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Modeling and Analysis of Single-phase Boost Converter with Power Factor Correction Control

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Presenter: Li Bao

Outline:

- Introduction
- System modeling
  - Mathematical model
  - Detailed model
  - Average model
- Steady-state analysis
  - System without PFC control
  - System with PFC control
  - Comparison
- Conclusion

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Introduction

- AC/DC converters have been widely used in Electric Vehicles (EV).

- The power factor correction (PFC) control is widely adopted in EV charging, home appliance for power factor correction by making current align with voltage.
  - Fred Lee of Virginia Tech designed PFC [1].

- Objective: Conduct harmonic analysis for an AC/DC circuit with PFC.

[1] C. Zhou, R. B. Ridley, and F. C. Lee, "Design and analysis of a hysteretic boost power factor correction circuit," in *21st Annual IEEE Conference on Power Electronics Specialists*. IEEE, 1990, pp. 800–807.

PFC circuit and control

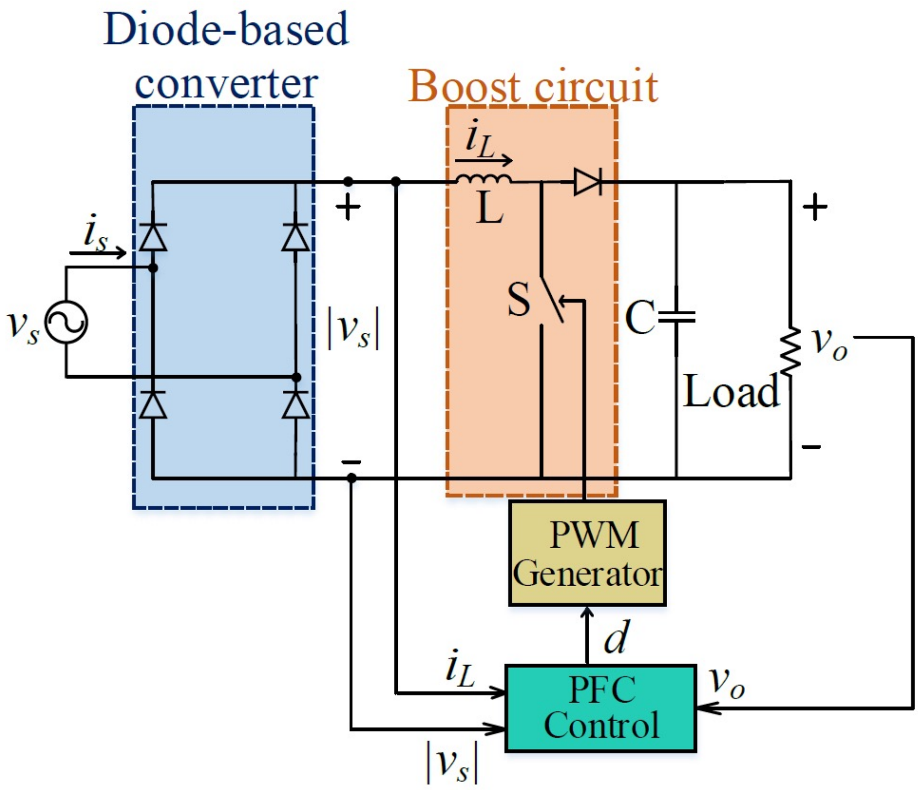

Figure 1. Single-phase converter with boost circuit.

