Performance improvement of three-phase boost rectifier using PI fuzzy controller

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Abstract: In this paper are presented the analysis of three-phase boost rectifier converters in close loop using PI classical controller and PI fuzzy controller. A multi-loop controller for the three-phase boost rectifier consists of an outer loop to regulate the output voltage and two inner current loops one each for the d and q axis input currents. The current loops control the decoupled channels of the power stage independently by adjusting their duty cycles. The both use controllers of type P. To have the currents in phase with the input voltages the reference signal for the q channel must be set to zero. The references for the d channel are provided by the voltage loop controller.

Key-Words: three-phase boost rectifier, multi loop controller, P controller, PI controller, PI fuzzy controller

1 Introduction

The boost rectifier front-end three-phase-to-dc power conversion from the synchronous generator to the dc distribution bus. The rectifier operates with unity power factor and draws sinusoidal currents from the three-phase source. When the output current reverses its direction, the boost rectifier reverses the power flow through it and operates as a voltage source inverter. In figure 1 is presented power stage topology of the three-phase boost rectifier [1].

The three-phase boost rectifier are usually represented by average models in rotating dq coordinates, synchronized with the input line voltages. The detailed derivation of the dq average models for the three-phase boost rectifier is presented in [1].

![Fig. 1 Power stage topology of the three-phase boost rectifier](image)
2 Close loop model of the three-phase boost rectifier in dq coordinates

2.1 PI classical controller

The small-signal of boost rectifier presented in [2] is utilized for design loop control. The control diagram for the boost rectifier is shown in figure 3. It decouples terms $\frac{3\omega L}{V_0}$ to eliminate cross-coupling between the $d$ and $q$ channels so that they could be controlled independently [2], [3].

\[
\begin{align*}
\frac{di_d}{dt} &= \frac{1}{3L}(v_{gd} - 3\omega Li_q + d_v v_0) \\
\frac{di_q}{dt} &= \frac{1}{3L}(v_{gg} + 3\omega Li_d + d_v v_0) \\
\frac{dv_d}{dt} &= \frac{1}{C}(3(d_i d + d_i q) + i_0) \\
v_0 &= v_c + R_c \left(\frac{3}{2}(d_i d + d_i q) - i_0\right)
\end{align*}
\]

where $i_d, i_q$ - input currents in dq coordinates, $v_d, v_q$ - input voltages in dq coordinates, $i_0$ - output dc current, $v_0$ - output dc voltage, $d_d, d_q$ duty cycles in dq coordinates, $\omega$ - angular frequency, $L$ - phase inductance, $C$ - output capacitance, $R_c$ - capacitor ESR.

Simulink model derived from these equations is shown in figure 4.

The model accepts dq voltages, dq duty cycles, and dc output current as input variables and supplies dc voltage and dq currents as output variables.

The output capacitor ESR is taken into consideration in order to reflect the converter dynamics more accurately.

The output dc voltage loop is superimposed on the $d$ - channel current loop. The $q$ - channel current reference is set to zero in order to have a unity power factor operation. $H_{id}, H_{iq}$ are current compensators for $d$ and $q$ channels respectively, $H_v$ is output voltage compensator. The current loops control the decoupled channels of the power stage independently by adjusting their duty cycle. The both use proportional controller with the same gain $k_{dp}$.

To have the currents in phase with the input voltages the reference signal for the $q$ channel must be set to zero. The reference signal for the $d$ channel is provided by the voltage loop compensator.

Close loop transfer functions for both current loops are loaded independently.

The voltage loop uses a proportional-integrator compensator with a transfer function [3].
The compensator PI provides fast response and no steady state error in output voltage. Control to output transfer function \( \frac{V_0}{I_{\text{dref}}} \) significantly depends on the load and direction of the power flow. This compensator can be optimized only for a specific load.

In order to use this type of control for the whole range of loads under bidirectional power low conditions as assumed in this paper a compromise in the compensator design was required. The resulting design provided a low closed-loop bandwidth yet stable operation and acceptable transient response under all load conditions.

\[
H_c(s) = \frac{300 \left( 1 + \frac{s}{1000} \right)}{s \left( 1 + \frac{s}{16000} \right)}
\]  

(2)

2.2 PI Fuzzy Logic Controller

Fuzzy sets were introduced forty years ago (Zadeh 1965), as a way of expressing non-probabilistic uncertainties. Since then, fuzzy set theory has developed and found applications in database management, operations analysis, decision support systems, signal processing, data classifications etc. The application area that has attracted most attention, however, is control [5]. Fuzzy set theory uses fuzzy inferencing to reason about linguistic variables, i.e. variables described by fuzzy sets. A number of different inference systems have been developed.

In fuzzy control it is, however, two inference systems that dominate: Mamdani fuzzy systems, also known as linguistic fuzzy systems and Takagi-Sugeno fuzzy systems [6].

