POWER ELECTRONICS AND CONTROL SYSTEMS RESEARCH GROUP

RESEARCH TOPICS

- 1 Non-Linear Control Applied to Power Electronics
- 2 Control Schemes under Grid Fault
- 3 Grid Synchronization Techniques
- 4 Microgrids Control

Modeling and Nonlinear Control of Three-phase Voltage-Sourced Converters

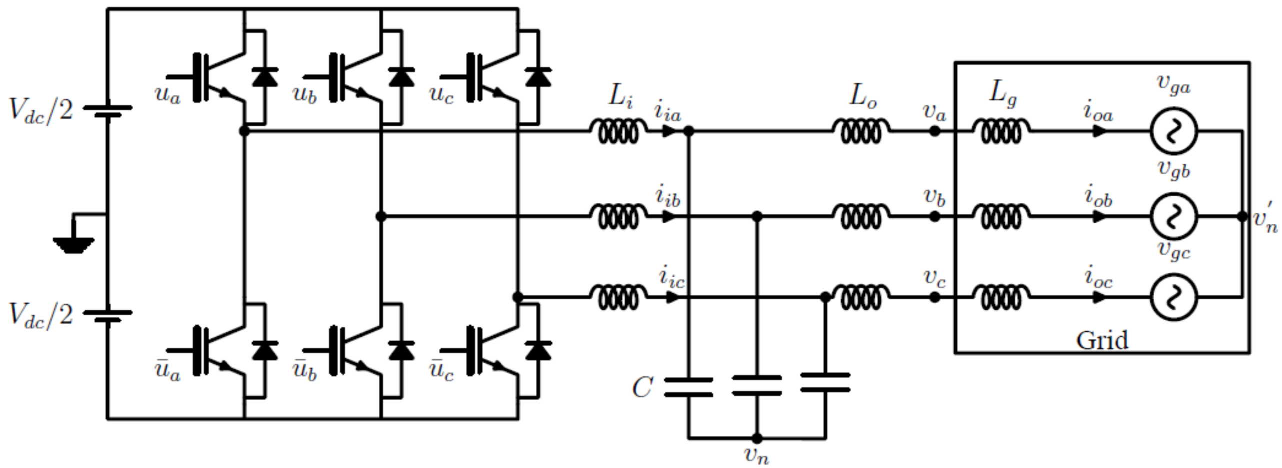
OUTLINE

- **Introduction**
- **Modeling a Three-phase Inverter with LCL Filter**
- **Extended Kalman Filter**
- **Conventional Sliding mode control**
- **Passive and active damping solution**
- **Sliding-mode control based on an Extended Kalman Filter**
- **Experimental results**
- **Conclusions**

INTRODUCTION

- Traditionally DSP control algorithms for three-phase power converters are designed in rotating or stationary reference frames.
- The aim is to applied the well-known sliding-mode control techniques used to single-phase converters in three-phase converters
- Three-phase systems in natural frame has an axis-coupling problem through the neutral point voltage
- The solution adopted is to use an Extended Kalman Filter to achieve axis decoupling
- Sliding-Mode Control solutions can be developed in the natural reference frame
- Three-phase system is decoupled and divided into three independent single-phase systems

MODELING OF A THREE-PHASE INVERTER WITH LCL-FILTER



$$L_i \frac{d\mathbf{i}_i}{dt} = \frac{V_{dc}}{2}\mathbf{u} - \mathbf{v}_c - v_n$$

$$C \frac{d\mathbf{v}_c}{dt} = \mathbf{i}_i - \mathbf{i}_o$$

$$L_o \frac{d\mathbf{i}_o}{dt} = \mathbf{v}_c - \mathbf{v}$$

$\mathbf{u} = [u_a \ \ u_b \ \ u_c]^T$ $\quad u_{a,b,c} \in \{\pm 1\}$ represent the on/off control signals

$$v_n = v_n' = \frac{V_{dc}}{6}(u_a + u_b + u_c)$$

Axis-coupling problem through the neutral point voltage

EXTENDED KALMAN FILTER

Why use a Kalman filter ?:

1) Decoupled controllers: Vn is substituted by V*n (in the model used to implement the Kalman algorithm)
2) Reduce the number of sensors: only the grid currents are sensed
3) All the variables used in the control algorithm are estimated and free of noise improving sliding motion.
4) The voltages at the Point of Common Coupling are estimated providing robustness against grid inductance changes
5)A sinusoidal third-harmonic voltage is imposed at the neutral point increasing the control dynamic range

$$v_n = v_n' = \frac{V_{dc}}{6}(u_a + u_b + u_c) \longrightarrow v_n^* = \frac{V_a}{6}[k_p \cos(3\omega_o t) + (1 + k_q)\sin(3\omega_o t)]$$

$$L_i \frac{d\mathbf{i}_i}{dt} = \frac{V_{dc}}{2}\mathbf{u} - \mathbf{v}_c - v_n$$

$$C\frac{d\mathbf{v}_c}{dt} = \mathbf{i}_i - \mathbf{i}_o$$

$$L_o \frac{d\mathbf{i}_o}{dt} = \mathbf{v}_c - \mathbf{v}$$

CONVENTIONAL SLIDING MODE CONTROL

Converter side current control

$$\mathbf{S} = \mathbf{i}^*_i - \mathbf{i}_i$$

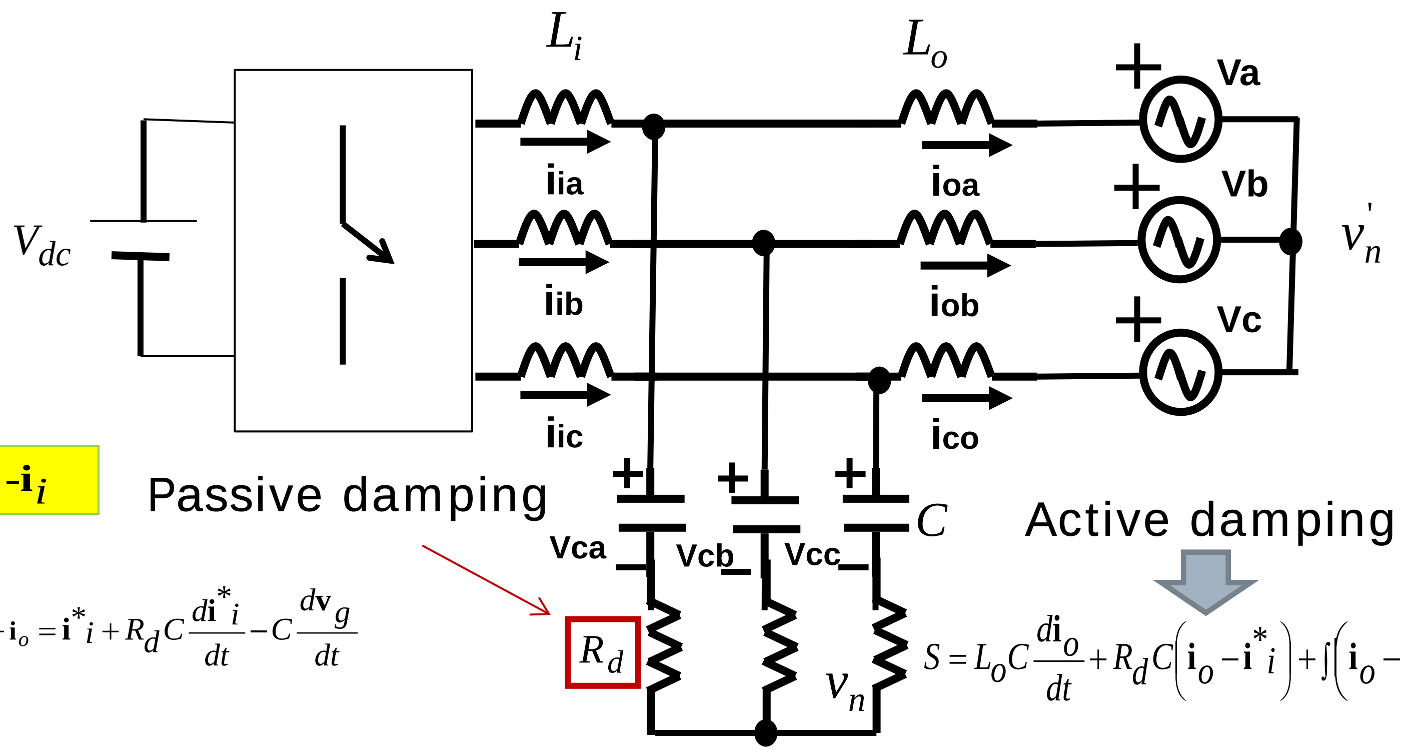
$$L_o C \frac{d^2 \mathbf{i}_o}{dt^2} + \mathbf{i}_o = \mathbf{i}_i^* - C \frac{d\mathbf{v}}{dt}$$

$$\mathbf{i}_o(s) = \frac{1}{L_o C s^2 + 1} \mathbf{i}_i^* - \frac{Cs}{L_o C s^2 + 1} \mathbf{v}$$

The output current dynamics is unstable!!

CONVENTIONAL SLIDING MODE CONTROL

Passive or active damping solution



$S = i^*_i - i_i$

Passive damping

Active damping

$$L_o C \frac{d^2 \mathbf{i}_o}{dt^2} + R_d C \frac{d\mathbf{i}_o}{dt} + \mathbf{i}_o = \mathbf{i}^*_i + R_d C \frac{d\mathbf{i}^*_i}{dt} - C \frac{d\mathbf{v}_g}{dt}$$

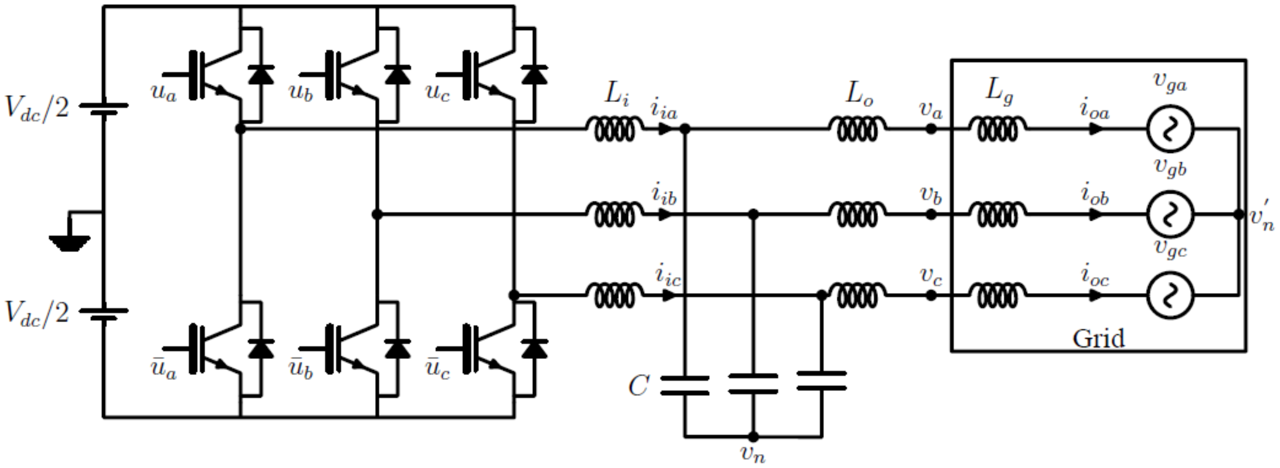
$$S = L_o C \frac{d\mathbf{i}_o}{dt} + R_d C\left(\mathbf{i}_o - \mathbf{i}^*_i\right) + \int\left(\mathbf{i}_o - \mathbf{i}^*_i\right)dt + C\mathbf{v}$$

$$\mathbf{i}_o(s) = \frac{1 + R_d C s}{L_o C s^2 + R_d C s + 1}\mathbf{i}_i^* - \frac{Cs}{L_o C s^2 + R_d C s + 1}\mathbf{v}$$

LOSSES!!