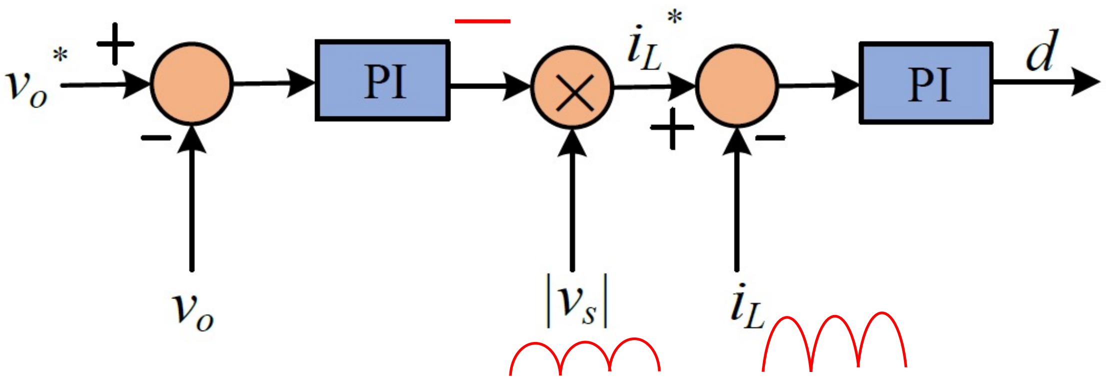

Figure 2. PFC control block.

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Detailed model

The detailed model is built in SimPowerSystems, and the solver for this model is ode4/Runge-Kutta.

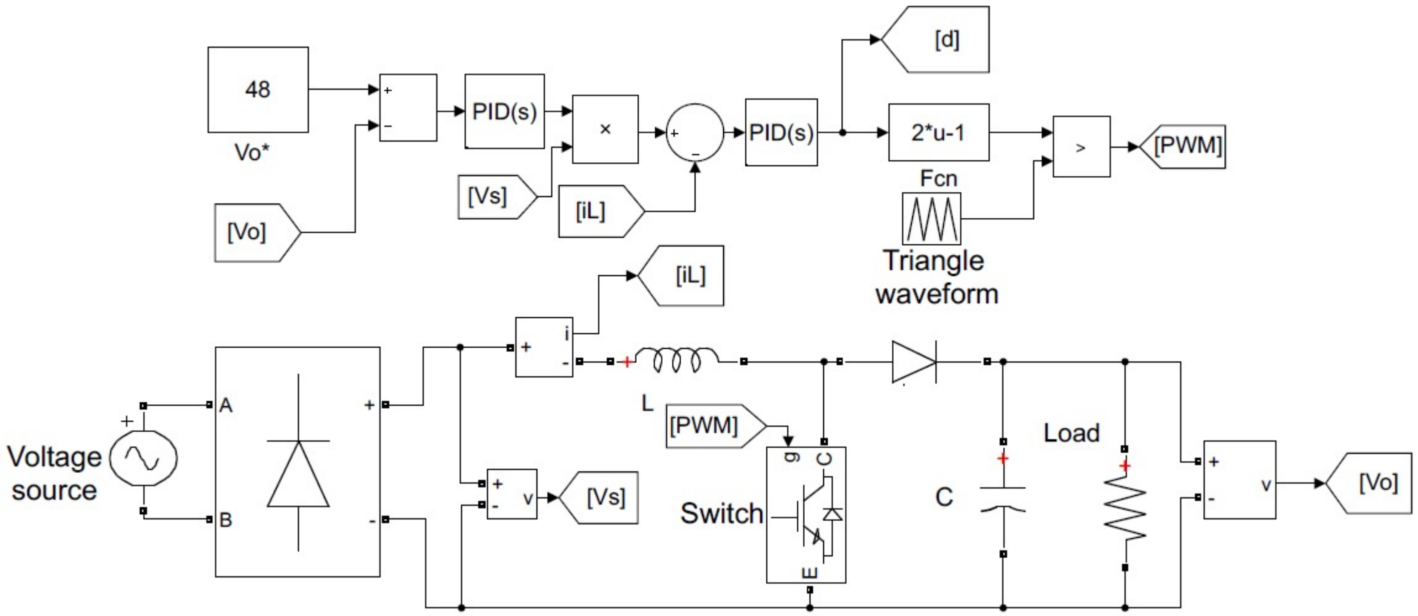

Figure 3. Detailed model

Average model

- The idea of average model is to replace switches by equivalent circuit based on the relationship of circuit's variables.

- Since the switching is replaced, there is no switching loss, and the input power is identical to output power.