The structure of a fuzzy controller is given in figure 7. The development of the control system based on fuzzy logic involves the following steps:

a. Fuzzification strategy;

b. Data base building;

c. Rule base elaboration;

d. Inference machine elaboration;

e. Defuzzification strategy.

The controller is Proportional plus Integral (PI) conventional fuzzy controller having inputs the error (E) and the integral error (IE) and as output the control action \( u \), that in figure 8.

In addition, design of fuzzy logic controller can provide desirable both small signal and large signal dynamic performance at same time, which is not possible with linear control technique.

Therefore, fuzzy logic controller has been potential ability to improve the robustness of the three-phase boost rectifier converters.

Fig. 5 Close loop Simulink model of the three-phase boost rectifier in dq coordinates using PI classical controller

Fig. 6 Close loop Simulink model of the three-phase boost rectifier in dq coordinates using PI fuzzy controller

Fig. 7 The structure of a fuzzy controller
The linguistic terms for error are: EN (error negative), EZ (error zero) and EP (error positive); for integral error are: IENB (Integral Error Negative Big), IENS (Integral Error Negative Small), IEZ (Integral Error Zero), IEPS (Integral Error Positive Small), IEPB (Integral Error Positive Big) and for output are: UPB (Command Positive Big), UPM (Command Positive Medium), UPS (Command Positive Small), UZ (Command Zero), UNB (Command Negative Big), UNM (Command Negative Medium), UNS (Command Negative Small). The membership functions for input and output are triangular and trapezoidal type. The structure of fuzzy controller realized in Matlab/Simulink is presented in figure 9. The membership functions for input 1 (error) are presented in figure 10, for input 2 (integral error) in figure 11 and for output in figure 12.
The rules of the fuzzy controller are:
1. If (error is EN) and (integral error is IENB) then (output1 is UPB)
2. If (error is EN) and (integral error is IENS) then (output1 is UPB)
3. If (error is EN) and (integral error is IEZ) then (output1 is UPM)
4. If (error is EN) and (integral error is IEPS) then (output1 is UPS)
5. If (error is EN) and (integral error is IEPB) then (output1 is UNM)
6. If (error is EZ) and (integral error is IENB) then (output1 is UPB)
7. If (error is EZ) and (integral error is IENS) then (output1 is UNB)
8. If (error is EZ) and (integral error is IEZ) then (output1 is UZ)
9. If (error is EZ) and (integral error is IEPS) then (output1 is UPB)
10. If (error is EZ) and (integral error is IEPB) then (output1 is UNB)
11. If (error is EP) and (integral error is IENB) then (output1 is UPM)
12. If (error is EP) and (integral error is IENS) then (output1 is UNS)
13. If (error is EP) and (integral error is IEZ) then (output1 is UNB)
14. If (error is EP) and (integral error is IEPS) then (output1 is UNB)
15. If (error is EP) and (integral error is IEPB) then (output1 is UNB).

A number of 15 fuzzy rules were obtained. These rules were constructed on the principle of correspondence between input and output. The centroid method was considered for defuzzification. The rules views are presented in figure 13 and the control surface in figure 14.

Fig. 13 The rule view of PI fuzzy controller

The membership functions for the fuzzification process were considered triangular type, uniform distributed from -1 to 1. The extremely functions were considered trapezoidal type with the maximum at -1 and 1 and extended to the error value of -2 and 2, for the integral error value of -6 and 6 and output value of -10 and 10. A

Fig. 14 The control surface

3 Simulation results
The closed loop performances of the three-phase boost rectifier were verified using simulation. Three-phase boost rectifier parameters are [3]: \( V_{L-N} = 120V_{\text{rms}} \), \( L = 200\mu\text{H} \), \( C = 200\mu\text{F} \), \( V_0 = 400\text{V} \), \( P_0 = 15\text{kW} \), \( F_s = 40\text{kHz} \), \( f = 400\text{Hz} \), \( H_{id} = H_{dq} = K_{dq} = 0.07 \).

In figure 15 is presented the output voltage in time, for classical and fuzzy PI controller approaches, in 100% load current case. The same voltage, for 50% load current case, is shown in figure 16.

Fig. 15 The output voltages in time using classical PI and fuzzy PI controller for 100% load current
4 Conclusion

In this paper are presented analysis of three-phase boost rectifier converters in closed loop using PI classical controller and PI fuzzy controller. A multi-loop controller for the three-phase boost rectifier consists of an outer loop to regulate the output voltage and two inner current loops one each for the d and q axis input currents. The current loops control the decoupled channels of the power stage independently by adjusting their duty cycles.

We could observe in both studies, from the Matlab/Simulink simulation, that the fuzzy controller has a good response with small oscillations comparing with classical controller.

References:

Fig. 16 The output voltage in time using classical PI and fuzzy PI controller for 100% load current