Error in the reference current tracking !! $\mathbf{i}^*_i \neq \mathbf{i}_o$

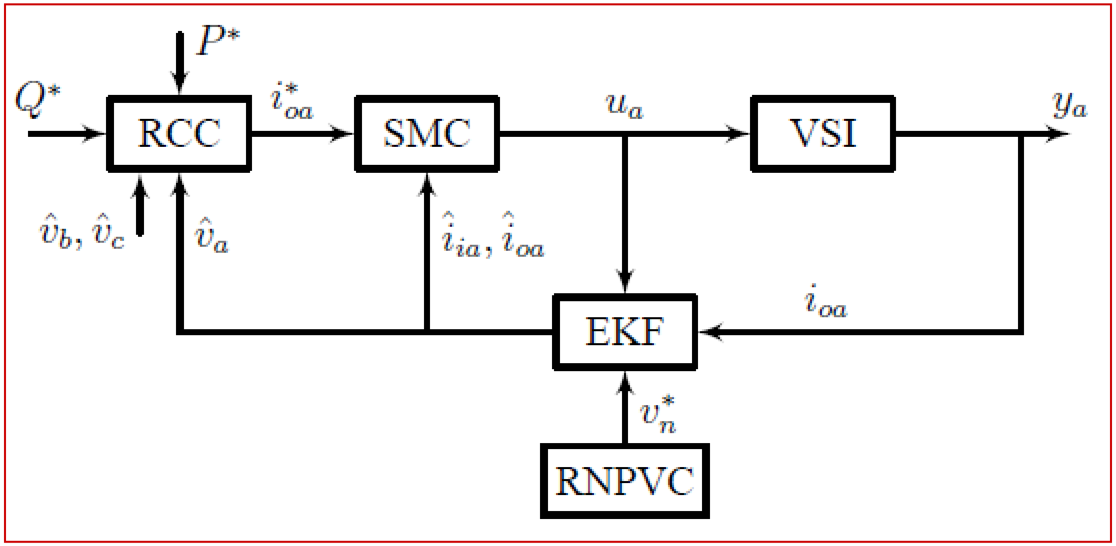
Sliding-Mode Control based on an Extended Kalman Filter for a Three-Phase Inverter with LCL-Filter



Problems in the design of controllers with active damping capability:

1) The computation of time derivative terms in control algorithms provoke noise problems
2) Difficulty on the tuning of the controller parameters
3) Grid inductance variations can provoke instability

Block diagram of the control system for phase-leg a.



RCC: Reference Current Calculator
EKF: Extended Kalman Filter
SMC : Sliding-Mode Controller
VSI: Voltage Source Inverters
RNVPVC: Reference Neutral Point Voltage Calculator

Reference Current Calculator

- Sliding Surfaces are designed in order to impose a desired dynamic behaviour on the system to achieve high current tracking accuracy with a stable dynamics
- The sliding surfaces provide a third order dynamics according to the system order
- The control objective is to achieve that the output current tracks without error the grid-current reference i*o

$$\mathbf{i}_\xi = \hat{\mathbf{i}}_o - \mathbf{i}_o^*$$

Desired grid-current error:

$$\sum_{n=0}^{3} \lambda_n \frac{d^n \mathbf{i}_\xi}{dt^n} = 0$$

Routh-Hurwitz stability criterion

$$\lambda_i > 0$$

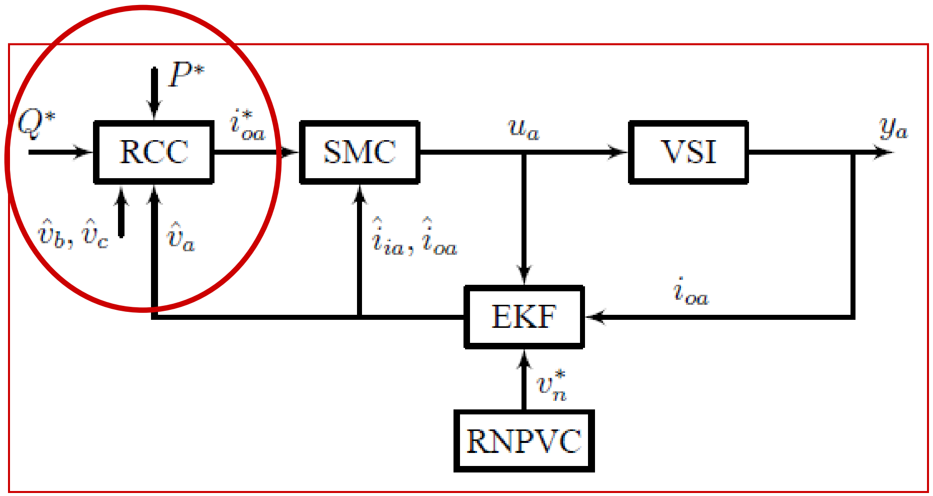
$$\lambda_1 \lambda_2 > \lambda_0 \lambda_3$$

being $i = 0, 1, 2, 3.$

Switching surface:

$$\mathbf{S} = \hat{\mathbf{i}}_i - \hat{\mathbf{i}}_o - C\frac{d\hat{\mathbf{v}}}{dt} - L_o C \frac{d^2 \hat{\mathbf{i}}_o}{dt^2} + \sum_{n=1}^{3} \lambda_n \frac{d^{n-1}\mathbf{i}_\xi}{dt^{n-1}} + \lambda_0 \int \mathbf{i}_\xi dt$$

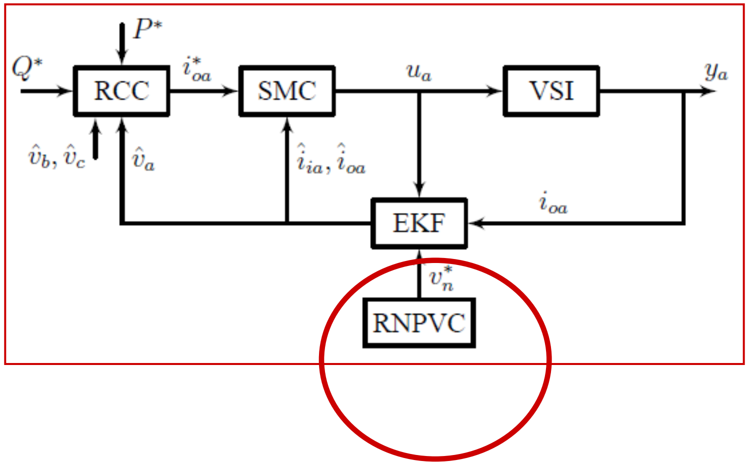
Reference Current Calculator



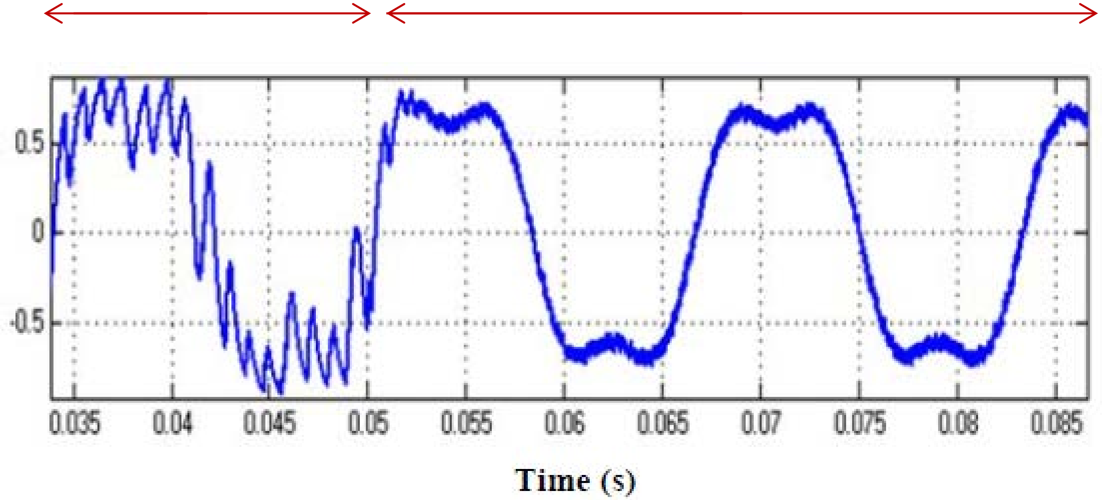
$$\mathbf{i}^*_{oab} = \frac{P^*}{|\hat{\mathbf{v}}|^2}\hat{\mathbf{v}}_{ab} + \frac{Q^*}{\sqrt{3}|\hat{\mathbf{v}}|^2}\begin{pmatrix} \hat{v}_b - \hat{v}_c \\ \hat{v}_c - \hat{v}_a \end{pmatrix}$$

REFERENCE NEUTRAL POINT VOLTAGE CALCULATOR

A sinusoidal third-harmonic voltage is imposed at the neutral point increasing control dynamic range



$$v_n^* = \frac{V_a}{6}[k_p \cos(3\omega_o t) + (1 + k_q)\sin(3\omega_o t)]$$



Equivalent control : $\langle u_a \rangle$

EXPERIMENTAL RESULTS

*Prototype was built using a 4.5-kVA SEMIKRON full-bridge

* TMS320F28M35 floating-point digital signal processor (DSP) as the control platform

