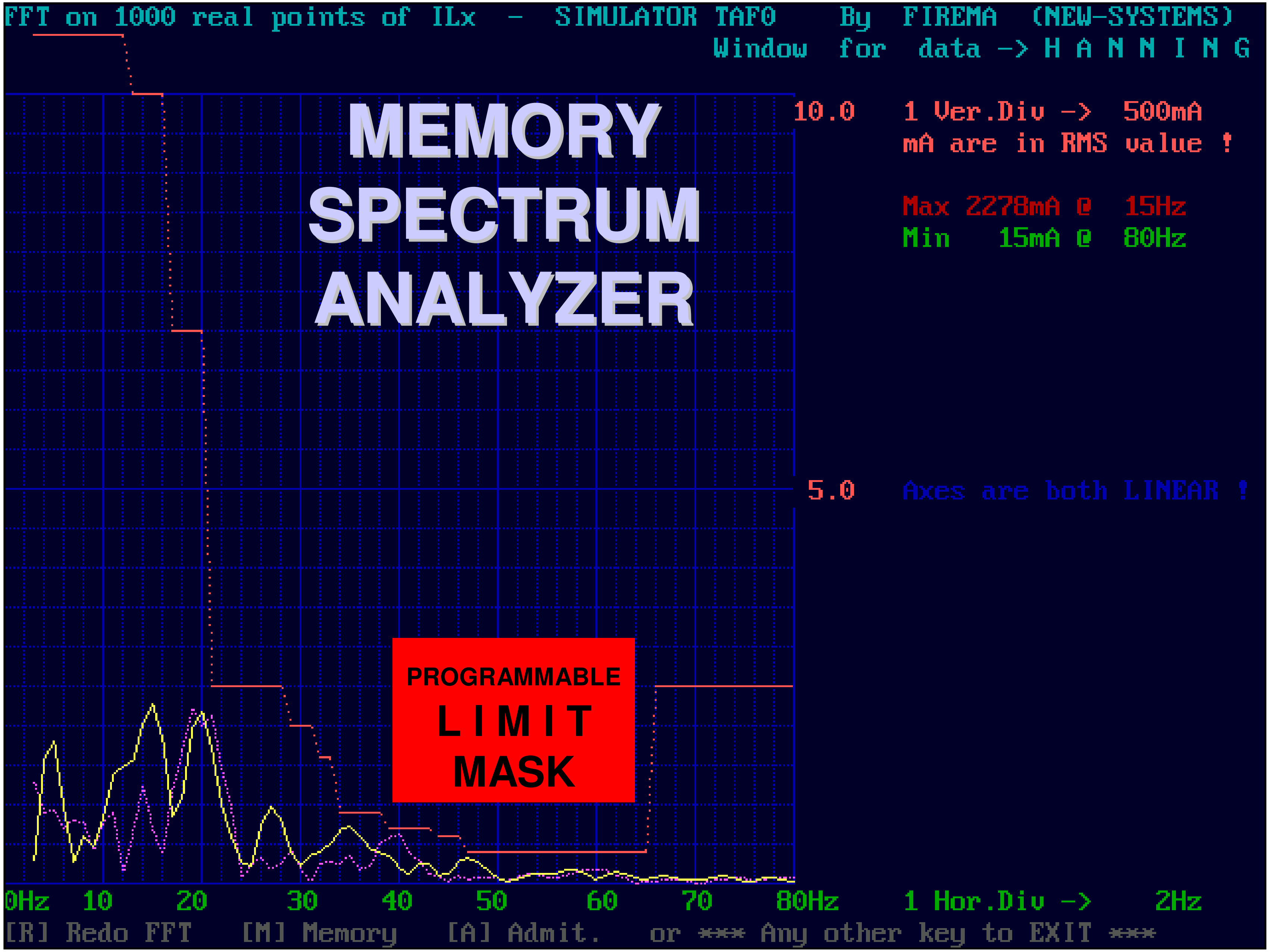

NEW SYSTEMS - MEHOPT
Grandezze eletriche FILTLIN in FRENATURA
== PWM ==
848.91
-CtraF
944.00
-261.26
ILM !
500.00
1500.0
Vpan
2000.0
1514.9
VCM
2000.0
0.00
IFreM
800.00
FB Iq&Id
Filtro OK
NO Noise
Yzoom 1.0
Fsta 39.056
Frot 40.000
Scor -0.944
Ctra -89.93
Flu% 99.88
BRAKE CHOPPER
KMod 0.6666
Nim 12
Km/h 28.5
NKL 0.0
0
-500.00
1000.00
1000.00
0
1500
Vpan
-90.00
Cref%
1.000
GSFil
1.000
GRInv
1.000
GRChf
0.0
KTEST
1.000
GAIN

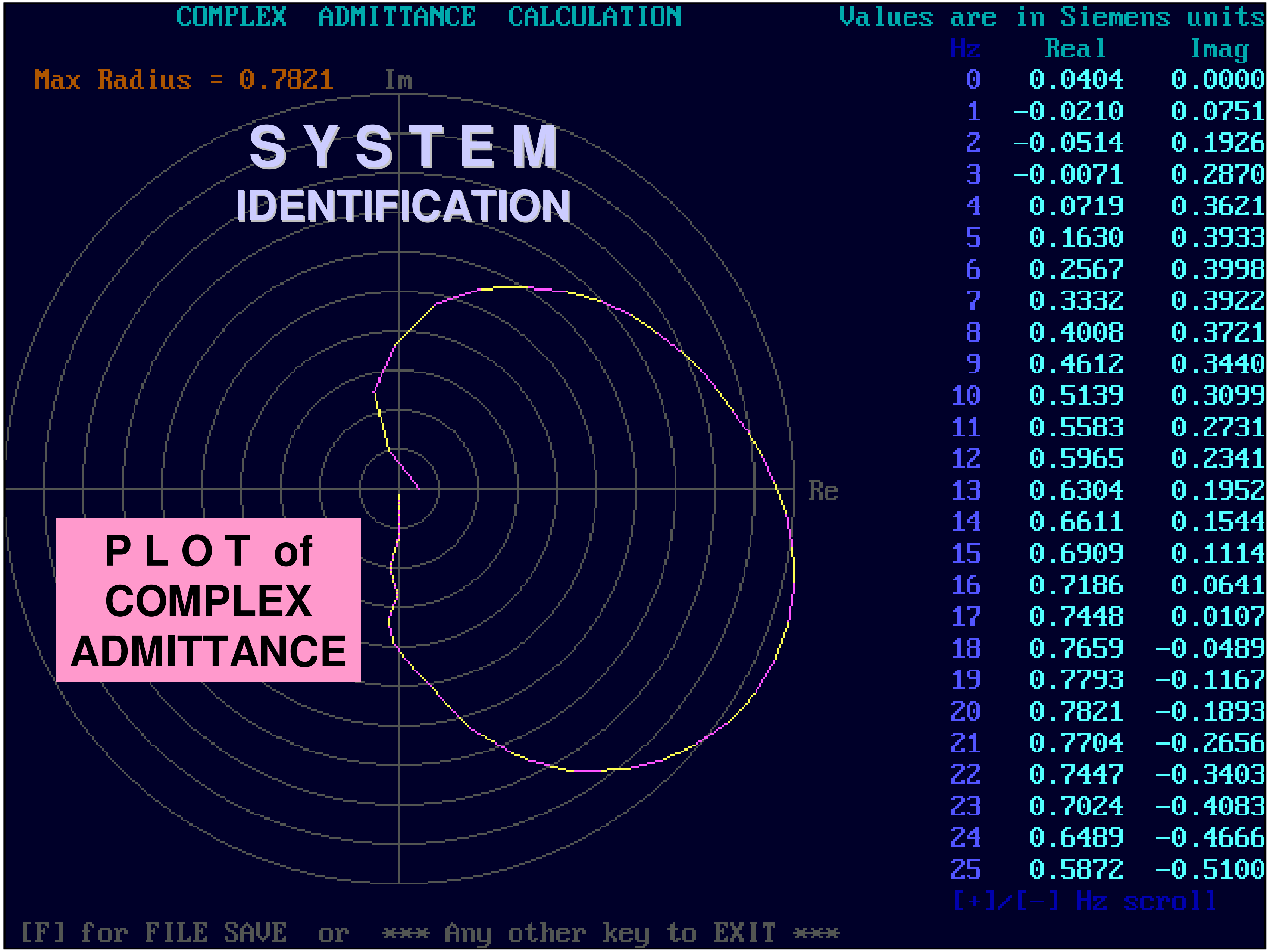

NEW SYSTEMS - MEHOPT
COPPIA e grandezze elettriche FILTLIN
== PWM ==
699.87
CtraF
255.91
ILM
1500.0
Vpan
0.0
IFreM
1485.9
VCM
FB Iq&Id
Filtro OK
NO Noise
Collecting 200.000 points for FFT on ILin
Time window = 1 s
TIME DATA COLLECTION WINDOW
TIME DATA
Td[ms] 50.0
Yzoom 1.0
Fsta 40.808
Frot 40.000
Scor 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
Vpan
75.00
Cref%
1.000
GSFil
1.000
GRInv
1.000
GRChf
0.0
KTEST
1.000
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[Invio] EXIT

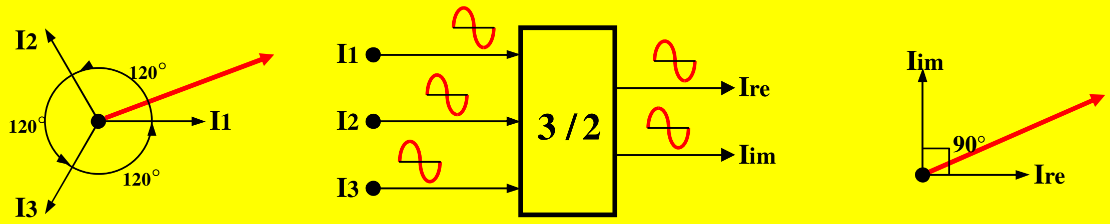

MEHOPT FFT 4000 punti,HANNING Window,BT=1s
Ctra Max = 202.5 @ 986 Hz
Fsta = 41.046 Cref = 100.00 Nim = 12 KMod = 0.75890
NO Noise
T SPECTRUM ANALYZER
TORQUE HARMONICS SPECTRUM
24°
981.1 Hz
202.5 Nm
15°
615.7 Hz
126.3 Nm
Ctra
125
NmPk
Hz 600 650 700 750 800 850 900 950 1000 1050
[<]/[>] Hz Range [↑]/[↓] Y Gain [M]/[C] Mem/Clear [Esc]o[Invio] EXIT


FFT on 1000 real points of ILx - SIMULATOR TAFO By FIREMA (NEW-SYSTEMS)
Window for data -> H A N N I N G
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 ***



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

C L A R K E   TRANSFORM



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

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

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)

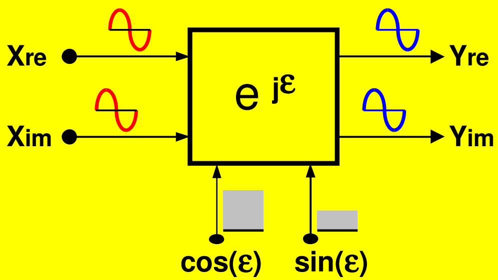
In the 2 phase reference we will perform all the vectorial operations we need ...

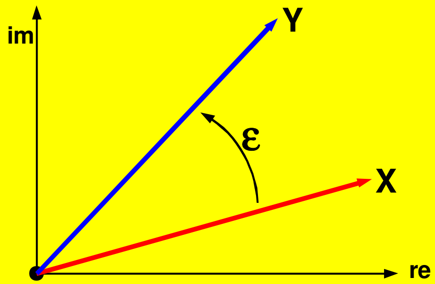
At the end we can return in the 3 phase reference with the inverse transform

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

D EPHASING a VECTOR



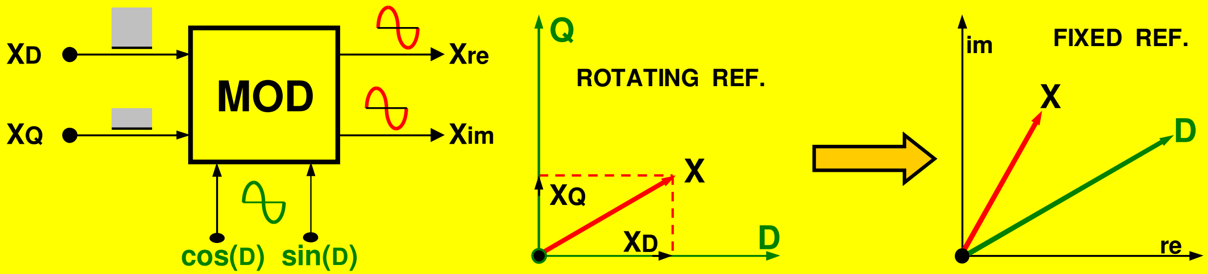


$Y = X e^{j\varepsilon}$ $\quad Y_{re} = X_{re} \cos(\varepsilon) - X_{im} \sin(\varepsilon)$ $\quad Y_{im} = X_{im} \cos(\varepsilon) + X_{re} \sin(\varepsilon)$

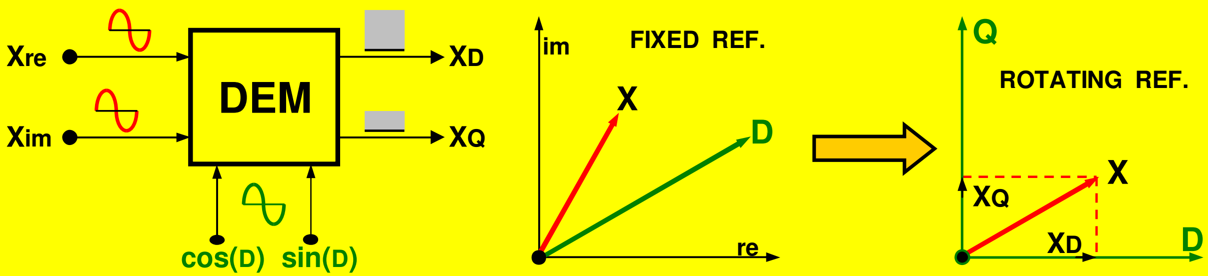
$X = Y / e^{j\varepsilon}$ $\quad X_{re} = Y_{re} \cos(\varepsilon) + Y_{im} \sin(\varepsilon)$ $\quad X_{im} = Y_{im} \cos(\varepsilon) - Y_{re} \sin(\varepsilon)$