- If the boost circuit is treated as a current source, the current value can be calculated as:

$$
\begin{aligned}
P &= v_{\text{in}} i_{\text{in}} = v_{\text{out}} i_{\text{out}} \\
\Rightarrow i_{\text{out}} &= \frac{v_{\text{in}} i_{\text{in}}}{v_{\text{out}}}.
\end{aligned}
$$

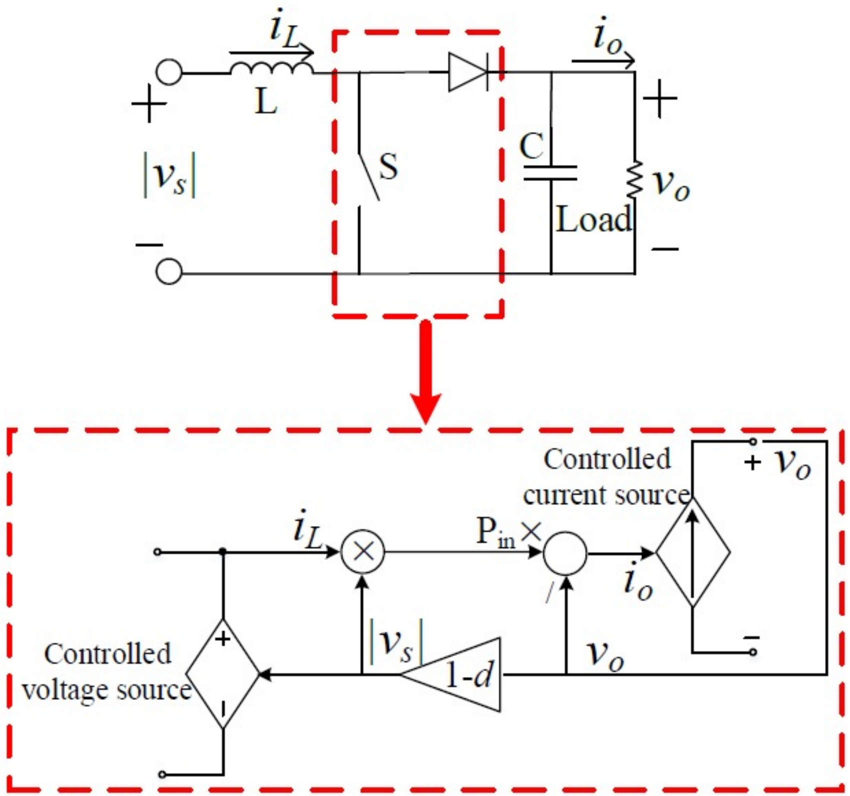

Figure 4. Average model

Mathematical model

- Mathematical model simulates the circuit by using the differential and algebraic equations of circuit variables.

- Assuming switches are ideal and a large capacitor C ensures the output voltage be a constant, then:

$$L\frac{di_L}{dt} = v_{in} - (1-d)v_o$$
$$C\frac{dv_o}{dt} = (1-d)i_L - \frac{v_o}{R}.$$

where i_L and v_o are state variables x_1 and x_2, respectively.

So $\dot{x} = [\frac{di_L}{dt}; \frac{dv_o}{dt}]$, input *u* is duty ratio *d*.