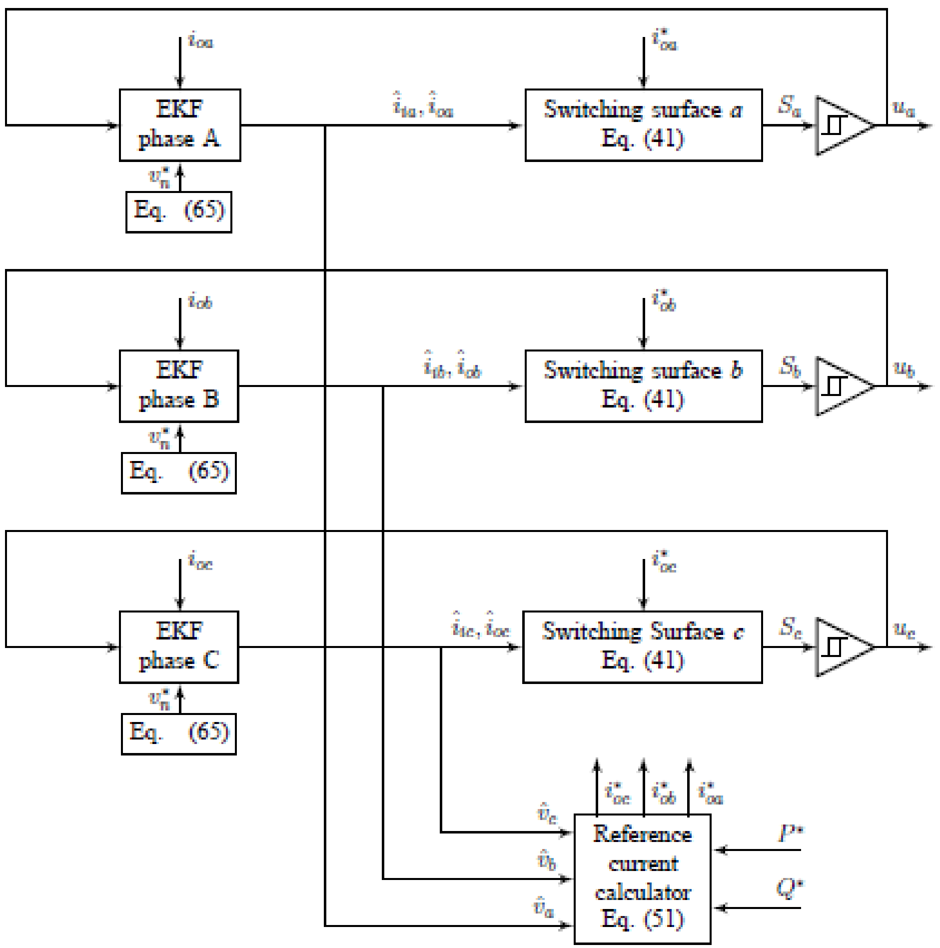
- Sampling frequency: 40 kHz.

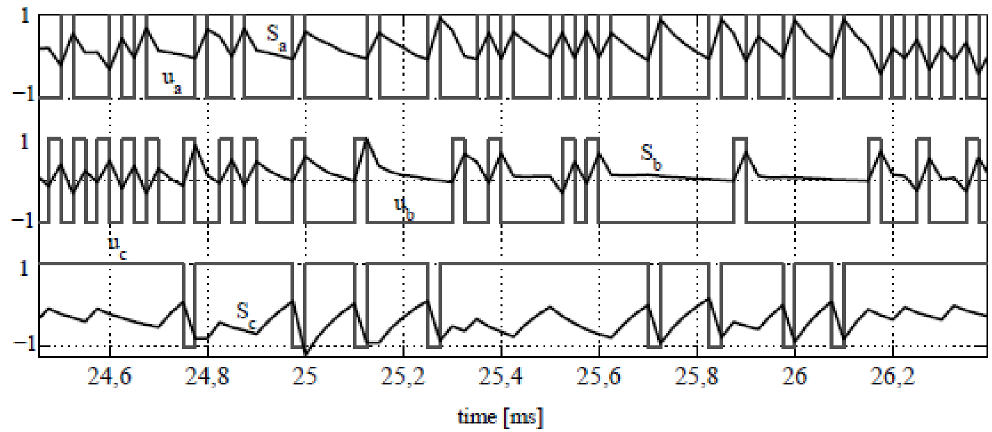
TABLE I: SYSTEM PARAMETERS

Symbol	Description	Value
L_i	Filter input inductance	7 mH
C	Filter Capacitor	6.8 uF
L_o	Filter output inductance	5 mH
L_g	Grid inductance	0.8 mH-5 mH
V_{dc}	DC-link Voltage	450 V
f_s	Sampling frequency	40 kHz
f_{grid}	Grid frequency	60 Hz
V_{grid}	Grid Voltage	110 V
P^*	Active Power	1.5 kW
Q^*	Reactive Power	0 kVAr

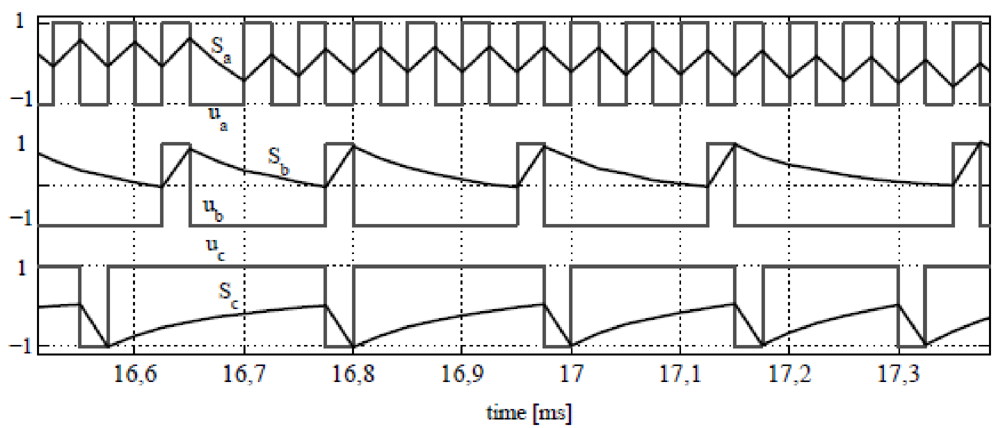
EXPERIMENTAL RESULTS

Proposed control system for three-phase VSI





(a) Coupled controllers.

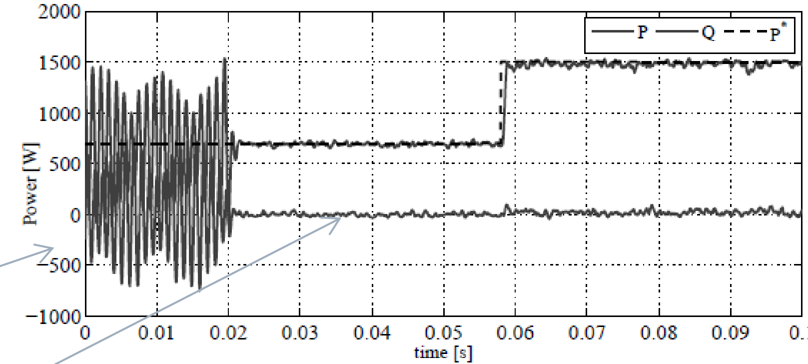


(b) Decoupled controllers.

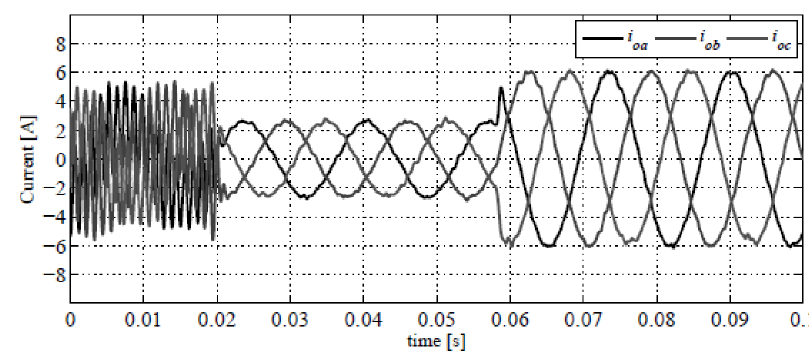
TABLE II
CONTROL SYSTEM PARAMETERS

Dynamics behaviour	λ_3	λ_2	λ_1	λ_0
Oscillation	3.4e-8	0	1	0
Stable	3.4e-8	1.36e-4	1.136	1000

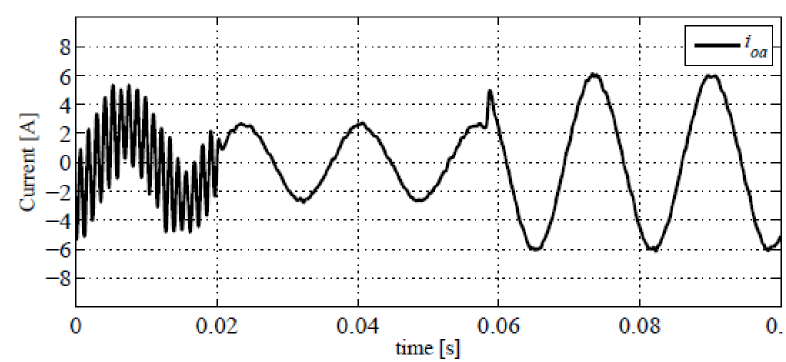
- Stability
- Fast dynamic response



(a) Active power step change

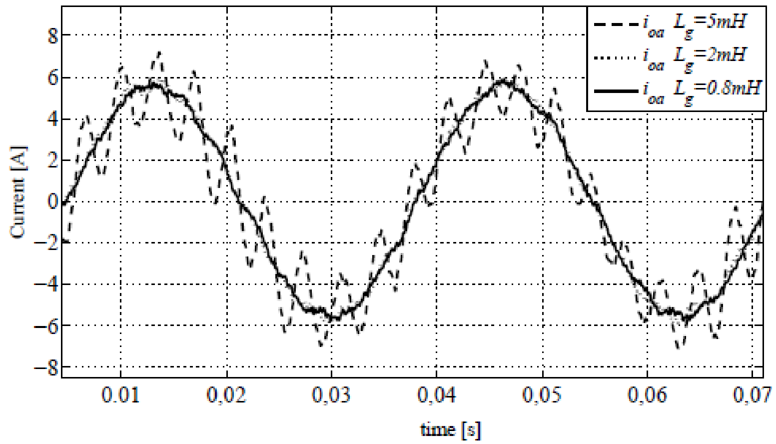


(b) Three-phase output-currents.