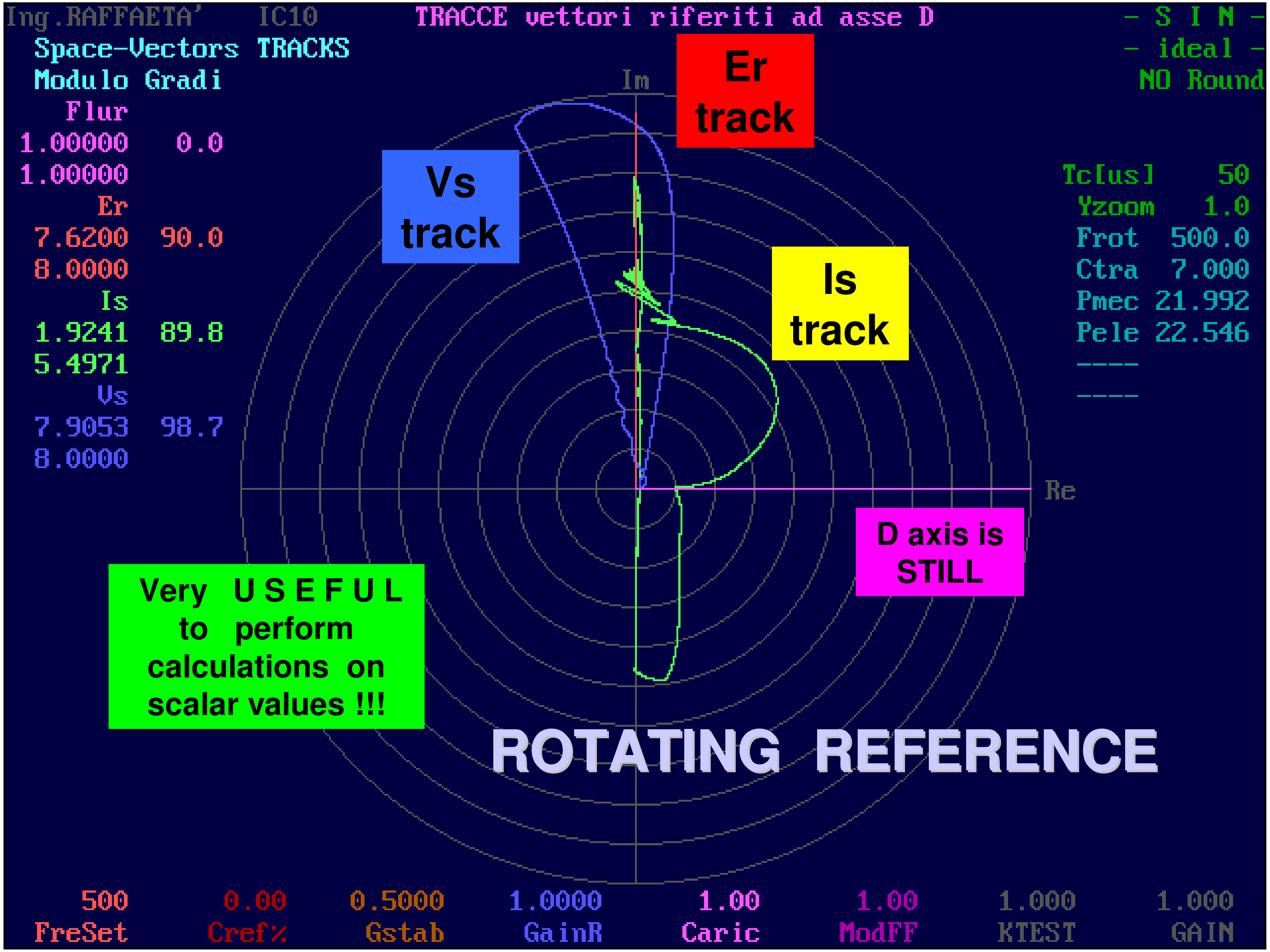
Passing in the most **useful REFERENCE**

SINCHRONOUS MODULATION



SINCHRONOUS DEMODULATION

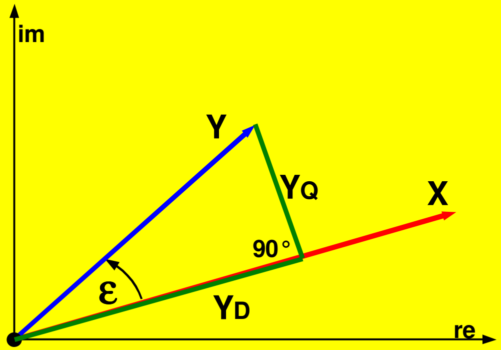


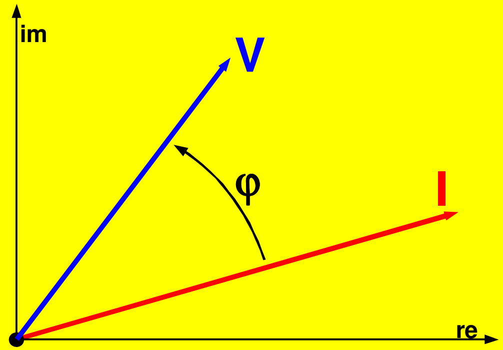


Ing.RAFFAETA' IC10
TRACCE vettori riferiti ad asse D
- S I N -
- ideal -
NO Round
Space-Vectors TRACKS
Modulo Gradi
Flur
1.00000 0.0
1.00000
Er
7.6200 90.0
8.0000
Is
1.9241 89.8
5.4971
Vs
7.9053 98.7
8.0000
Tc[us] 50
Yzoom 1.0
Frot 500.0
Ctra 7.000
Pmec 21.992
Pele 22.546
Im
Re
Er track
Vs track
Is track
D axis is STILL
Very U S E F U L to perform calculations on scalar values !!!
ROTATING REFERENCE
500 FreSet
0.00 Cref%
0.5000 Gstab
1.0000 GainR
1.00 Caric
1.00 ModFF
1.000 KTEST
1.000 GAIN

VECTOR COMPONENTS

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





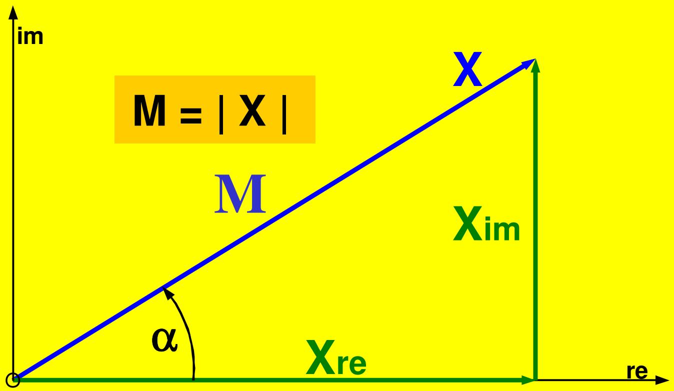
Yd = | Y | cos(ε)   Yq = | Y | sin(ε)
Yd = (Xre Yre + Xim Yim) / | X |
Yq = (Xim Yre – Xre Yim) / | X |

P = |V| |I| cos(ε)   Q = |V| |I| sin(ε)
P = Ire Vre + Iim Vim
Q = Iim Vre – Ire Vim

These formulas (all particular case of a Park transform) are very useful to project Is on the **D axis** to obtain **Id & Iq** or on the **Vs axis** to obtain **P & Q** ; in any case , we obtain a **couple of scalar values** that are the input of our regulators …

VECTOR MODULUS

In **1986** , I developed a **very fast algorithm** to calculate the modulus of the vector **without using the square root** , using the **tangent symmetry** that repeats **every 45°…**



$X_{re} = M \cos(\alpha)$ $X_{im} = M \sin(\alpha)$

$X_{im} / X_{re} = \tan(\alpha) = T$

$X_{re} + X_{im} = M(\cos(\alpha) + \sin(\alpha))$

$\cos(\alpha) + \sin(\alpha) = (1+T) / \sqrt{1+T^2}$

$F(T) = \sqrt{1+T^2} / (1+T) = 1 / (\cos(\alpha) + \sin(\alpha))$

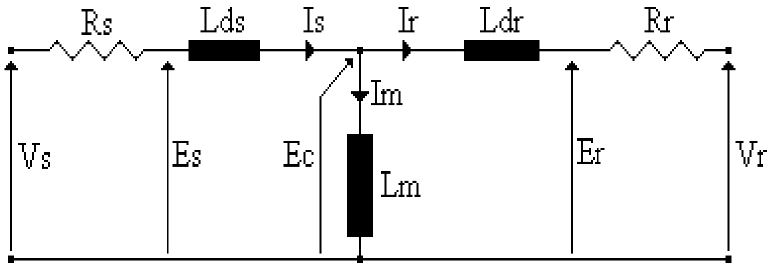
$$M = (|X_{re}| + |X_{im}|) \bullet F(T)$$

The F(T) is stored in a **look-up table** indexed by **T** : F (0) = 1 for α = 0 and F (1) = √2/2 for α = 45°

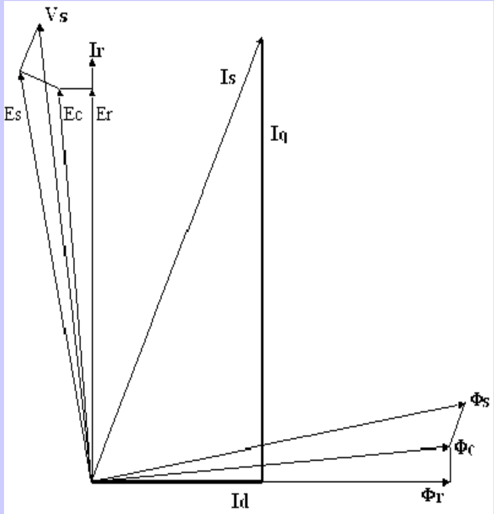
1) **Num = ABS (Xim)** ‘Absolute Value of the imaginary component
2) **Den = ABS (Xre)** ‘Absolute Value of the real component
3) **IF Num > Den THEN SWAP Den , Num** ‘To obtain Num <= Den (Ok range from 0 to 45°)
4) **Pointer = (Num / Den) * TabLen** ‘Preparing the pointer according to length of Table F ( )
5) **M = (Num + Den) * F (Pointer)** ‘**Ok the modulus is ready and valid for any angle α**

EQUIVALENT CIRCUITS

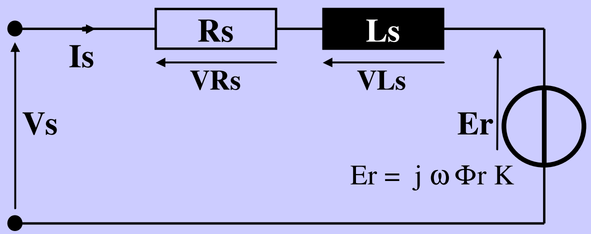
ASYNCRONOUS MOTOR



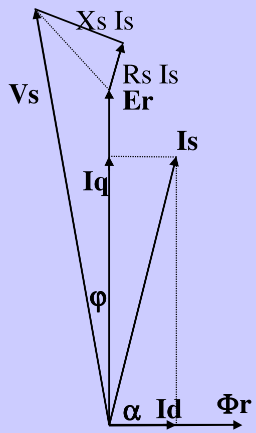
Er = Vr + Rr Ir **Vr = j ω Φr**

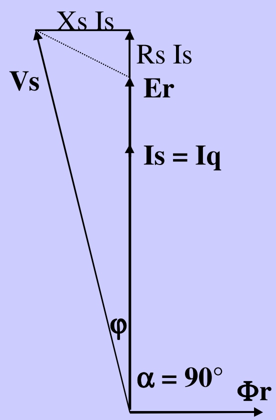


SYNCRONOUS MOTOR



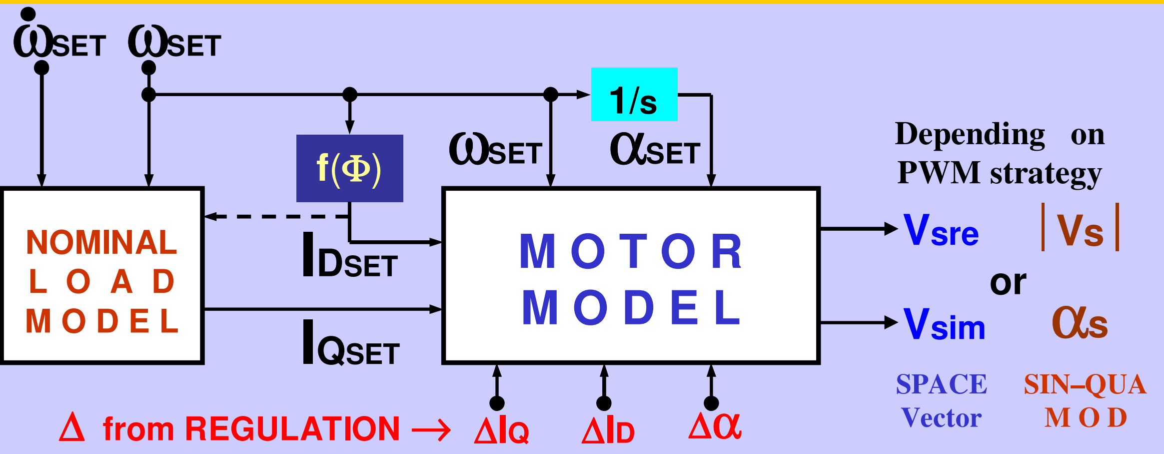
Er = j ω Φr Ke





M O T O R   M O D E L S

This structure can change if **accurate positioning** is needed or for special tasks …