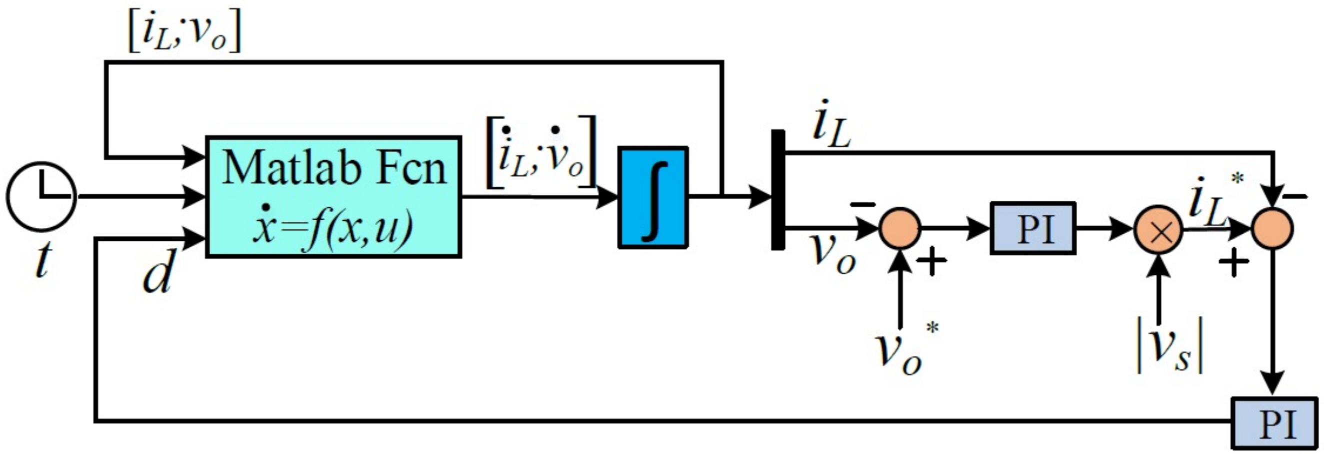

Figure 5. Mathematical model.

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Input voltage

In single-phase converter, the rectified voltage can be presented as:

$$|v_s(t)| = \hat{V}_s |\sin(\omega t)|$$

The Fourier series of the $|V_s(t)|$ is calculated as:

$$|v_s(t)| = \frac{2}{\pi}\hat{V}_s - \frac{\hat{V}_s}{\pi}\frac{4}{n^2-1}\cos(n\omega t) \quad n = 2, 4, 6, ...$$

If we only consider the fundamental (dc value) and second harmonic component:

$$\begin{aligned} |v_s(t)| &= \underbrace{\hat{V}_s \times \frac{2}{\pi}}_{V_{\mathrm{DC}}} - \underbrace{\hat{V}_s \times \frac{4}{3\pi}}_{\hat{V}_2} \cos 2\omega t \\ &= 21.61 - 14.4\cos(2\omega t). \end{aligned}$$

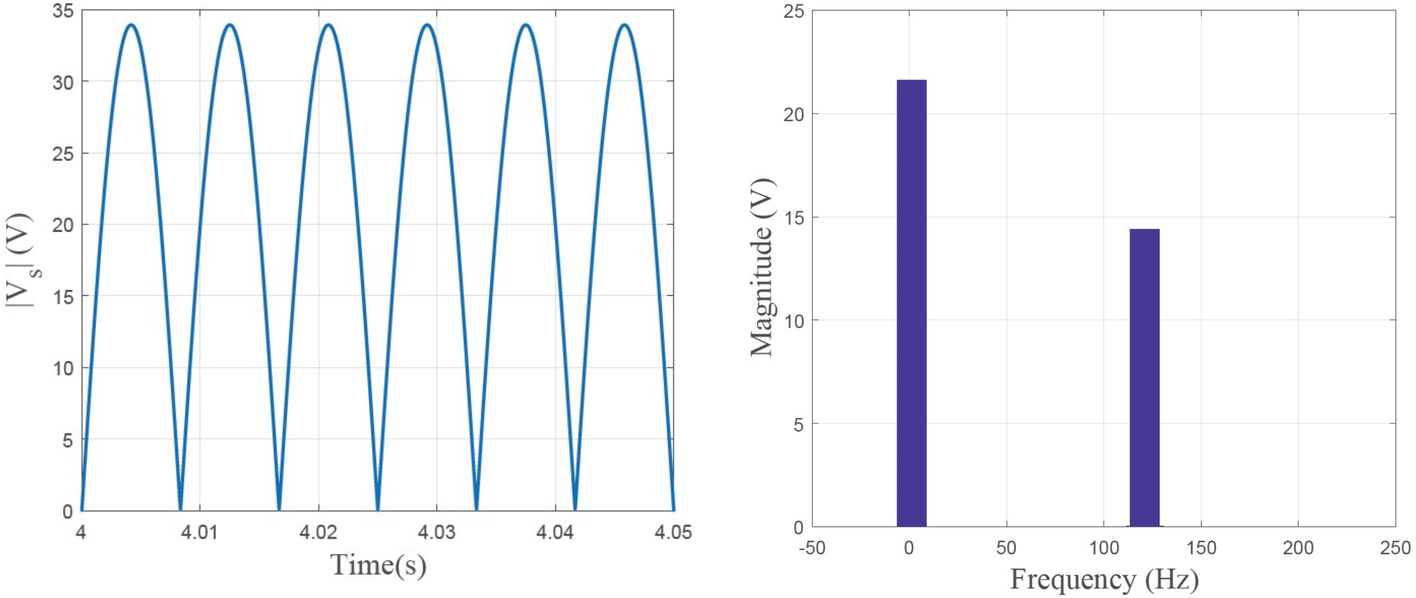

Figure 6. $|V_s|$ and its FFT analysis.