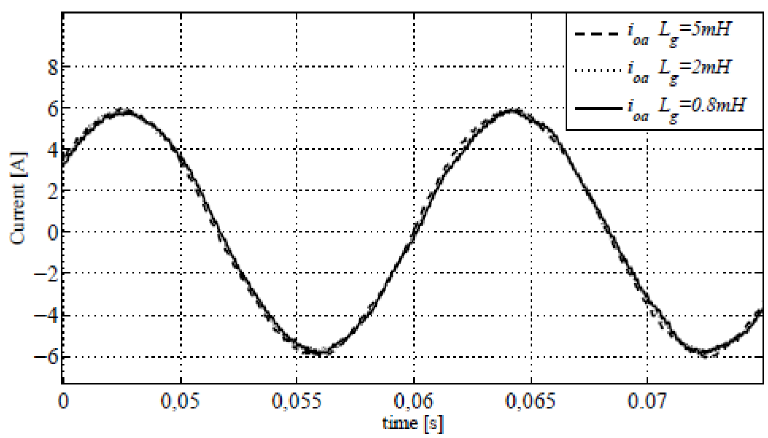


(c) Output-current of phase-leg *a*.

Grid-side current of phase-leg *a* for different grid inductance values



(a) With PCC measured voltages.



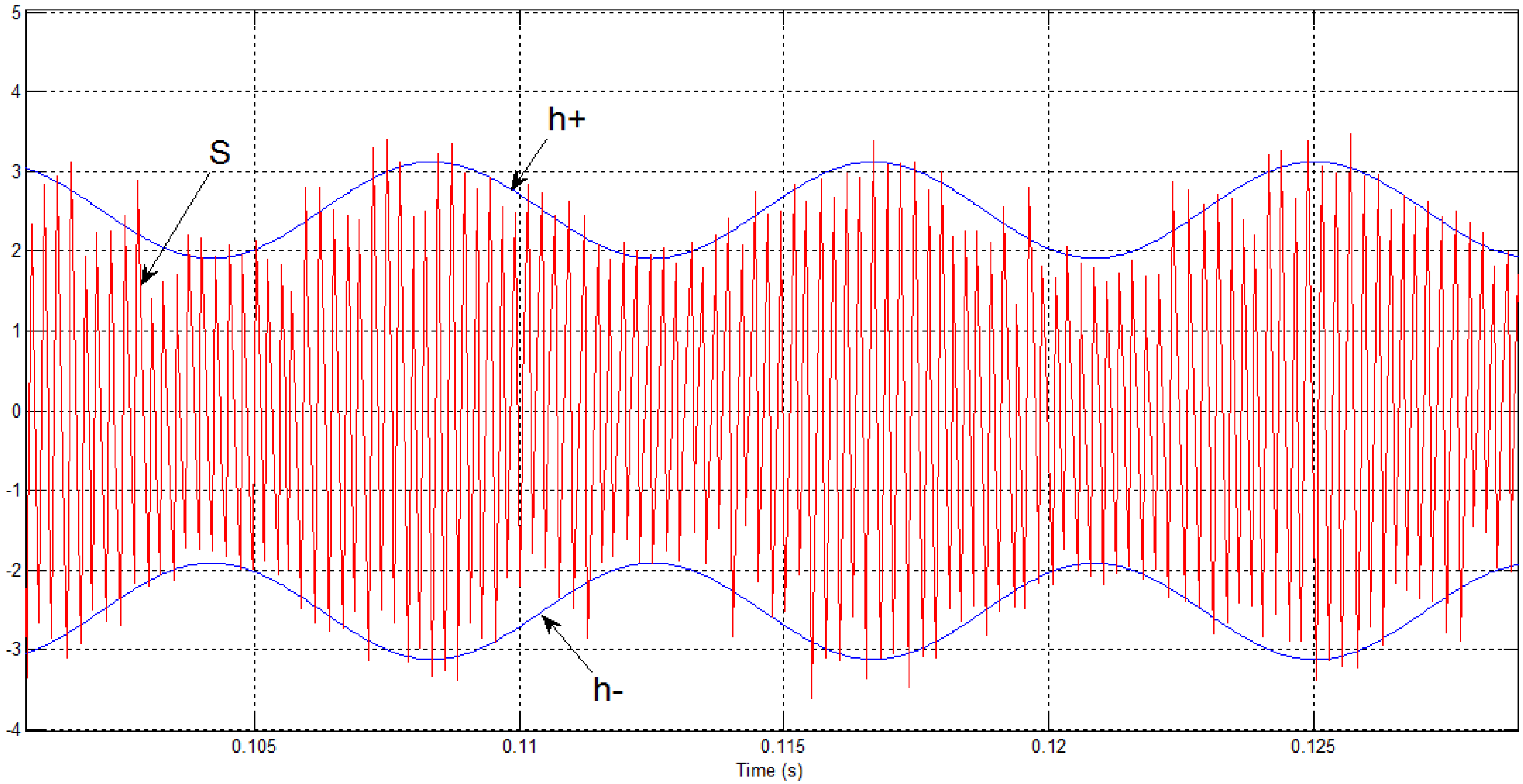
(b) With PCC estimated voltages.

Robustness to variations of the line inductance values

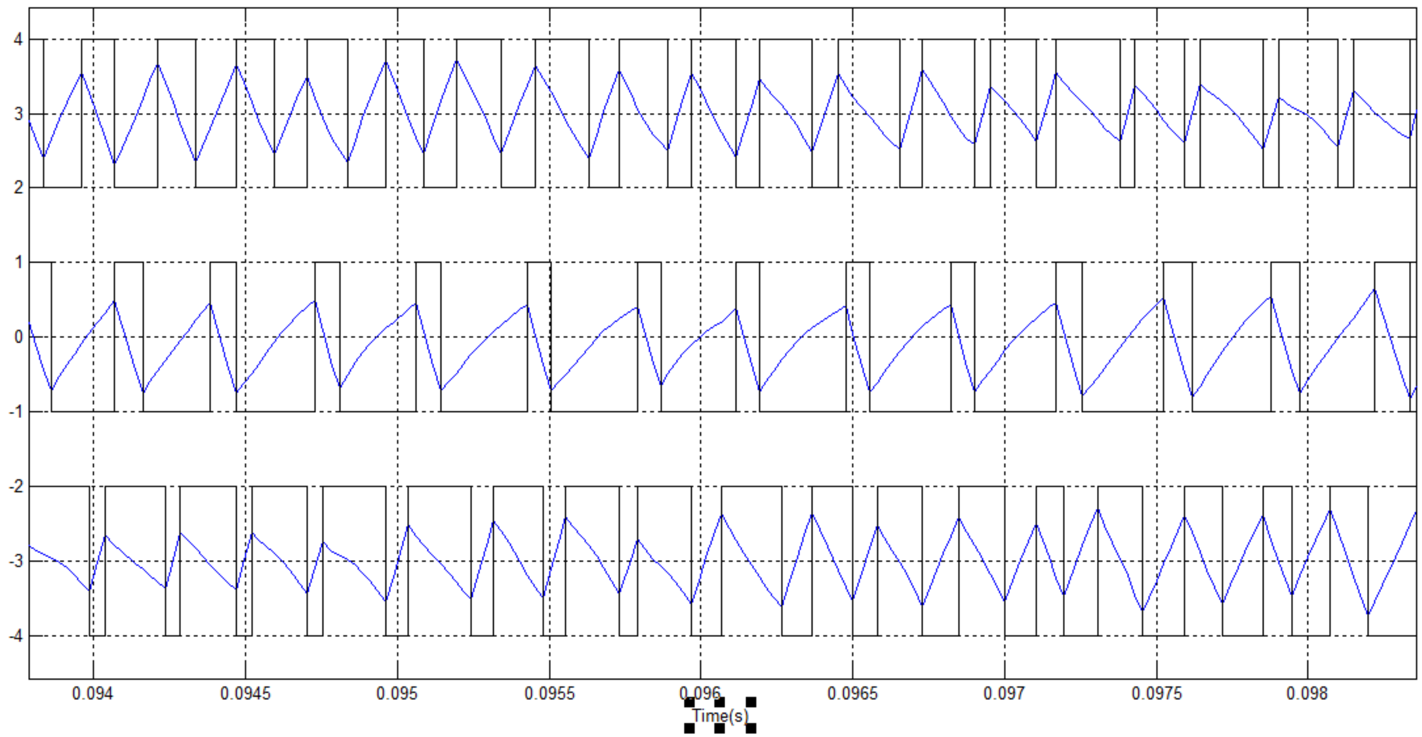
CONCLUSIONS

1) Three-phase system is decoupled and divided into three independent single-phase systems
2) Sliding mode switching surfaces with excellent reference tracking ability
3) Robustness to variations of the line inductance values
4) A third harmonic injection sliding mode controller to increase modulation range
5) The possibility to extend this control methodology to others converters: UPS inverters, unity power rectifiers, active filters…
6) Fix switching frequency