ASYNCRONOUS M O T O R

$Id = \Phi r / Lm$ $\omega s = \omega r + \omega slip$

$Iq = Id\ \omega slip\ \tau r$ $\tau r = Lr / Rr$

$Tt = Kt\ Id\ Iq$ $Kt = 3/2\ Pp\ Lm^2 / Lr$

$Vd = Rs\ Id - \omega s\ Lk\ Iq$ $+ Kd\ \Delta Id/\Delta t$

$Vq = Rs\ Iq + \omega s\ Ls\ Id$ $+ Kq\ \Delta Iq/\Delta t$

$Lk = Ls - Lm^2 / Lr$

SYNCRONOUS M O T O R

$Id \approx 0$ $\omega s = \omega r$

$Iq = Tt / Kt$ $Ke = Er / \omega r$

$Tt = Kt\ Iq$ $Kt = 3/2\ Pp\ Ke$

$Vd = Rs\ Id - \omega r\ Ls\ Iq$ $+ Kd\ \Delta Id/\Delta t$

$Vq = Rs\ Iq + \omega r\ Ls\ Id + Er$ $+ Kd\ \Delta Iq/\Delta t$

$Er = Ke\ \omega r$ $\tau s = Ls / Rs$

M O D E L S may be also ADAPTIVE or SLIDING …

A GENERAL APPROACH …

We know **Vs** because we generate it at every iteration and we also know **Is** 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 …**

α = atn(Iq / Id)

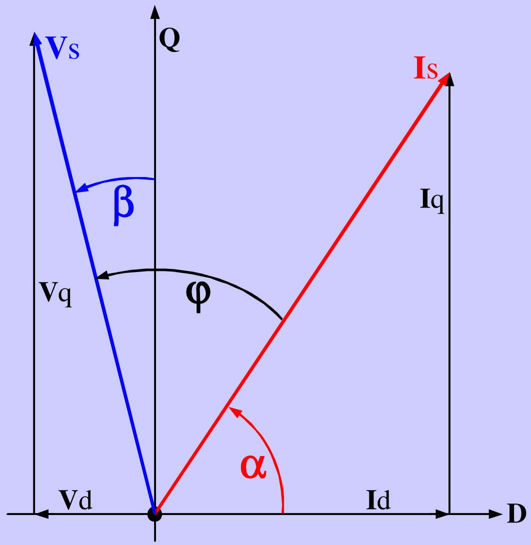
β = atn(-Vd/Vq)

$\varphi = \beta + 90° - \alpha$

A = 3 / 2 |Vs| |Is|

P = A cos(φ)

Q = A sin(φ)



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.

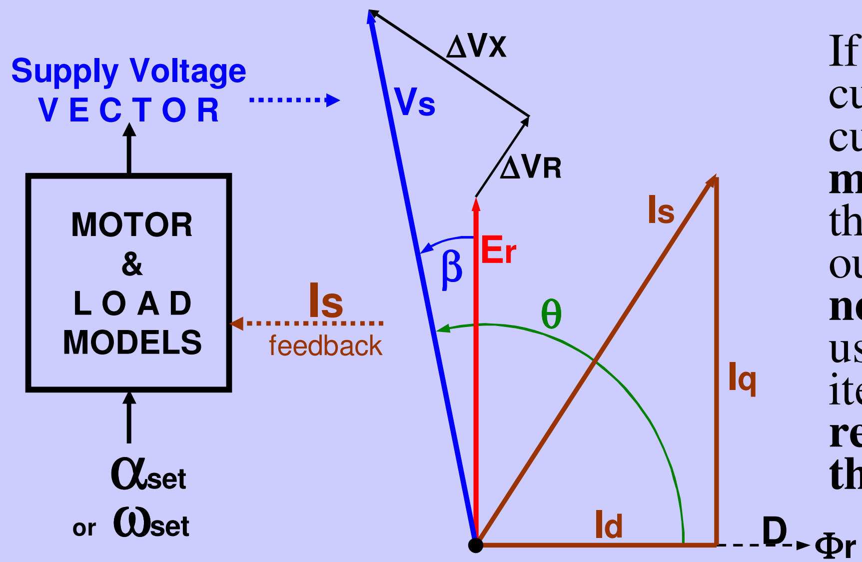
This method **works well** and it is quite **easy to implement in FPGA** , it is also **self convergent** and **robust** and can be **adapted** to the desired performances of the drive …

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

BASIC CONSIDERATIONS

A **motor model** calculates Vs and so **we know** , in function of Idset & Iqset , ωset , αset , … Vd , Vq , β , θ , … , and so **we can derive the D virtual direction angle**.

Measuring Is , after few calculations , we obtain the **Is components** on **D & Q** that we define as **Idm & Iqm** (from real and true measurement)



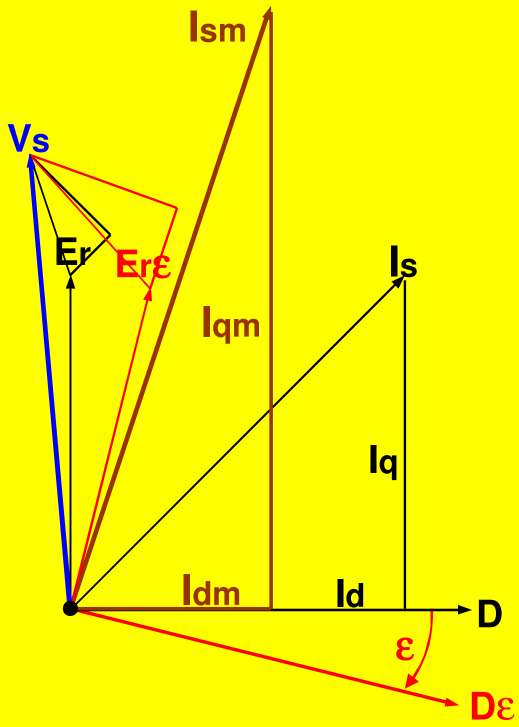
If we compare the measured currents **Idm & Iqm** with the currents **Id & Iq used by our motor model** , we can correct these in order to obtain in output of the motor model a **new vector Vs** which will give us in a **very short time** (few iterations) a **coincidence** of the **real measured current** 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



Le we suppose that the **LOAD is increasing**

ROTOR begins to **DECELERATE**

Rotor Direction **LAGS** from our Virtual **D**

Er LAGS with the same angle **ε**

Vs – Er start to increase on the impedance

Is leads and augments its modulus

Iqm becomes **greater** than our model **Iq**

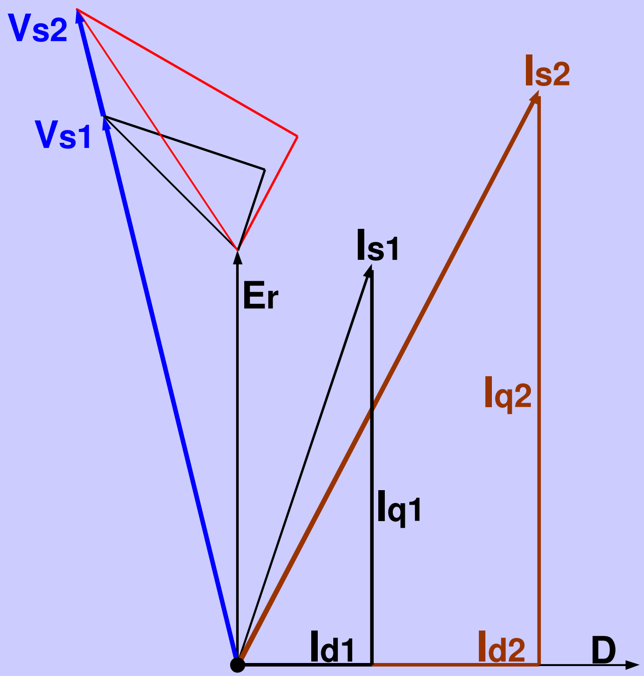
So **we increase Iqset** in our **model** and the resulting **Vs** gives to the motor a **greater torque** that **accelerates the rotor** in order to obtain a coincidence of the rotor direction with our virtual D reference ; at this point **we have restored a new equilibrium point with new correct Id & Iq**

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

This choice will adjust any rotor parameter detuning in Rr , Lr , Φr , ωr , Tt … 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) Vs1 pass to Vs2 , we will obtain new measured Iq2 & Id2 that are very different from the Iq1 & Id1 of the model.

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

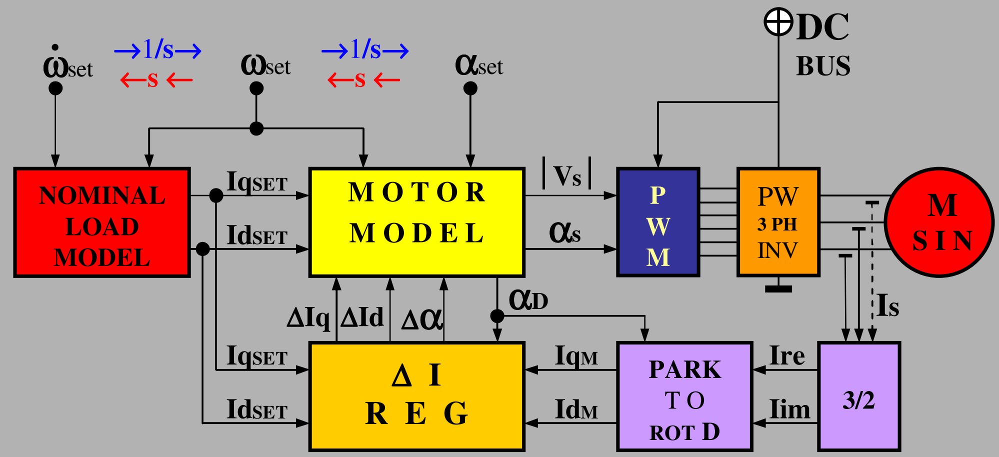
The flux and and torque have a great apparent increase … the controllers restore the system up to the coincidence of the model Is with the measured Is , and at this point also stator parametric detuning is well reduced … Rs , Ls , Φs …

The rotor & stator detuning is so **well reduced** … but a decrease in **Lm** (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 **Is on the D axis** (rotor flux) , but sometimes , for special applications it is better to project **Is on Vs 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.



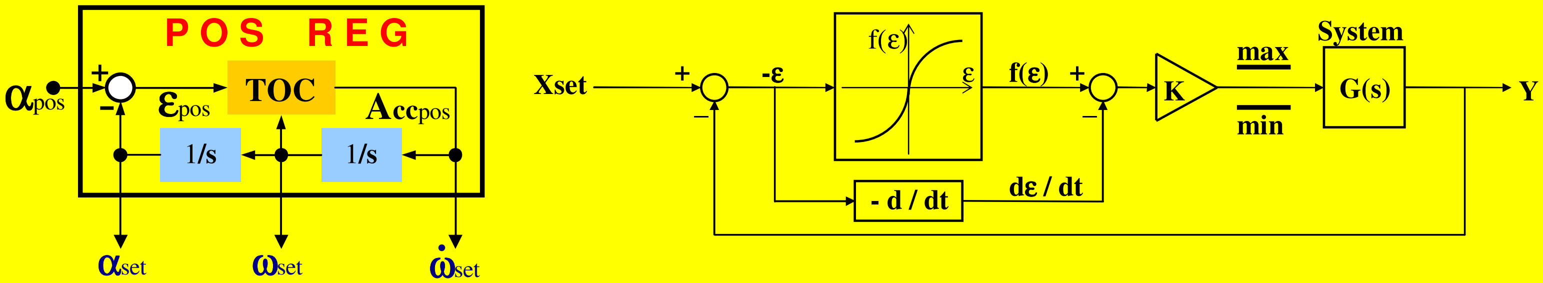
For the regulation block on **ΔI** , we can use the strategy we prefer , but **we have to consider all the dynamic characteristic of the PWM & MOTOR we use** …

In order to obtain a good dynamic and stability , we have to consider that the **Iq (Torque) regulator can be generally fast** but we must pay attention to the Id (Flux) regulator and use this feedback action in a light and smooth way … some filtered functions of ΔId 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 $\omega^2 = 2\,Acc\,\alpha$, 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.