System with PFC

- The input voltage and current are regulated to be in same phase
- Both of them are composed of a dc and a second harmonic component
- The total power of the circuit transferred is their sum.

$$P_{\mathrm{DC}} = \frac{4}{\pi^2}\hat{V}_s\hat{I}_L$$
$$P_2 = \frac{1}{2}\left(\frac{4}{3\pi}\right)^2\hat{V}_s\hat{I}_L$$
$$P = P_{\mathrm{DC}} + P_2.$$

- The power from dc component is accounted as 81.43% of the total power, so the rest of 18.57% is generated from the second harmonic component.

$$I_{\mathrm{DC}} = \frac{81.43\% \times P}{\frac{2}{\pi}\hat{V}_s} = \frac{81.43\% \times 329.15}{\frac{2}{\pi} \times 24\sqrt{2}} = 12.4\,A.$$

- And the current in second harmonic component is:

$$\hat{I}_2 = \frac{\pi}{2} \times I_{\mathrm{DC}} \times \frac{4}{3\pi} = 8.27\,A$$

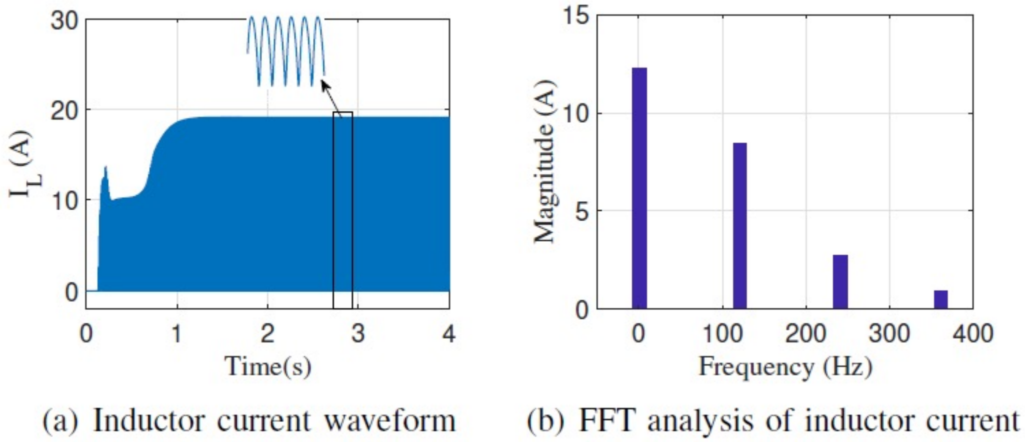

Figure 9. Inductor waveform with PFC control and its FFT analysis.

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$$
\begin{aligned}
V_{s1} &= V_{DC} \\
\bar{V}_{s2} &= V_2 - j2\omega L I_2 \\
&= \frac{1}{\sqrt{2}}\sqrt{\hat{V}_2^2 + (2\omega L\hat{I}_2)^2}\angle\theta
\end{aligned}
$$

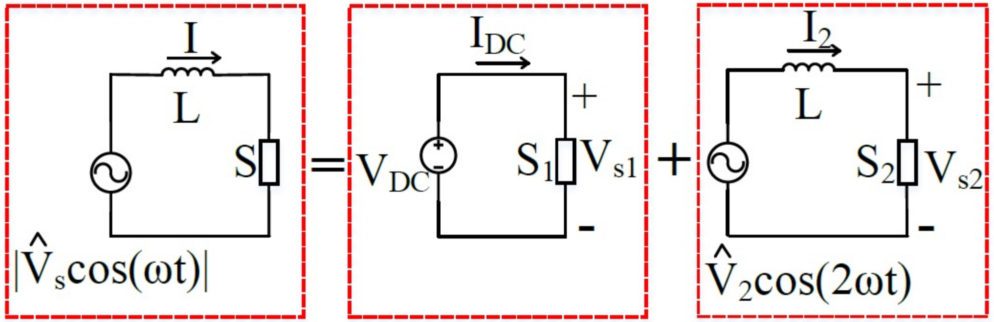

Figure. 10 The boost equivalent circuit.