FIX SWITCHING FREQUENCY

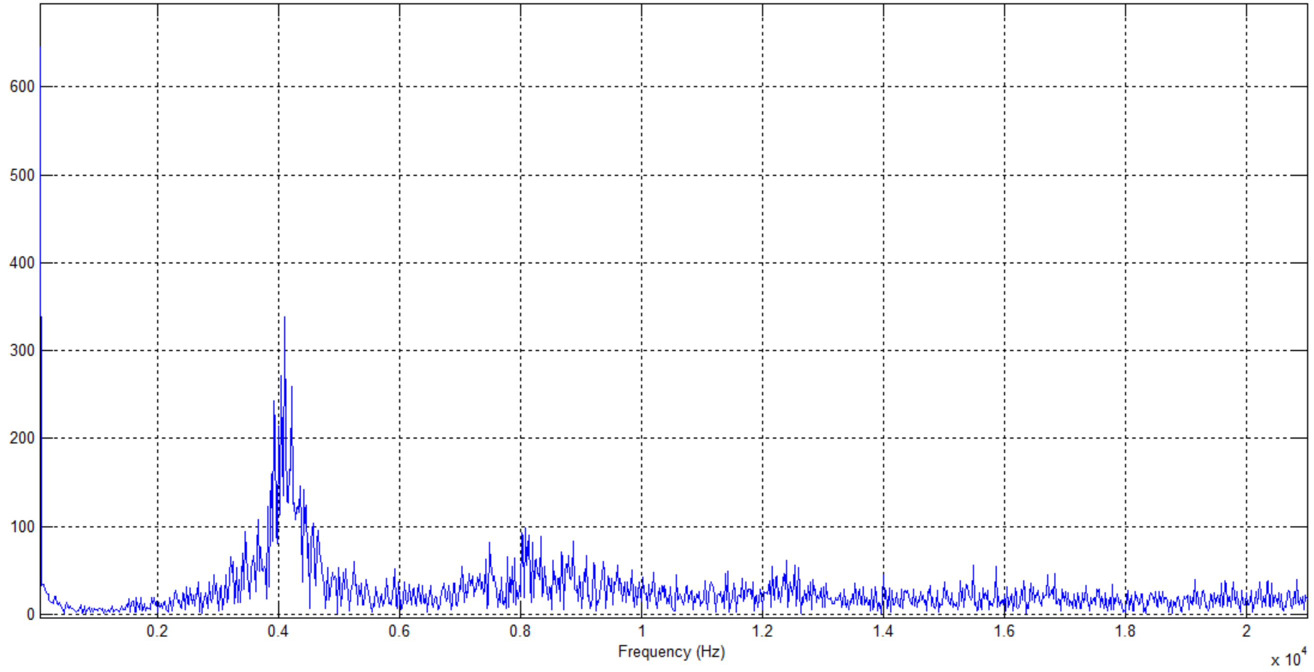


Variable hysteresis band

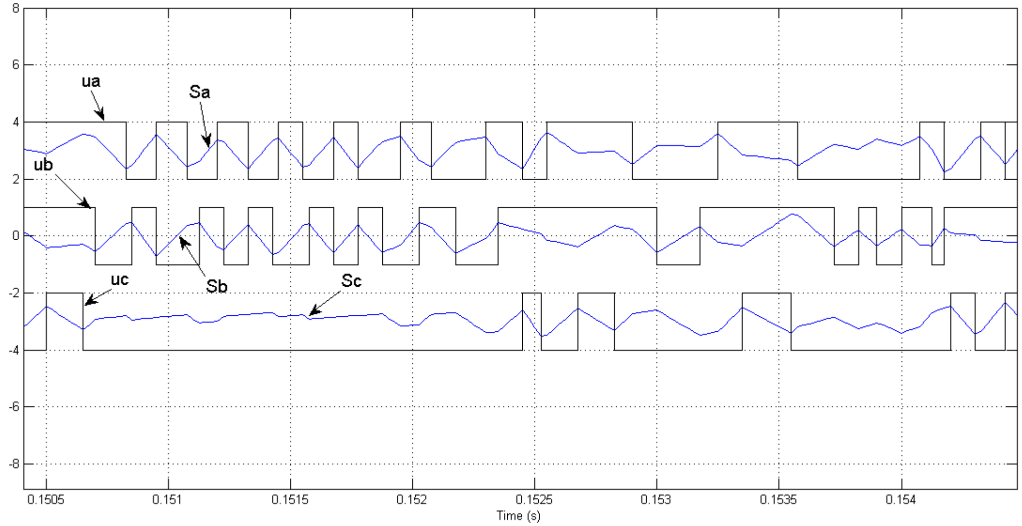


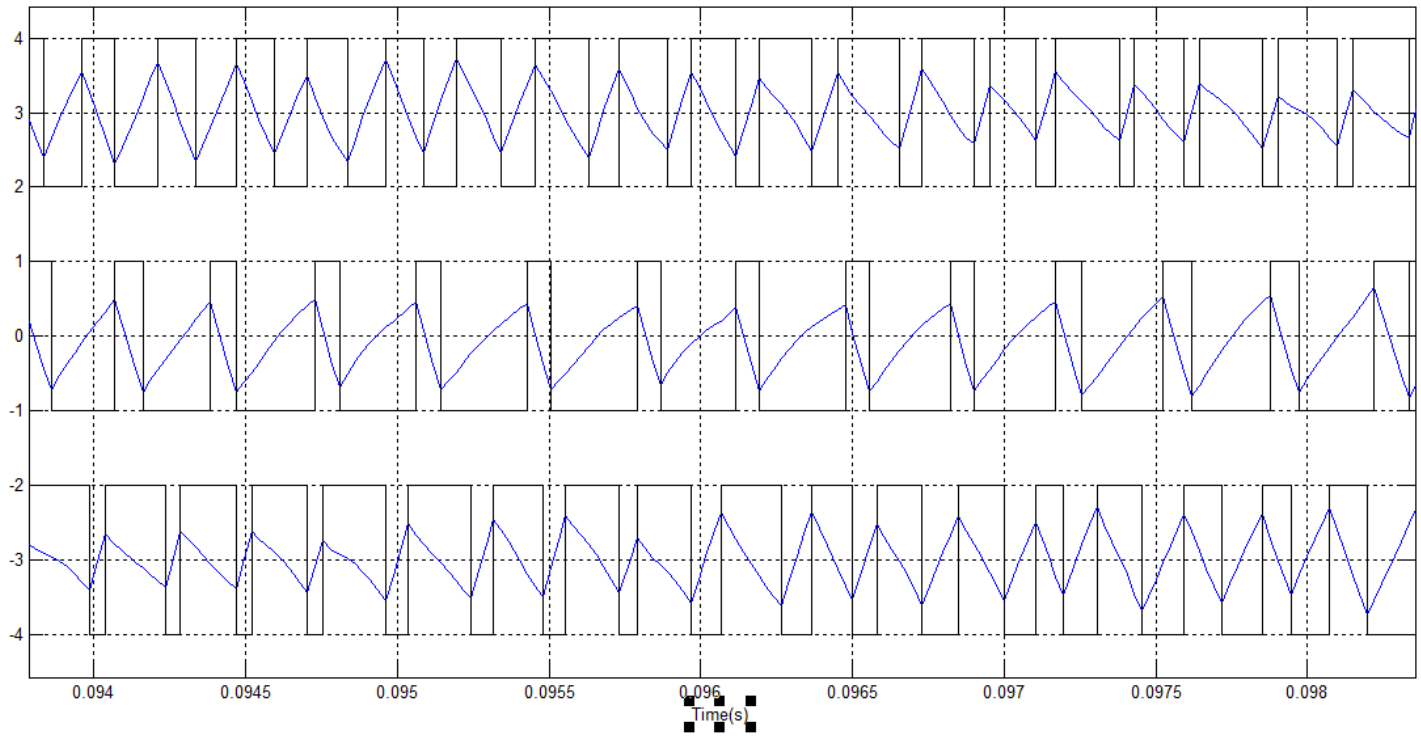
- Three-phase system is decoupled and divided into three independent single-phase systems
- Fix switching frequency

Frequency spectrum



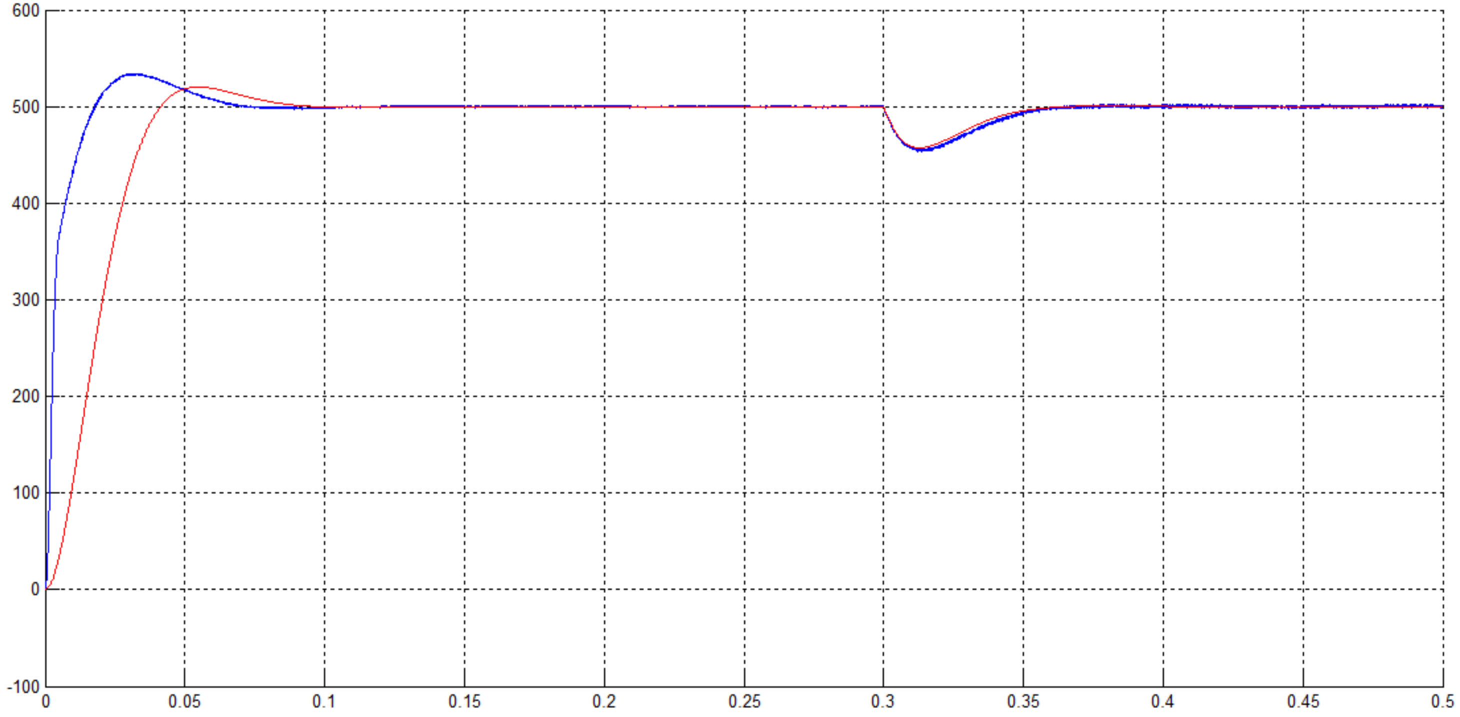
THREE-PHASE UNITY POWER FACTOR RECTIFIER