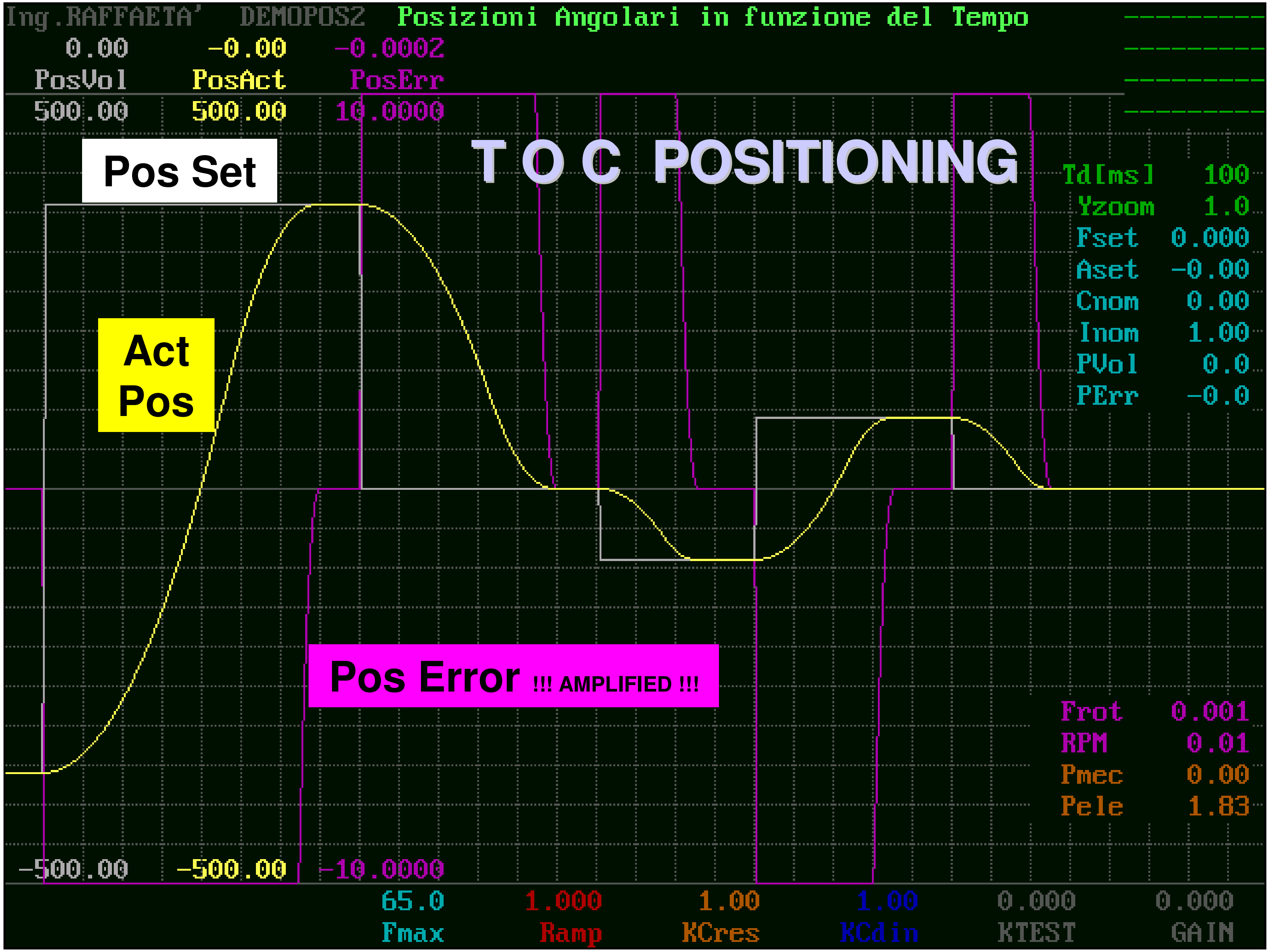
1) Very fast and perfectly controlled positioning without any overshoot

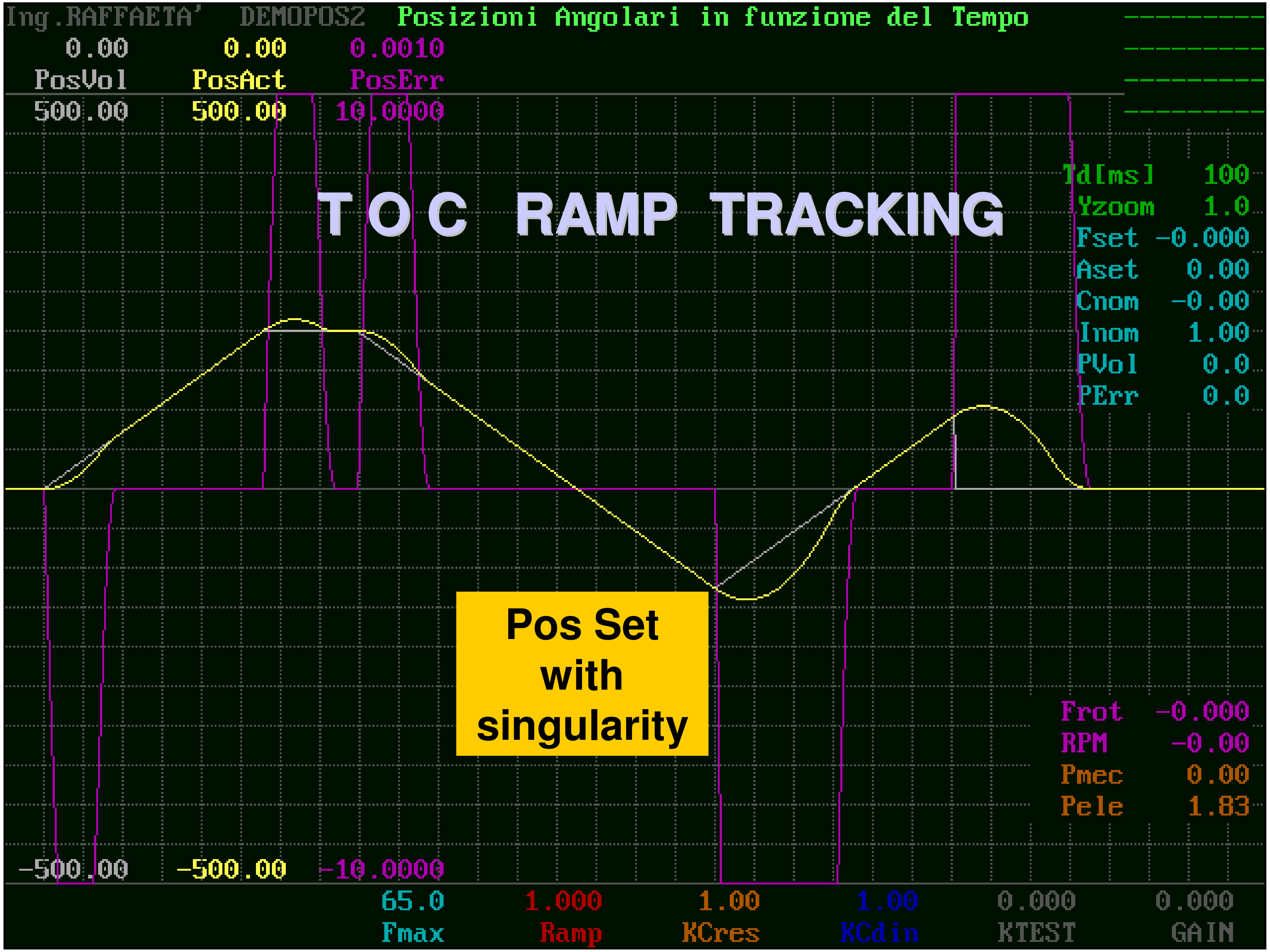
2) The best stability with null error at the positioning end

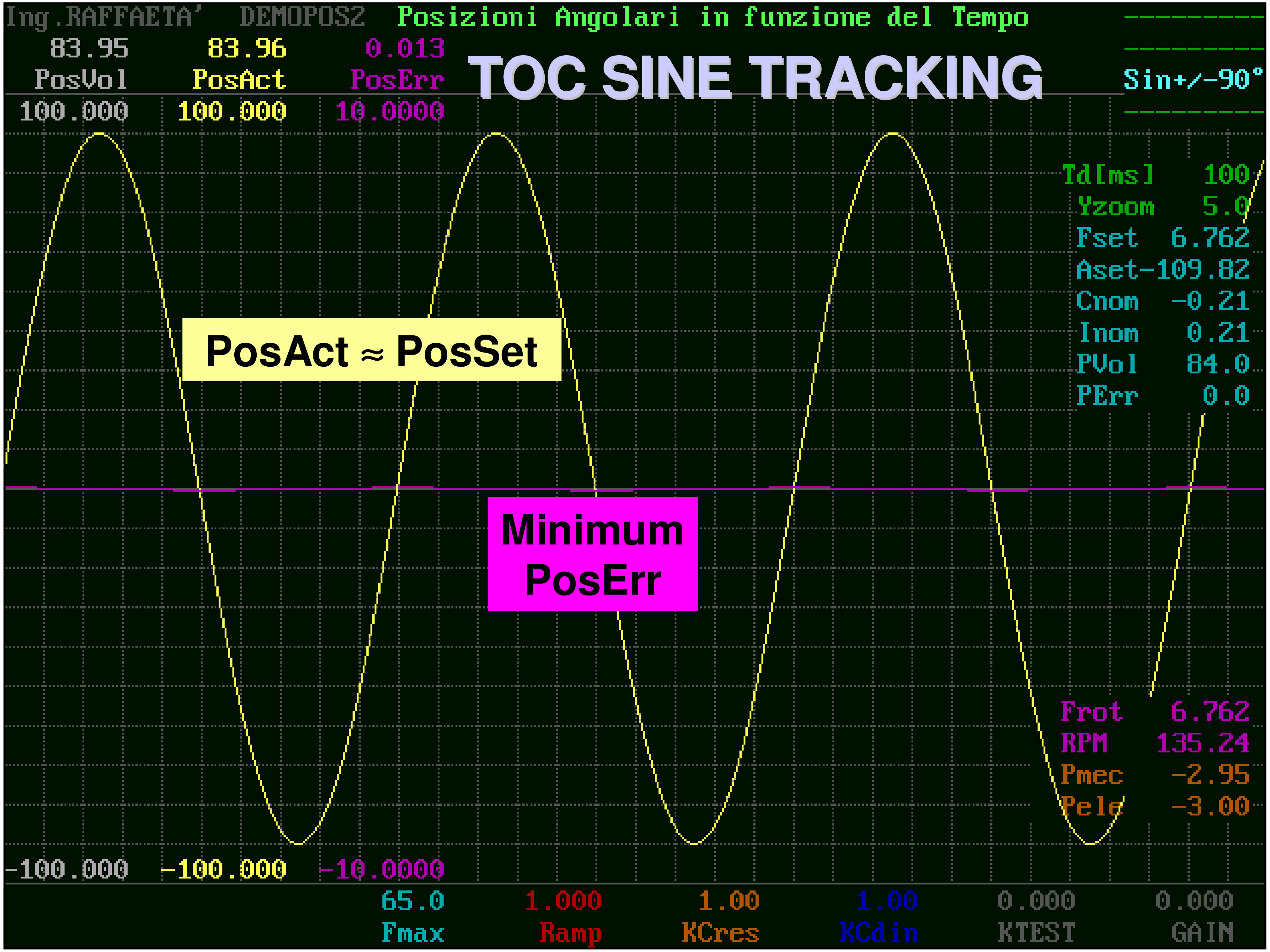
3) Absolute tracking on ramps also with no explicit integrative actions

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

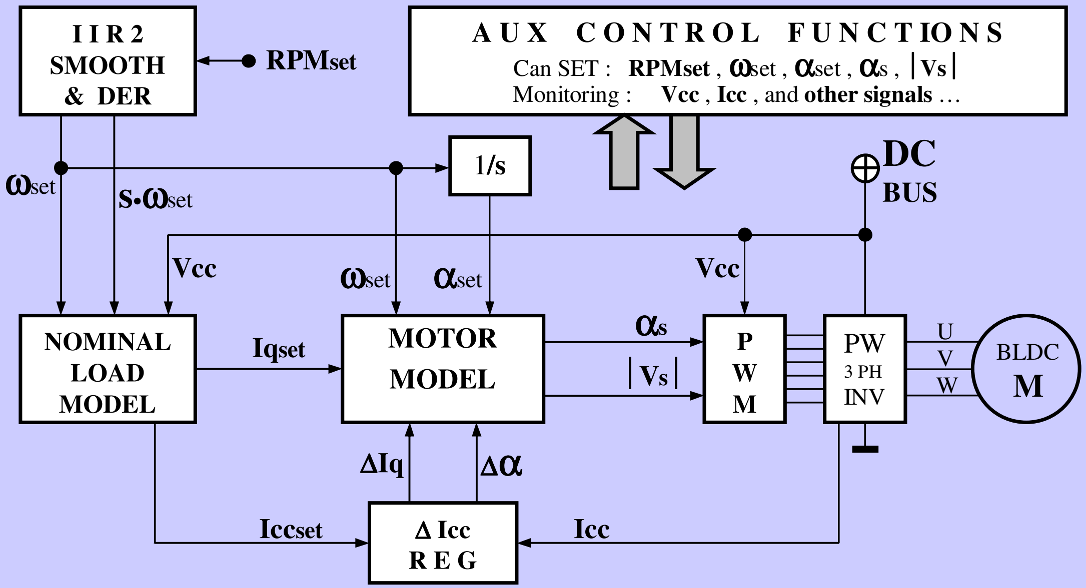

Ing.RAFFAETA'
DEMOPOS2
Posizioni Angolari in funzione del Tempo
0.00
-0.00
-0.0002
PosVol
PosAct
PosErr
500.00
500.00
10.0000
Pos Set
T O C POSITIONING
Act Pos
Td[ms] 100
Yzoom 1.0
Fset 0.000
Aset -0.00
Cnom 0.00
Inom 1.00
PVol 0.0
PErr -0.0
Pos Error !!! AMPLIFIED !!!
Frot 0.001
RPM 0.01
Pmec 0.00
Pele 1.83
-500.00
-500.00
-10.0000
65.0 Fmax
1.000 Ramp
1.00 KCres
1.00 KCdin
0.000 KTEST
0.000 GAIN


Ing.RAFFAETA' DEMOPOS2 Posizioni Angolari in funzione del Tempo
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
Pos Set with singularity
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