$$
1 - d = \frac{V_{s1} + \bar{V}_{s2}}{V_o}
$$

$$
\Longrightarrow d = (1 - \frac{V_{DC}}{V_o}) - \frac{\sqrt{\hat{V}_2^2 + (2\omega L\hat{I}_2)^2}}{V_o}\cos(2\omega t - \theta)
$$

$$
= 0.55 - 0.33\cos(2\omega t - 23.4^o).
$$

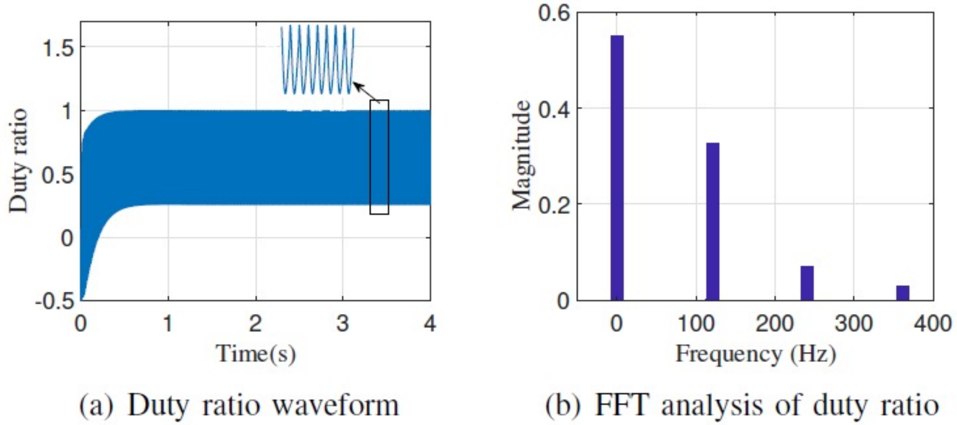

Figure 11. Duty ratio waveform with PFC control and its FFT analysis.

Comparison

- This figure compares the input voltage and current waveform with and without PFC control.
- The voltage and current almost are in synchronization under the PFC control, which ensures unity power factor and high efficiency.
- The current is discontinuous and has a phase shift with voltage if there is no the PFC control.