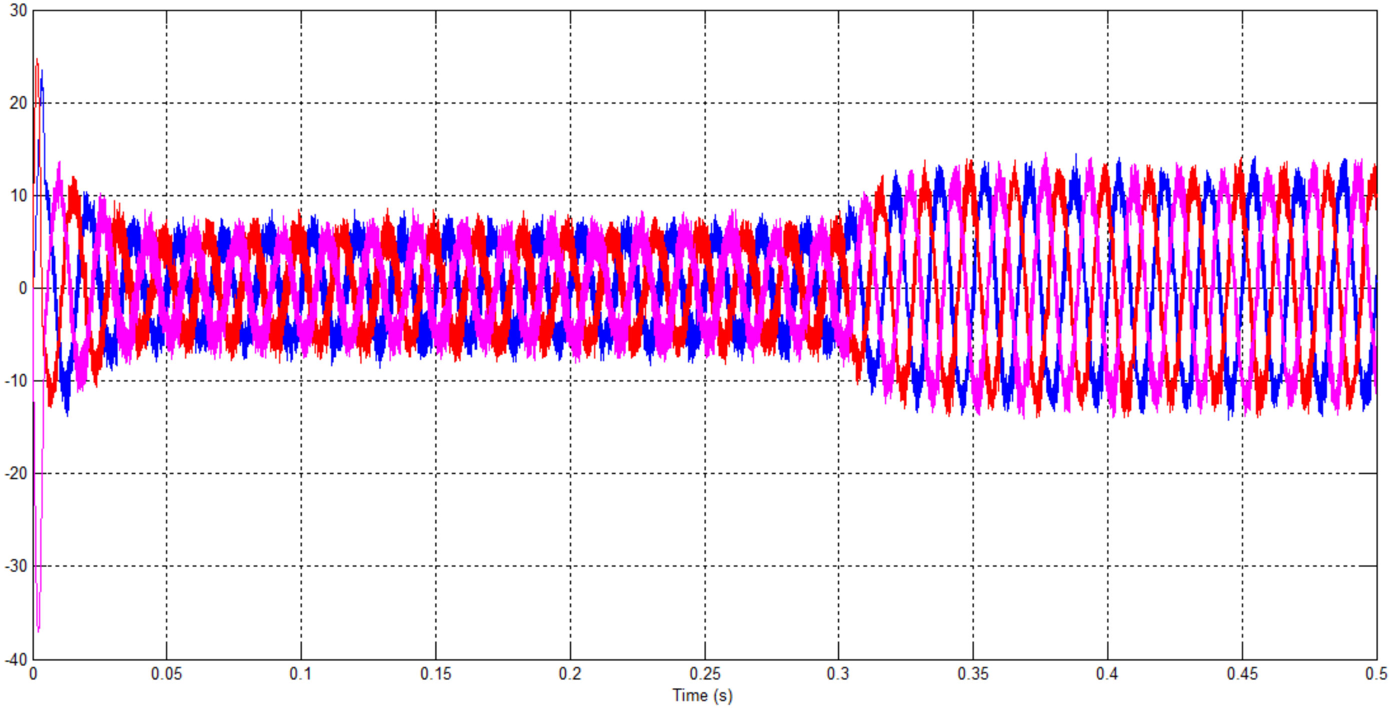


4
3
2
1
0
-1
-2
-3
-4
0.094
0.0945
0.095
0.0955
0.096
0.0965
0.097
0.0975
0.098
Time(s)

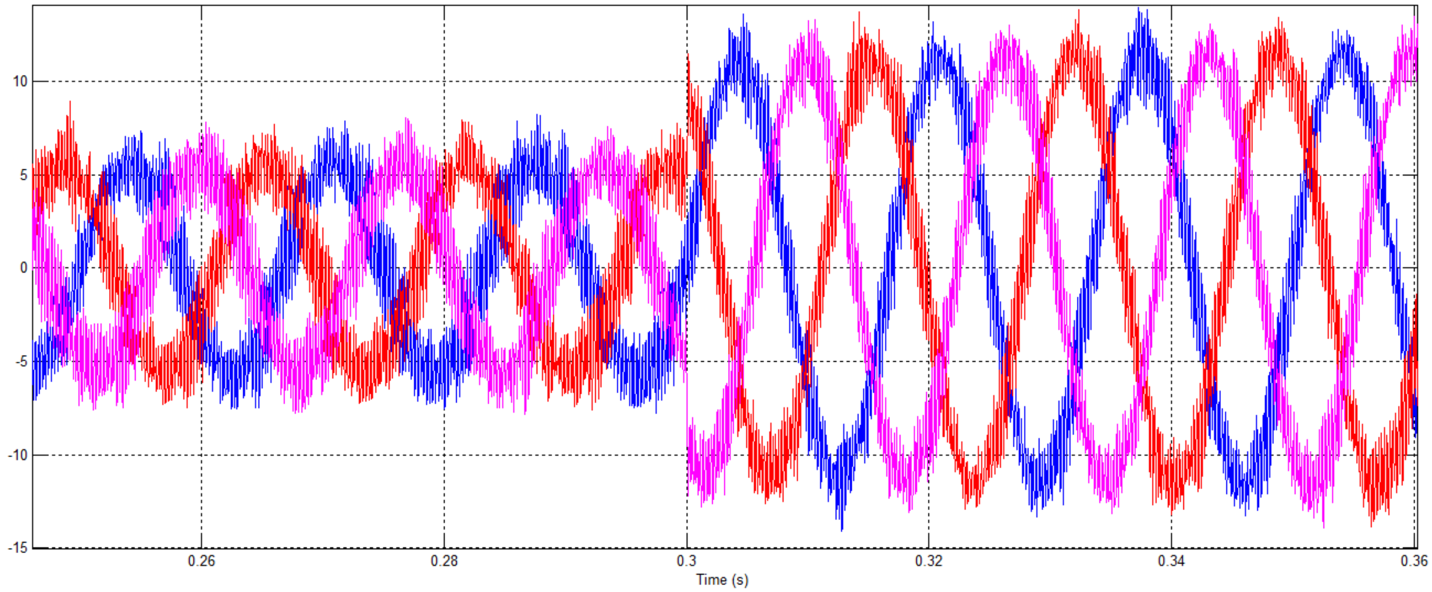
THREE-PHASE UNITY POWER FACTOR RECTIFIER



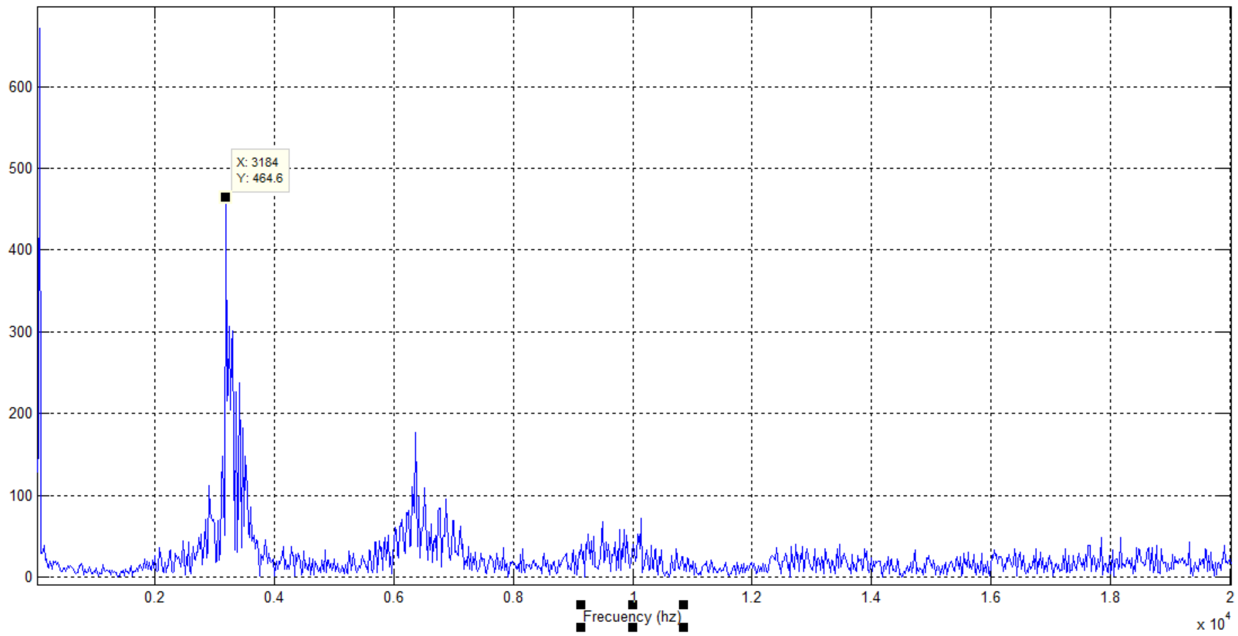
THREE-PHASE UNITY POWER FACTOR RECTIFIER



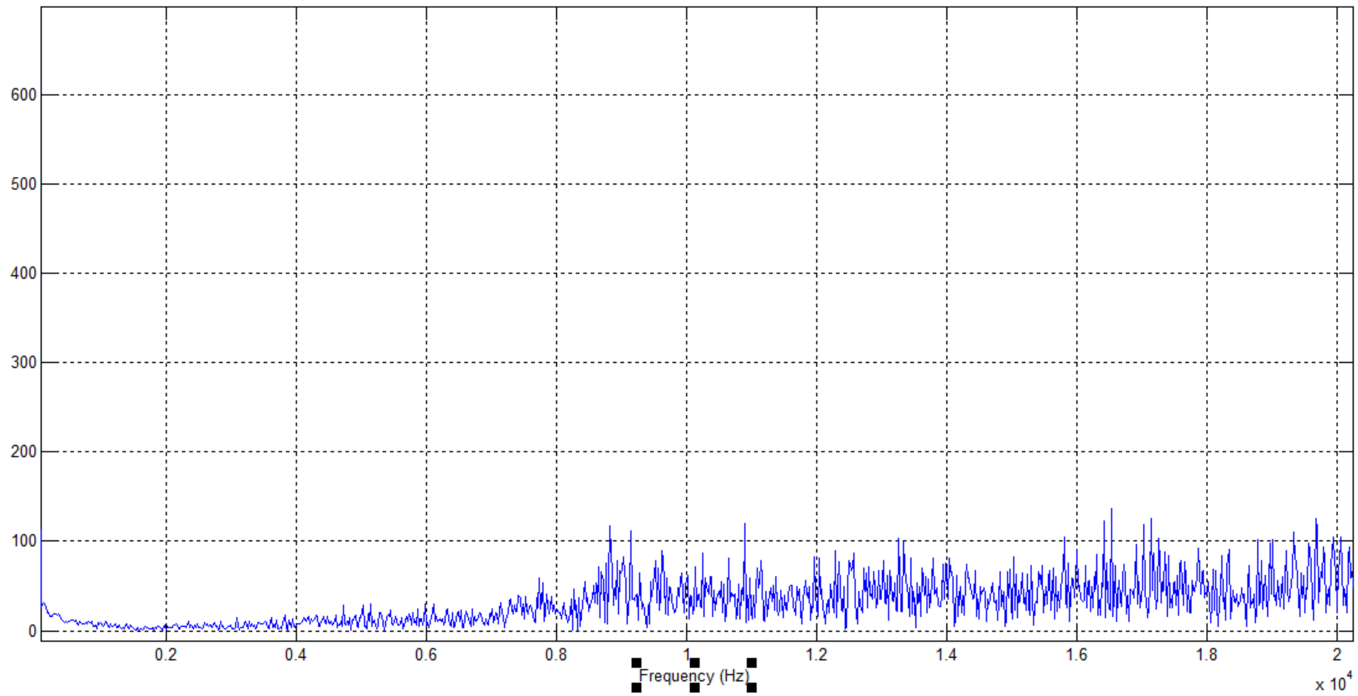
THREE-PHASE UNITY POWER FACTOR RECTIFIER