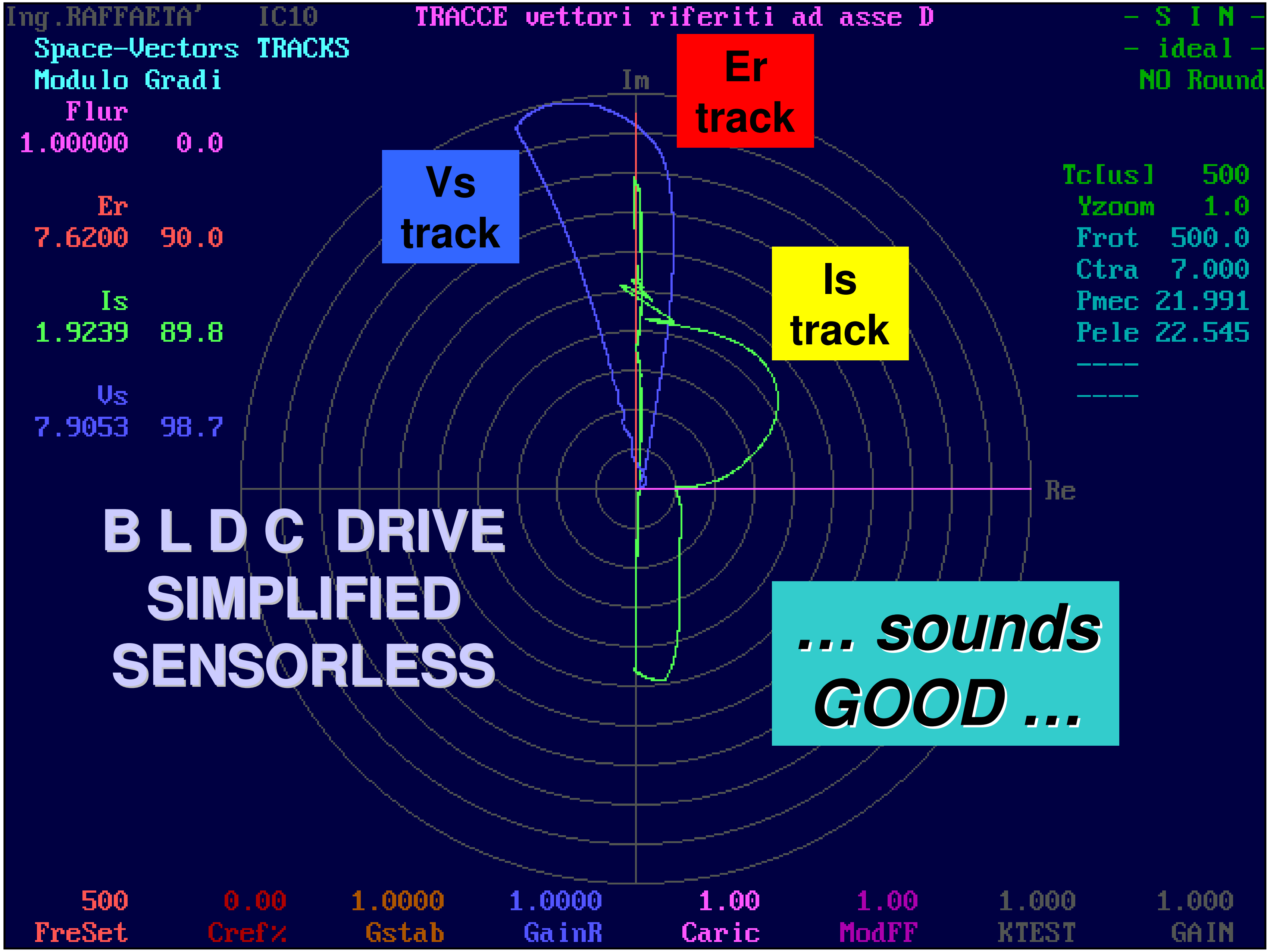

Ing.RAFFAETA' DEMOPOS2 Posizioni Angolari in funzione del Tempo
83.95 83.96 0.013
PosVol PosAct PosErr
TOC SINE TRACKING
Sin+/-90°
100.000 100.000 10.0000
Td[ms] 100
Yzoom 5.0
Fset 6.762
Aset-109.82
Cnom -0.21
Inom 0.21
PVol 84.0
PErr 0.0
PosAct ≈ PosSet
Minimum PosErr
Frot 6.762
RPM 135.24
Pmec -2.95
Pele -3.00
-100.000 -100.000 -10.0000
65.0 Fmax
1.000 Ramp
1.00 KCres
1.00 KCdin
0.000 KTEST
0.000 GAIN

SIMPLIFIED SENSORLESS

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

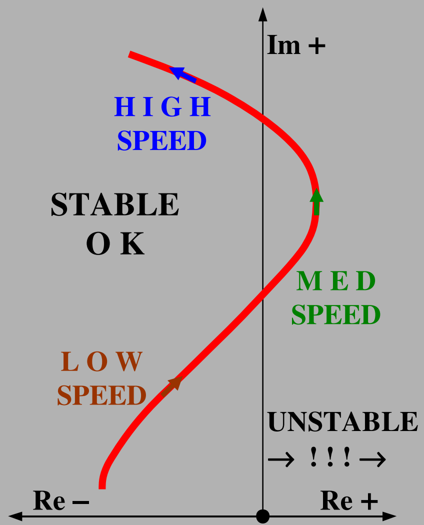


This is an example of a complete drive we have used for a low-cost but **high-speed BLCD** motor ; the only feedback is **Icc** (DC bus current) which is a scalar value and that it is easy to measure. This motor is **unstable** (in open loop condition) in the region of the medium speeds. The **Δ Icc** 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
- S I N -
- ideal -
NO Round
Space-Vectors TRACKS
Modulo Gradi
Flur
1.00000 0.0
Er
7.6200 90.0
Is
1.9239 89.8
Vs
7.9053 98.7
Im
Re
Er track
Vs track
Is track
Tc[us] 500
Yzoom 1.0
Frot 500.0
Ctra 7.000
Pmec 21.991
Pele 22.545
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

O P E N   L O O P   D R I V E S

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 …**

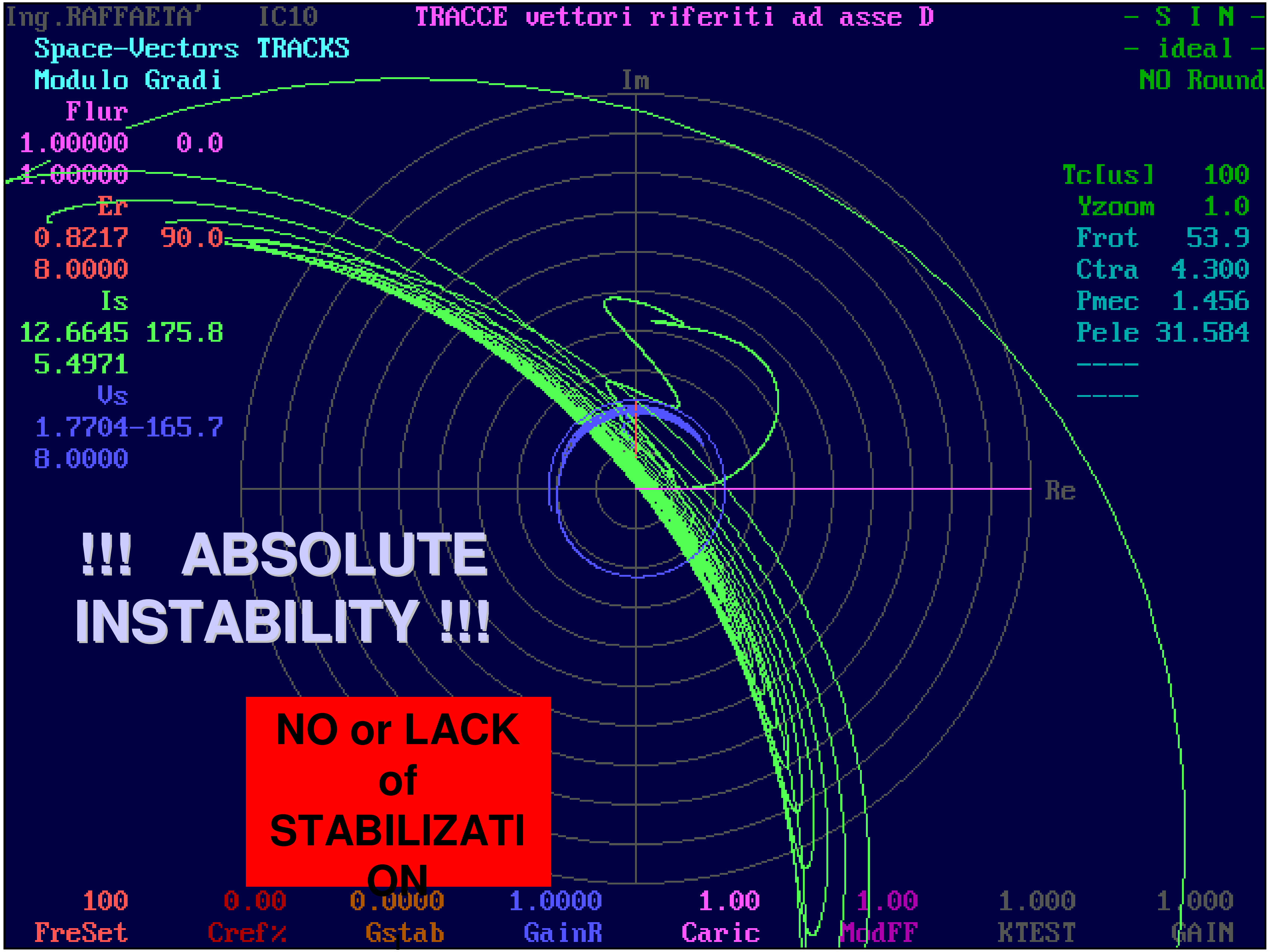


Also in steady-state conditions , all the motors have a transfer function with some complex conjugate pairs.

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.

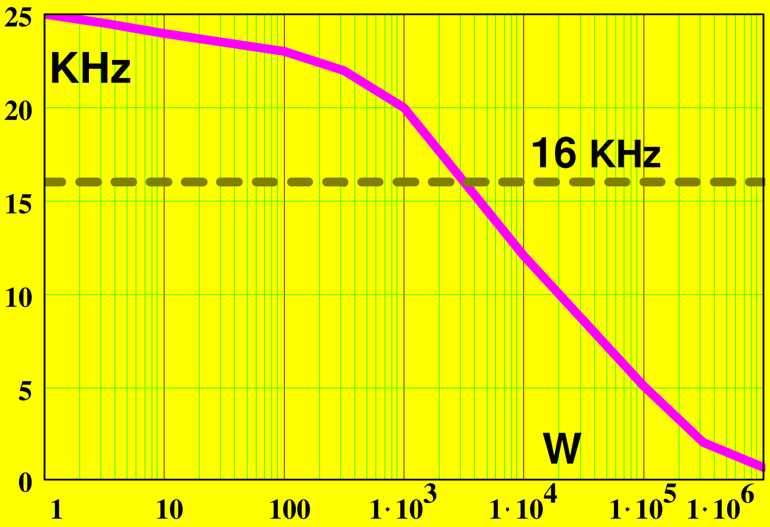


Ing.RAFFAETA'
IC10
TRACCE vettori riferiti ad asse D
- S I N -
- ideal -
NO Round
Space-Vectors TRACKS
Modulo Gradi
Flur
1.00000 0.0
1.00000
Er
0.8217 90.0
8.0000
Is
12.6645 175.8
5.4971
Vs
1.7704-165.7
8.0000
Im
Re
Tc[us] 100
Yzoom 1.0
Frot 53.9
Ctra 4.300
Pmec 1.456
Pele 31.584
!!! ABSOLUTE INSTABILITY !!!
NO or LACK of STABILIZATION
100 FreSet
0.00 Cref%
0.0000 Gstab
1.0000 GainR
1.00 Caric
1.00 ModFF
1.000 KTEST
1.000 GAIN

P W M MODULATORS

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

P O W E R	KW	FREQUENCY	SWITCHES
L O W	up to 1 KW	16 ÷ 24 KHz	MOSFET (TRANSISTOR)
MEDIUM	1 ÷ 100 KW	2 ÷ 18 KHz	I G B T (MOSFET)
H I G H	over 100 KW	0.4 ÷ 5 KHz	I G B T – G T O



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.

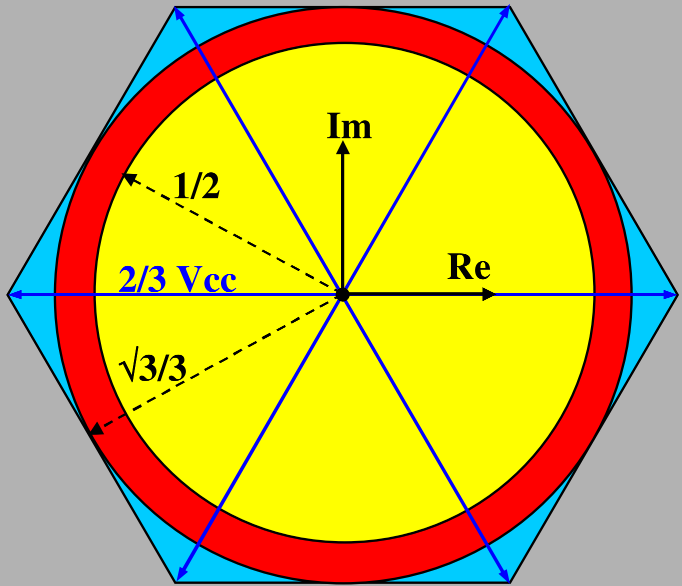
For LOW & MEDIUM power is advisable to operate over 16 KHz in order to work in the not audible range. All we hope to have in the future **high power IGBT** working at higher frequencies with low losses.

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 Vcc) 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** Vcc (yellow region in the figure).