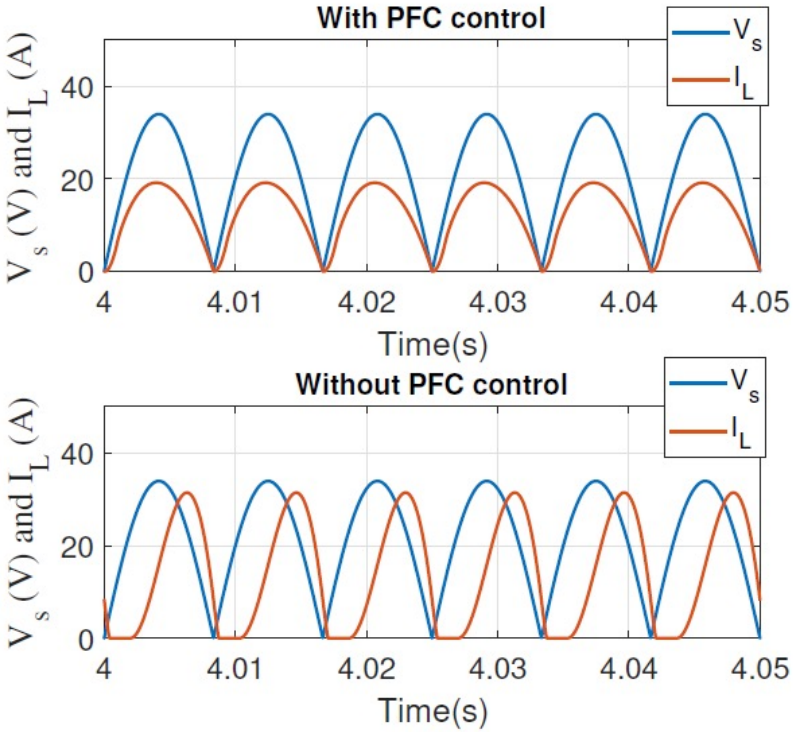

Figure 12. Inductor current and rectified voltage with and without PFC.

Comparison

The three models are compared for the inductor current, duty ratio and simulation time.

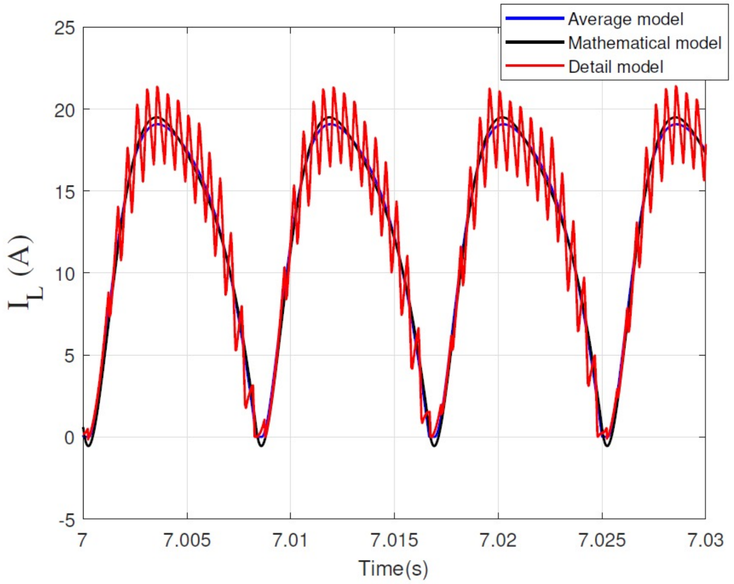

Figure 13. The comparison of inductor current I_L.

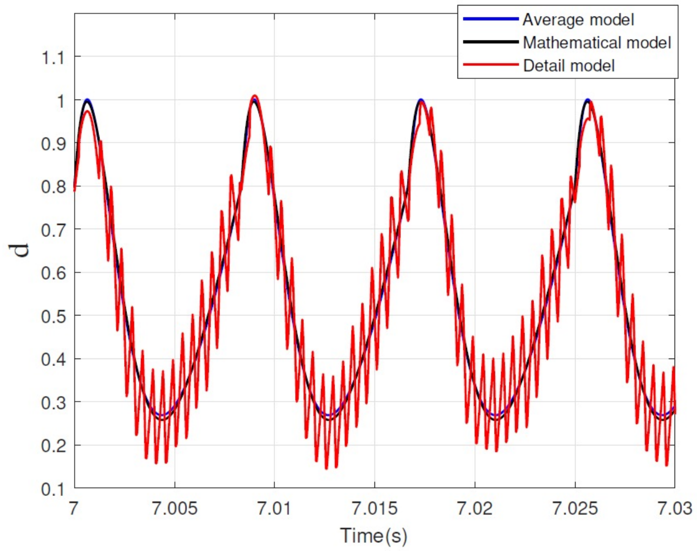

Figure 14. The comparison of duty ratio *d.*

TABLE I: Comparison of execution time

Time to be simulated	Average model	Detail model	Mathematical model
2 sec	21 sec	17 sec	7 sec
8 sec	1 min 2 sec	57 sec	21 sec
30 sec	5 min 33 sec	4 min 22 sec	1 min 23 sec

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Conclusion

- Results show that the power factor of the system with PFC control is greatly improved.
- Harmonic analysis is also implemented for line current and duty ratio of the boost circuit and is validated by simulation results.
- Mathematical model is the most efficient.
- Average has the lowest simulation speed.
- Detailed model shows the highest harmonics.

Thank you!