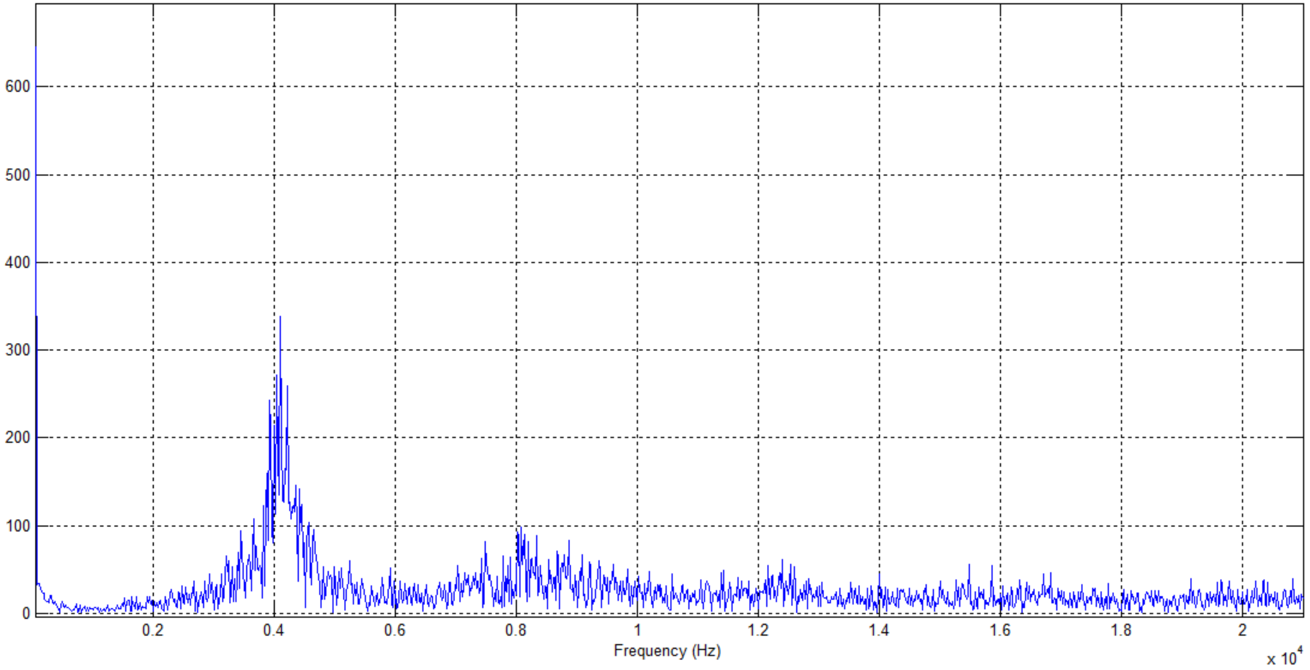
THREE-PHASE UNITY POWER FACTOR RECTIFIER



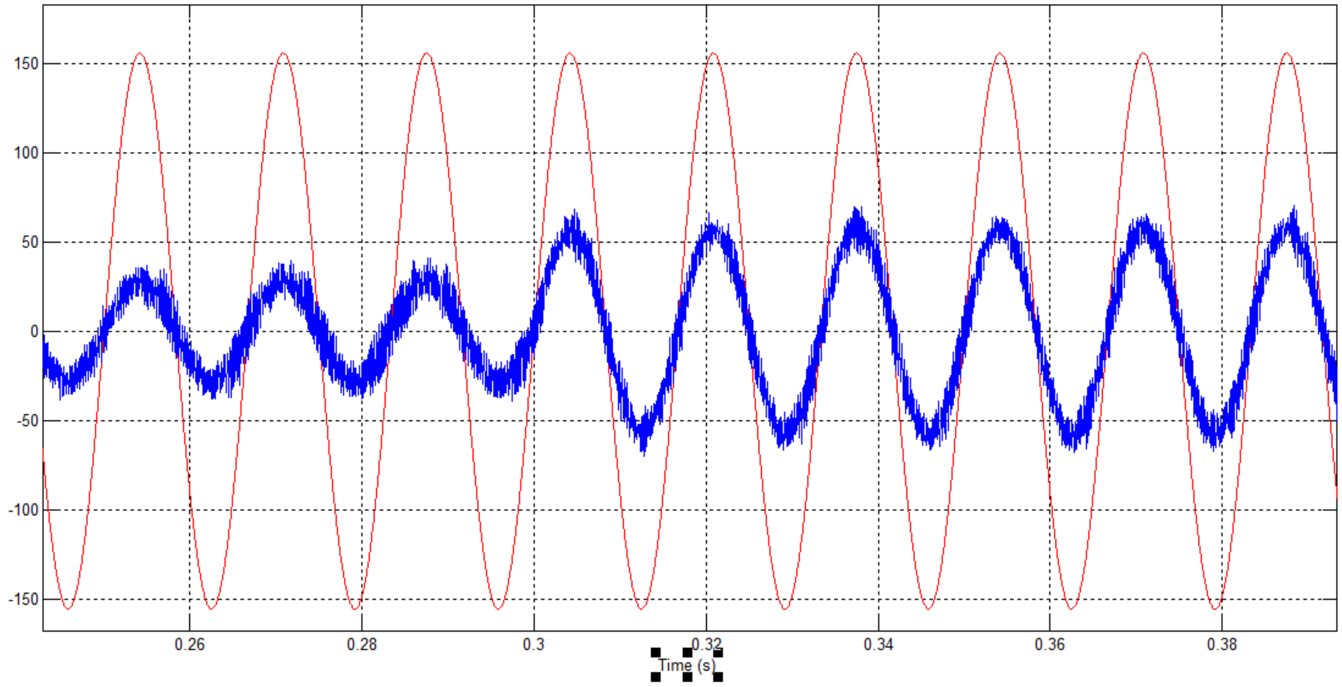
THREE-PHASE UNITY POWER FACTOR RECTIFIER



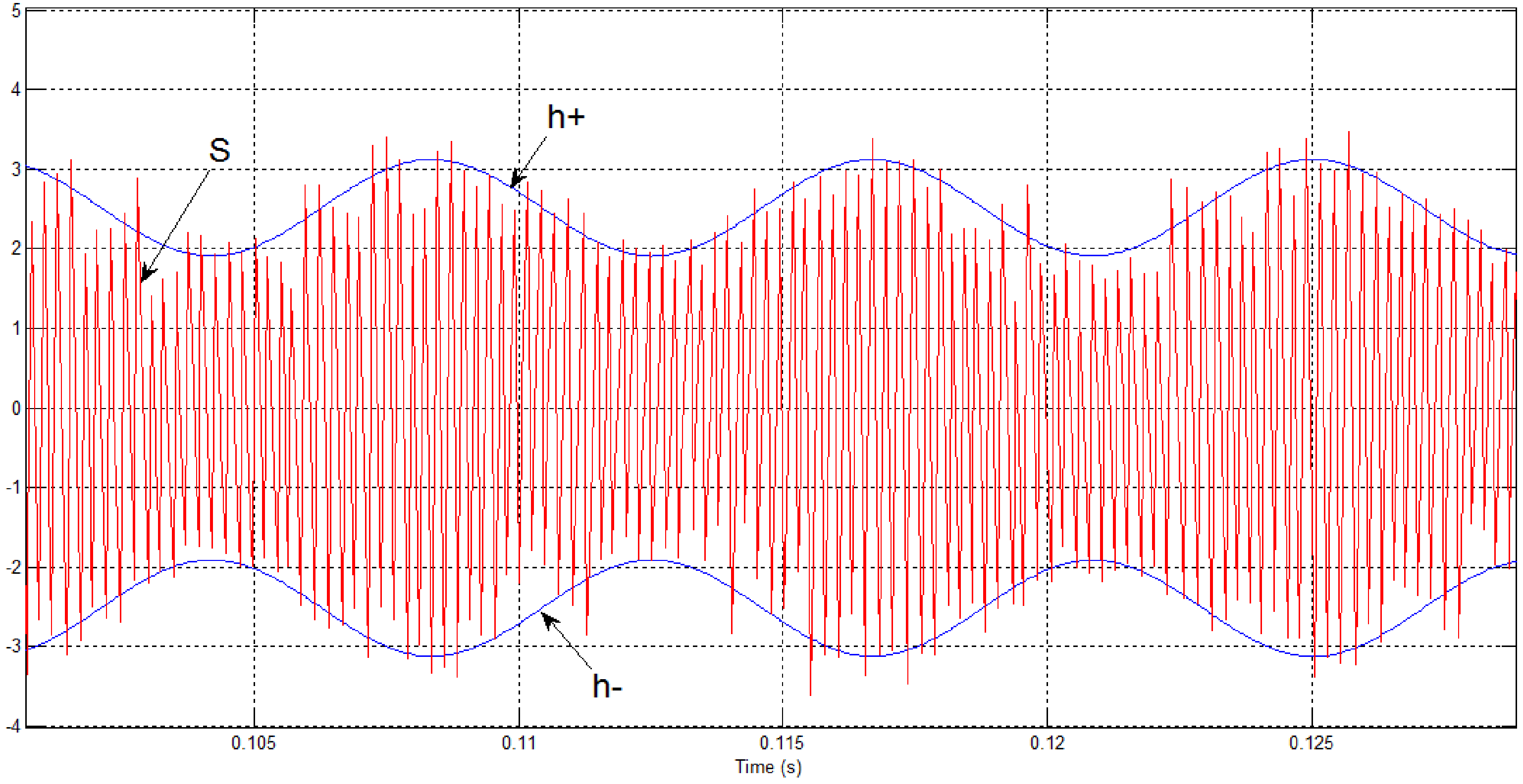
THREE-PHASE UNITY POWER FACTOR RECTIFIER