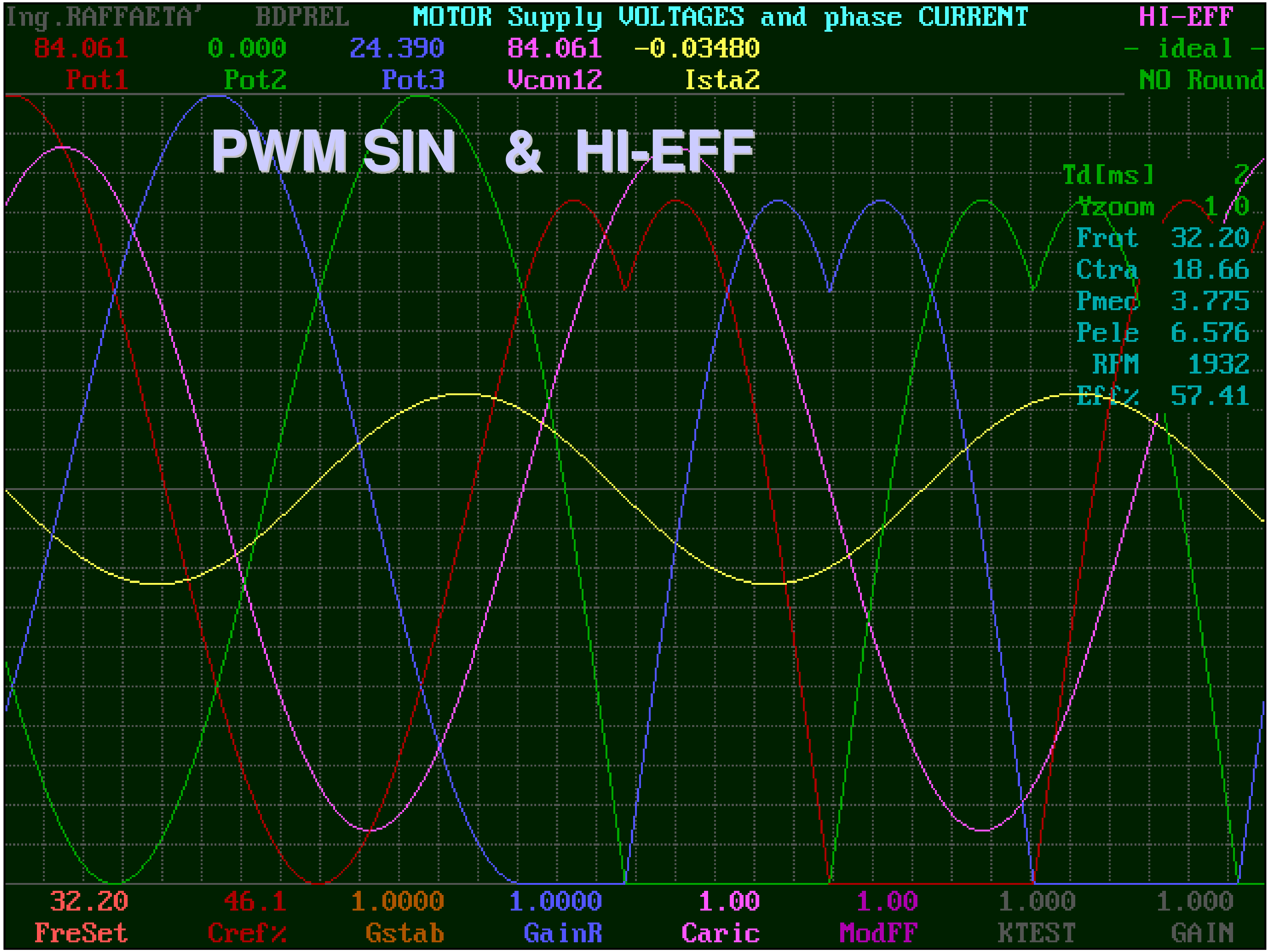
But if we **offset** the 3 inverter potentials with 3 **identical voltages** (also varying in the time), **concatenated voltages** and **phase currents** in the motor **remain identical**.

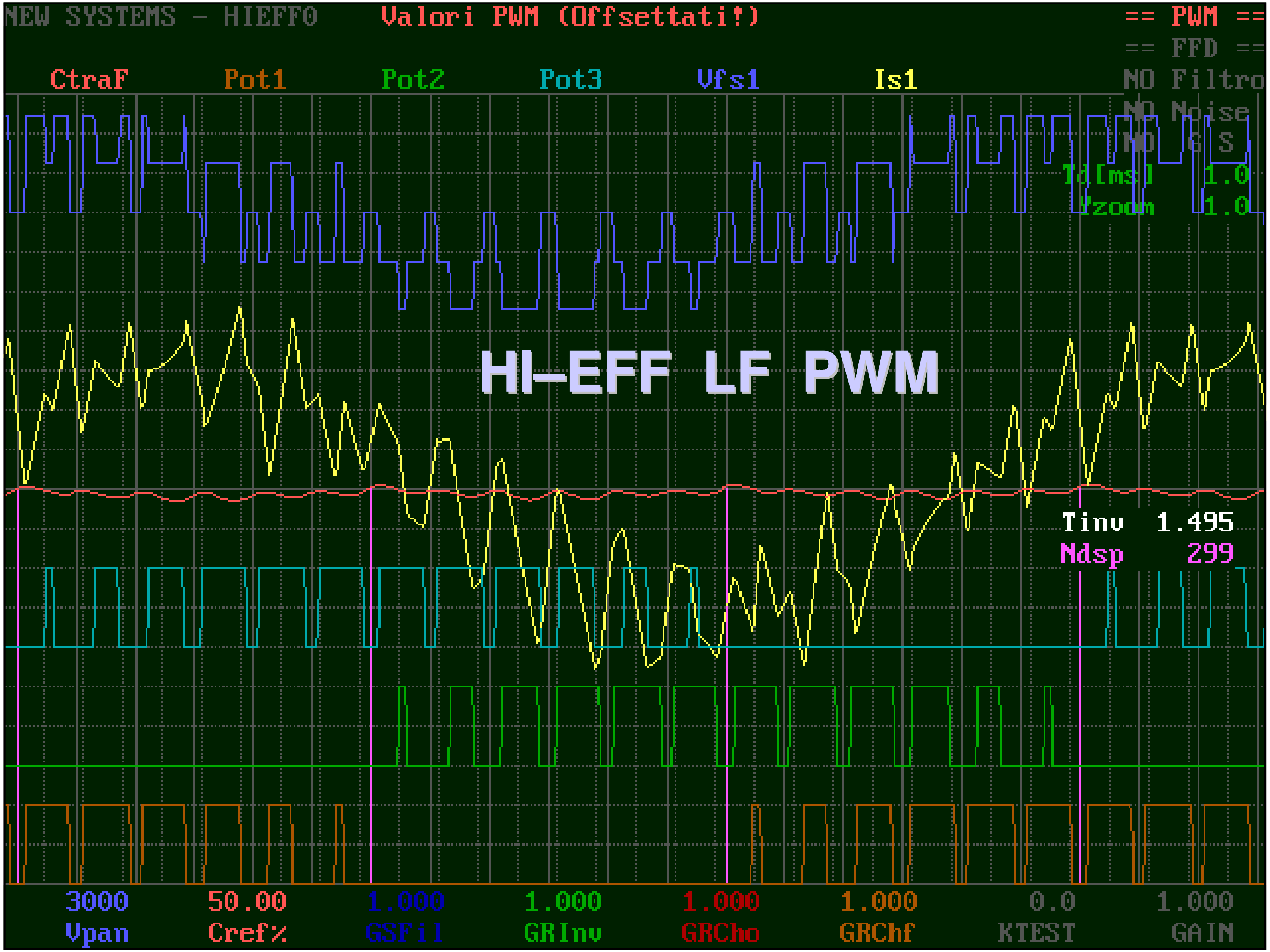
This fact allows us to have a lot of solutions to obtain **higher unclipped sinusoidal voltages** (red region in the figure)

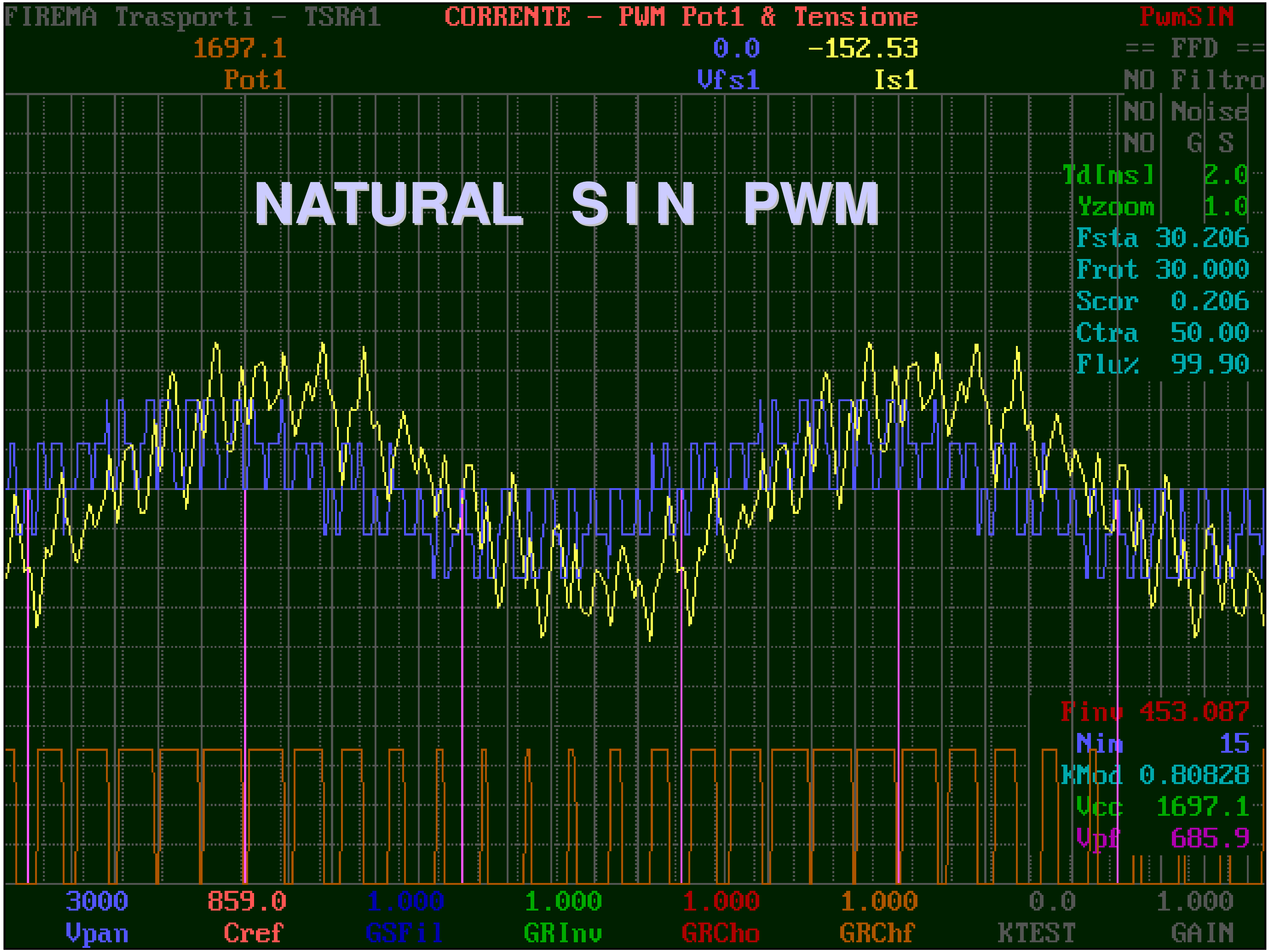
All researchers have their own preferred offset receipt , and personally I prefer **HI–EFF** modulation (I developed in 1995) for the reason that can use all the red region ad above all because reduces the commutation losses by a factor **2/3** ≈ 0.667 (33.3% gain)

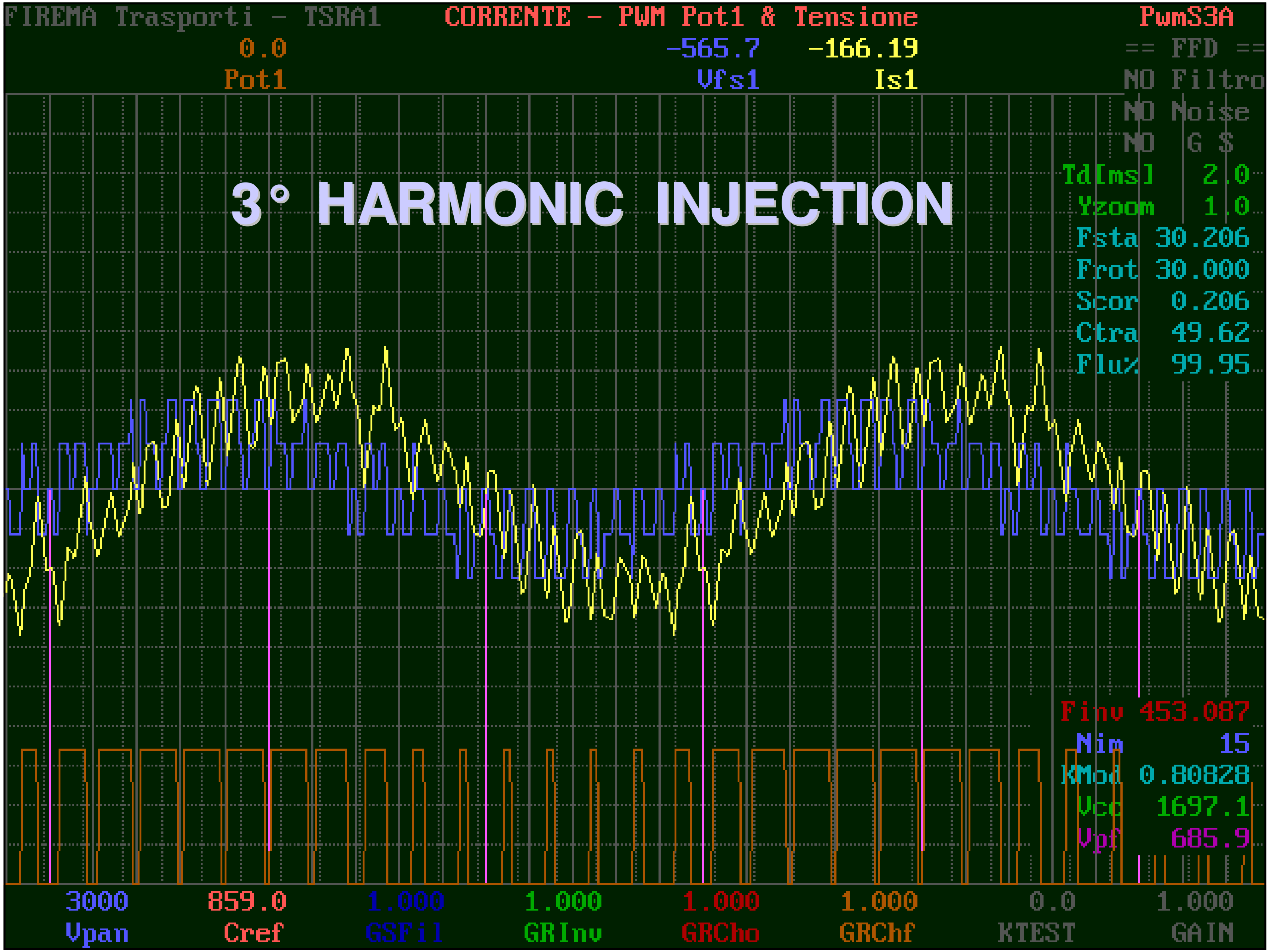
In literature you can find many other solutions so to select the best.

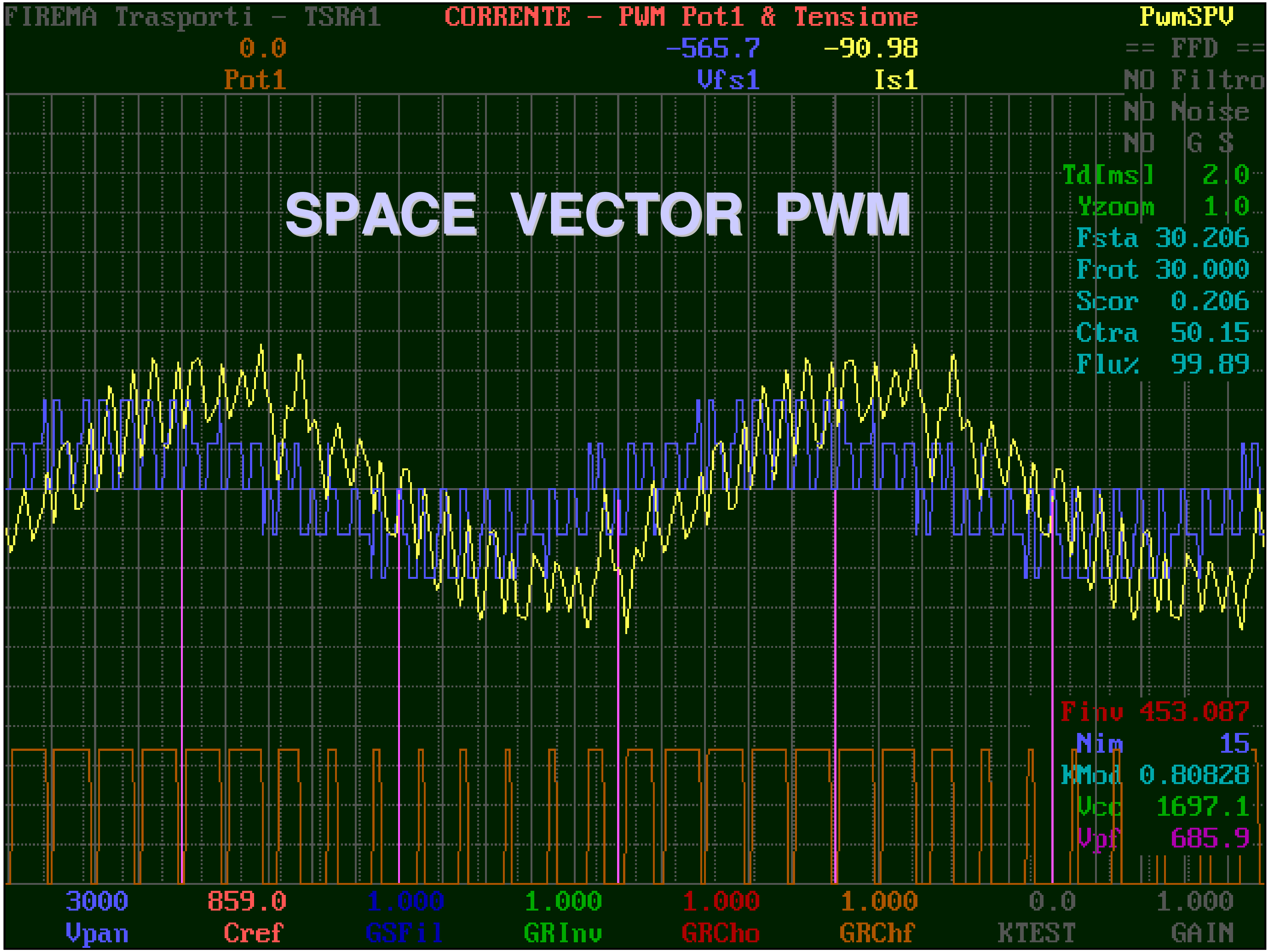
The **SPACE VECTOR** modulation is a time weighted average of the basic vectors with 2/3 Vcc amplitude and can operate in **all the voltage hexagon** (blue region in the figure) ; but also in this case , if we go out of the red circle , we will obtain clipped sinusoids (SATURATION). **!!! The hexagon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

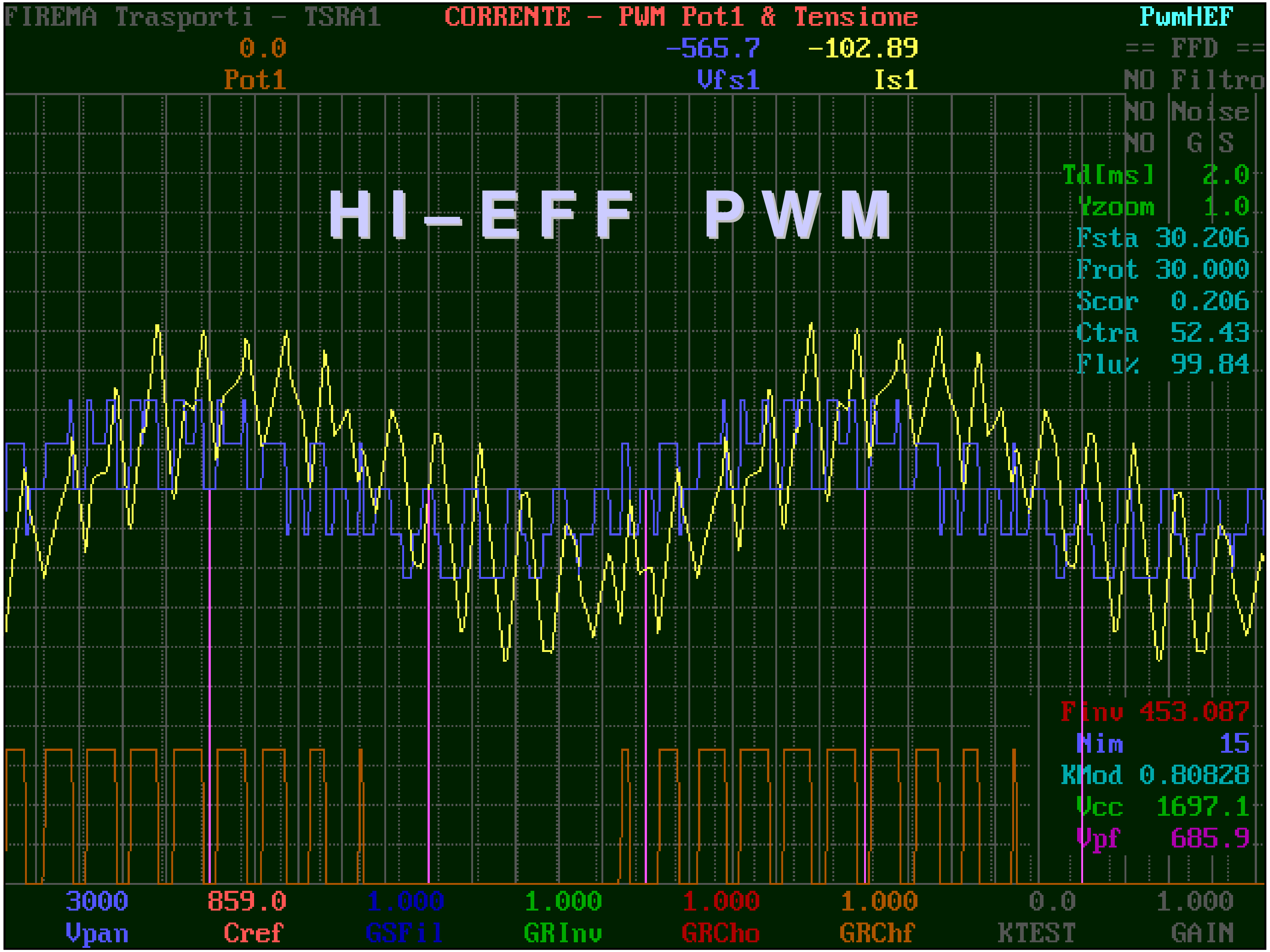

Ing.RAFFAETA'
BDPREL
MOTOR Supply VOLTAGES and phase CURRENT
HI-EFF
84.061
0.000
24.390
84.061
-0.03480
- ideal -
Pot1
Pot2
Pot3
Vcon12
Ista2
NO Round
PWM SIN & HI-EFF
Td[ms] 2
Yzoom 1.0
Frot 32.20
Ctra 18.66
Pmec 3.775
Pele 6.576
RPM 1932
Eff% 57.41
32.20
46.1
1.0000
1.0000
1.00
1.00
1.000
1.000
FreSet
Cref%
Gstab
GainR
Caric
ModFF
KTEST
GAIN


NEW SYSTEMS - HIEFFO
Valori PWM (Offsettati!)
== PWM ==
== FFD ==
NO Filtro
NO Noise
NO G S
Td[ms] 1.0
Yzoom 1.0
CtraF
Pot1
Pot2
Pot3
Vfs1
Is1
HI-EFF LF PWM
Tinv 1.495
Ndsp 299
3000
Vpan
50.00
Cref%
1.000
GSFil
1.000
GRInv
1.000
GRCho
1.000
GRChf
0.0
KTEST
1.000
GAIN


FIREMA Trasporti - TSRA1
CORRENTE - PWM Pot1 & Tensione
PwmSIN
1697.1
Pot1
0.0
Vfs1
-152.53
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 50.00
Flu% 99.90
NATURAL SIN PWM
Finv 453.087
Nim 15
KMod 0.80828
Vcc 1697.1
Vpf 685.9
3000
Vpan
859.0
Cref
1.000
GSFil
1.000
GRInv
1.000
GRCho
1.000
GRChf
0.0
KTEST
1.000
GAIN


FIREMA Trasporti - TSRA1
CORRENTE - PWM Pot1 & Tensione
PwmS3A
0.0
Pot1
-565.7
Vfs1
-166.19
Is1
== FFD ==
NO Filtro
NO Noise
NO G $
Td[ms] 2.0
Yzoom 1.0
Fsta 30.206
Frot 30.000
Scor 0.206
Ctra 49.62
Flu% 99.95
3° HARMONIC INJECTION
Finv 453.087
Nim 15
KMod 0.80828
Vcc 1697.1
Vpf 685.9
3000
Vpan
859.0
Cref
1.000
GSFil
1.000
GRInv
1.000
GRCho
1.000
GRChf
0.0
KTEST
1.000
GAIN

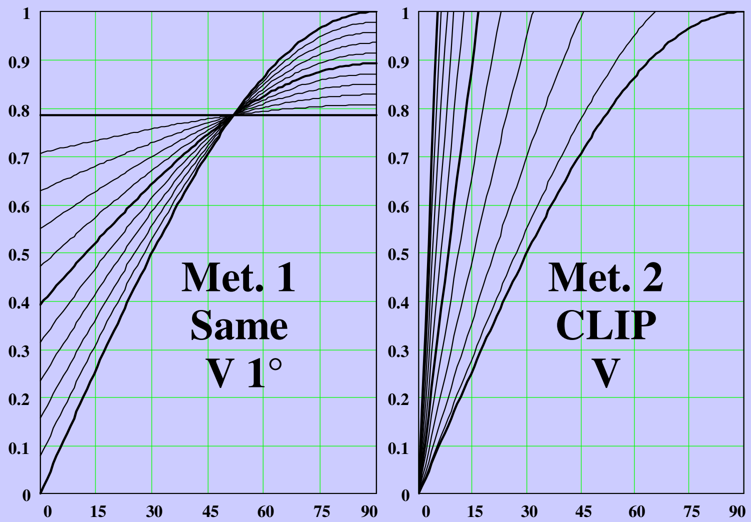

FIREMA Trasporti - TSRA1
CORRENTE - PWM Pot1 & Tensione
PwmSPV
0.0
Pot1
-565.7
Vfs1
-90.98
Is1
== FFD ==
NO Filtro
NO Noise
NO G S
Td[ms] 2.0
Yzoom 1.0
Fsta 30.206
Frot 30.000
Scor 0.206
Ctra 50.15
Flu% 99.89
SPACE VECTOR PWM
Finv 453.087
Nim 15
KMod 0.80828
Vcc 1697.1
Vpf 685.9
3000 Vpan
859.0 Cref
1.000 GSFil
1.000 GRInv
1.000 GRCho
1.000 GRChf
0.0 KTEST
1.000 GAIN


FIREMA Trasporti - TSRA1
CORRENTE - PWM Pot1 & Tensione
PwmHEF
0.0
Pot1
-565.7
Vfs1
-102.89
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 52.43
Flu% 99.84
HI-EFF PWM
Finv 453.087
Nim 15
KMod 0.80828
Vcc 1697.1
Vpf 685.9
3000
Vpan
859.0
Cref
1.000
GSFil
1.000
GRInv
1.000
GRCho
1.000
GRChf
0.0
KTEST
1.000
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 Vcc , **SATURATION** appears and we must pass in square wave supply voltage which has a fundamental peak value of $2/\pi \approx 0.637$ Vcc.