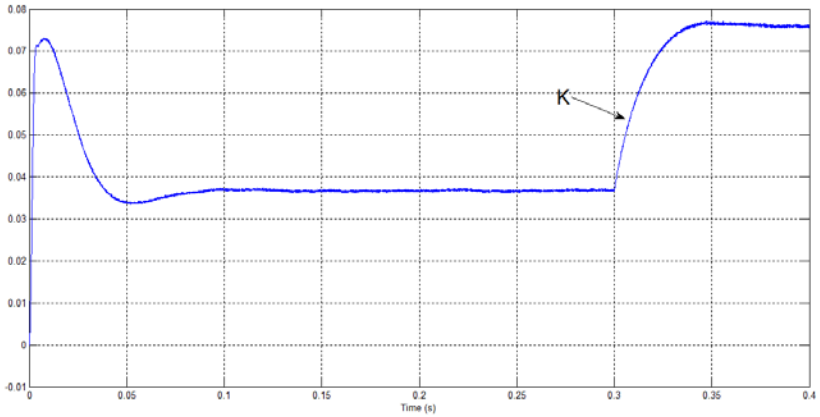
THREE-PHASE UNITY POWER FACTOR RECTIFIER

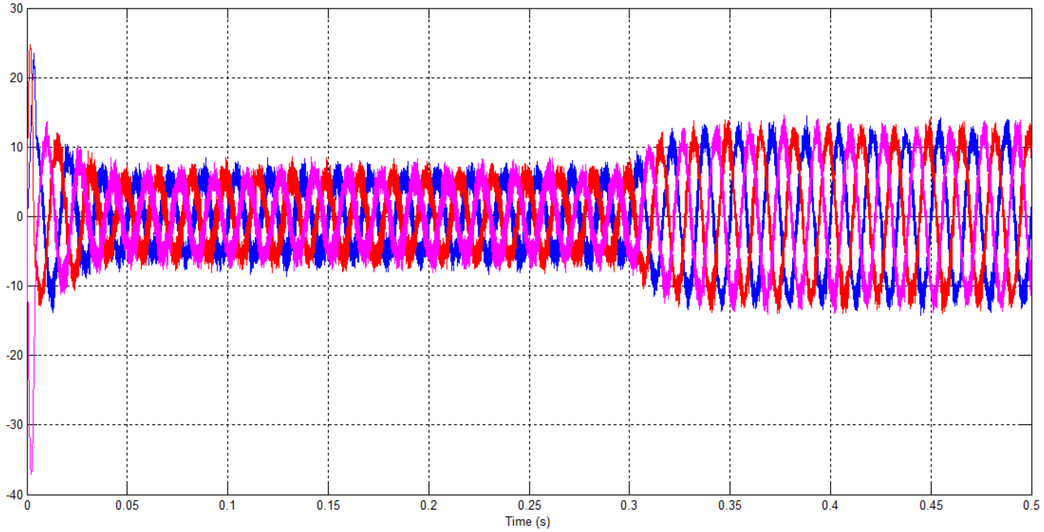


THREE-PHASE UNITY POWER FACTOR RECTIFIER

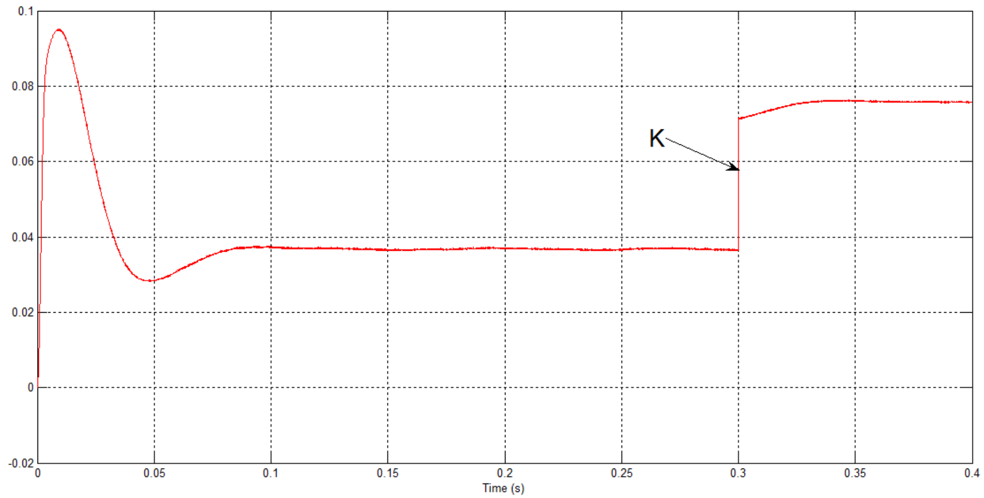


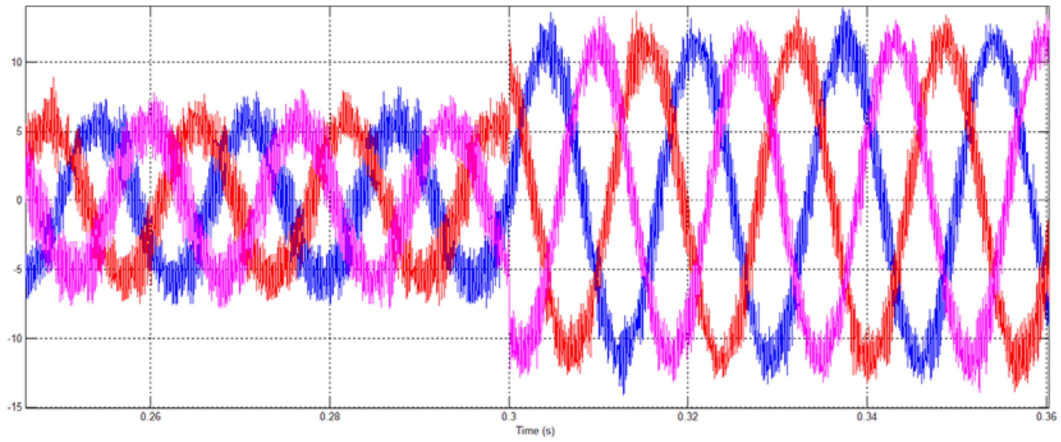
THREE-PHASE UNITY POWER FACTOR RECTIFIER



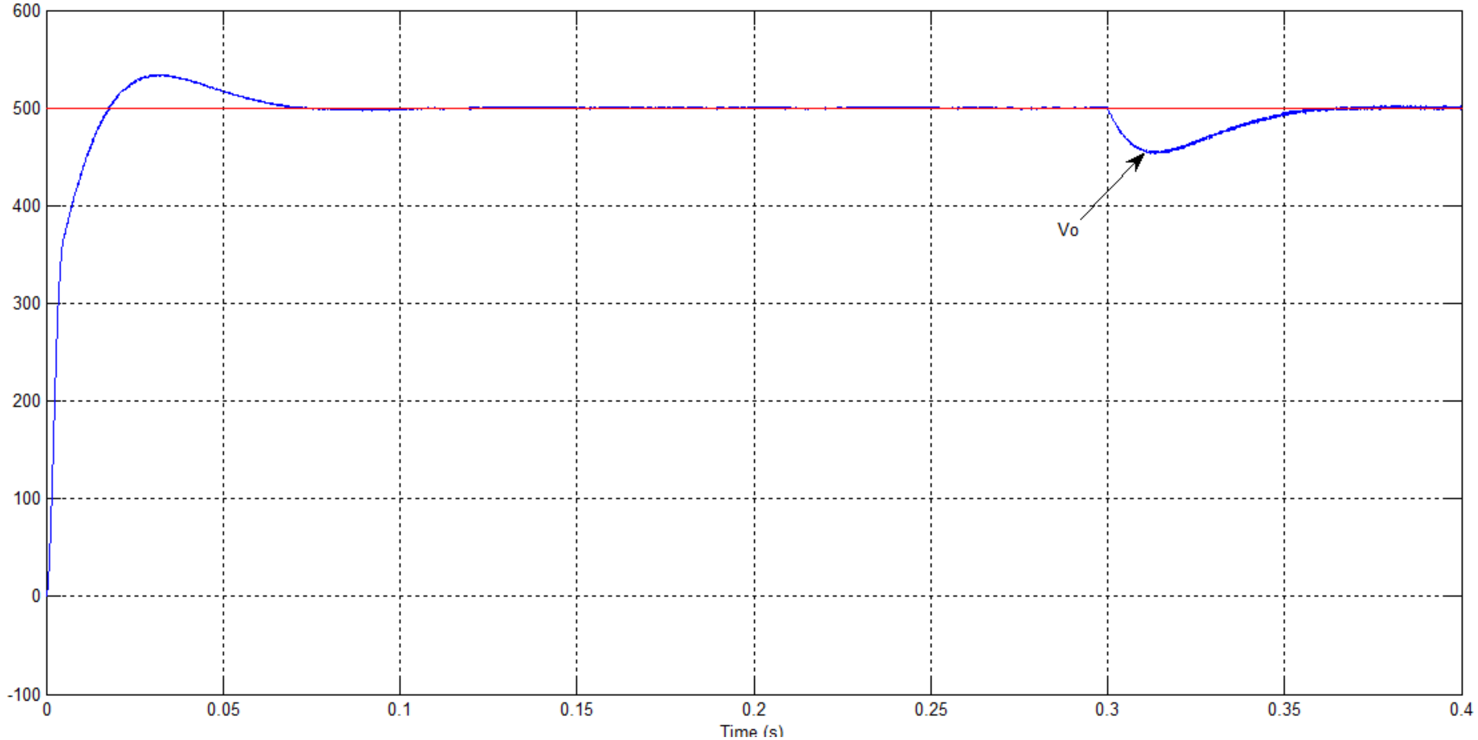


THREE-PHASE UNITY POWER FACTOR RECTIFIER





THREE-PHASE UNITY POWER FACTOR RECTIFIER



THREE-PHASE UNITY POWER FACTOR RECTIFIER