To avoid hard transitory we must S M O O T H 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**

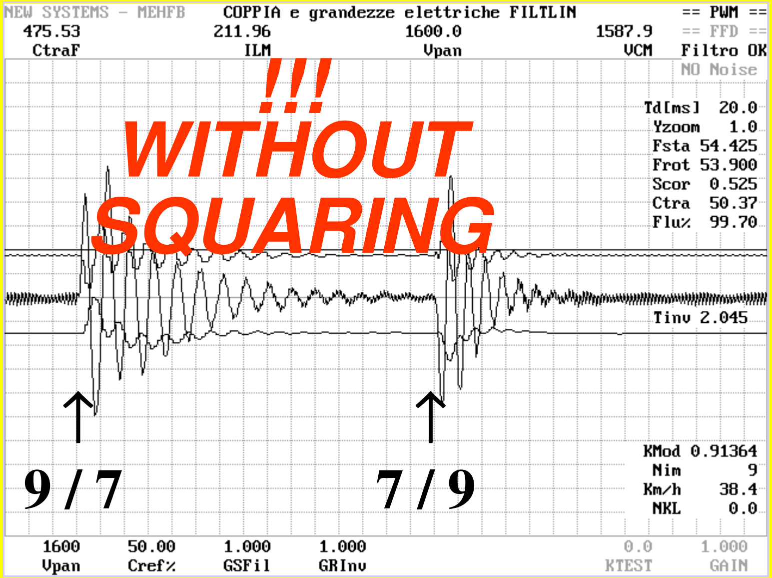
Method **2** is a calculation of a **family** of **clipped sinusoid** that must have the **desired value** for the **fundamental** ; it **requires a look-up table because calculations are too long to be processed in real-time** , and I named **SIN-CLIP**

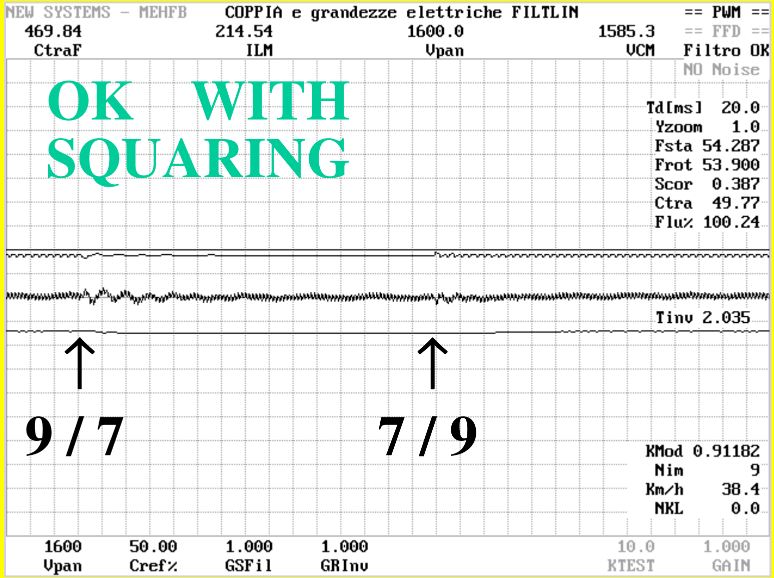
When the modulation coefficient (**m = K |Vs| / Vcc**) is raising to its maximum value , before saturation condition , we have to smoothly pass to the square wave ; the use of method 1 or 2 depend on application requirements and on other factors …

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 HARMONICHS whose amplitudes decrease while the modulation frequency increases … so where it is possible use an high frequency modulator ,… FPGA driven.

VOLTAGE HARMONICHS have order **6 K +/– 1** (with some exceptions)

CURRENT HARMONICHS have order **6 K +/– 1** (with other exceptions)

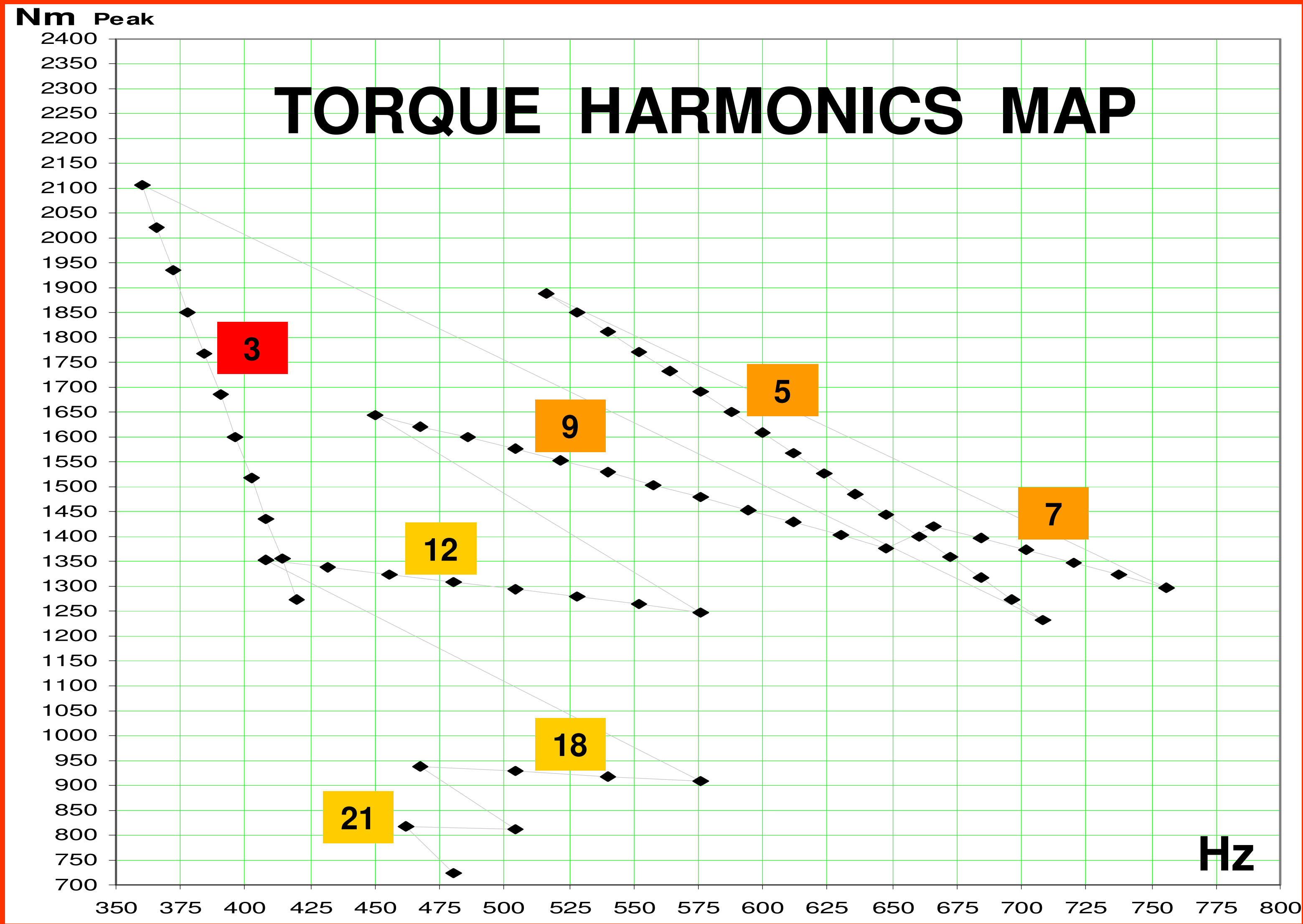
TORQUE & **DC BUS** HARMONICHS have order **6 K** plus **N K** …

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 …

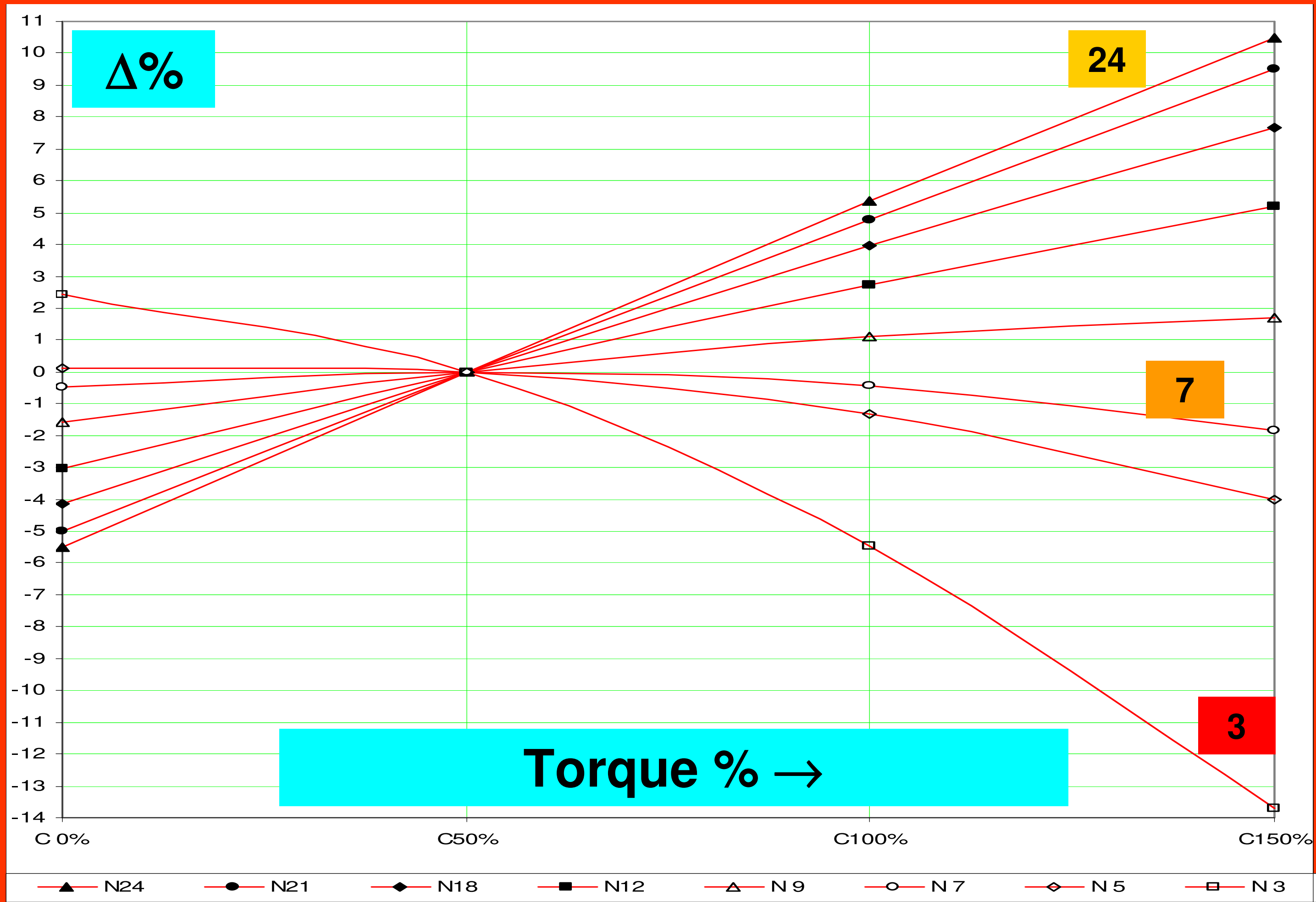
A reduction of the global harmonic content (or better a **frequency shift** in a not dangerous range) is generally possible varying the **pulse position** inside a pulse pattern or using (moderate) **spread spectrum techniques**…

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



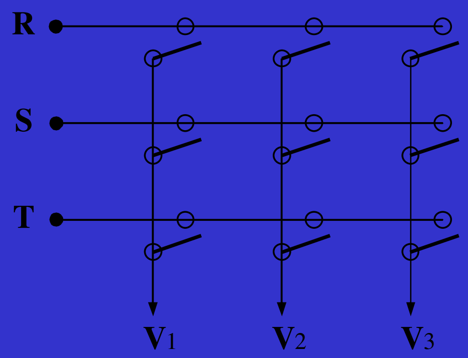
Nm Peak
TORQUE HARMONICS MAP
2400
2350
2300
2250
2200
2150
2100
2050
2000
1950
1900
1850
1800
1750
1700
1650
1600
1550
1500
1450
1400
1350
1300
1250
1200
1150
1100
1050
1000
950
900
850
800
750
700
3
5
9
7
12
18
21
Hz
350
375
400
425
450
475
500
525
550
575
600
625
650
675
700
725
750
775
800

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 …

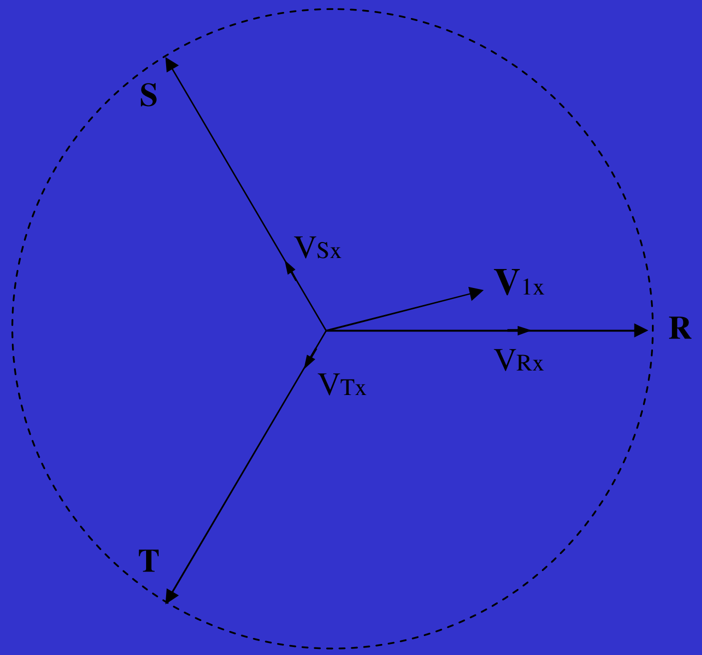


$V1x = VRx + VSx + VTx$

$VRx = R * tR / tC$

$VSx = S * tS / tC$

$VTx = T * tT / tC$



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 Vs and the feedback current Is …

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 Vs 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** …

NEW SYSTEMS

NOTHING BUT THE BEST

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For your INNOVATIVE SOLUTIONS …

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