High-Efficiency Isolated Single-Phase Inverter Using a Phase-Shifted Full-Bridge Converter and Unfolding circuit With DQ-Repetitive Control

PEEC Laboratry

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Table of Contents

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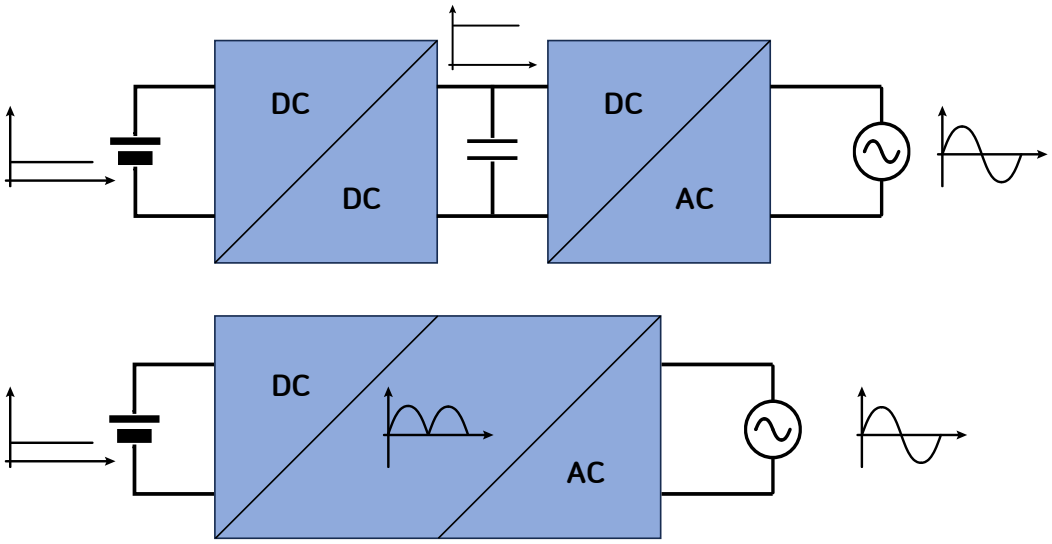
System Architecture of the Unfolding Circuit

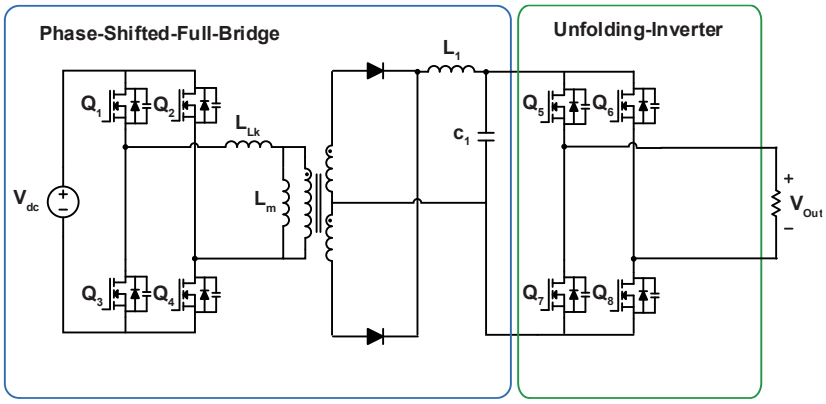
▪ Operation of the Unfolding Circuit



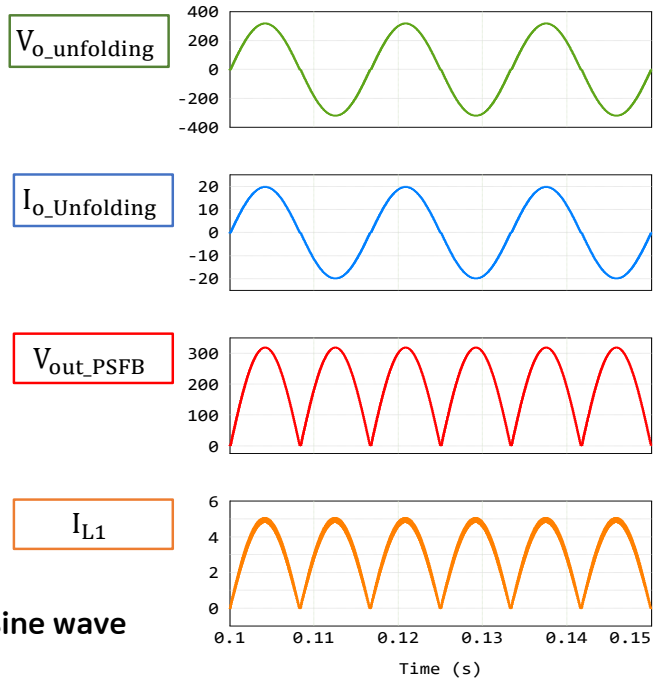
▪ Unlike conventional PWM inverters, the unfolding circuit operates in a single stage where the DC/DC converter generates the absolute value of a sine wave, and the DC/AC inverter performs polarity reversal control.

- System Architecture of the Unfolding Circuit

  - PSFB-Unfolding Inverter Open Loop



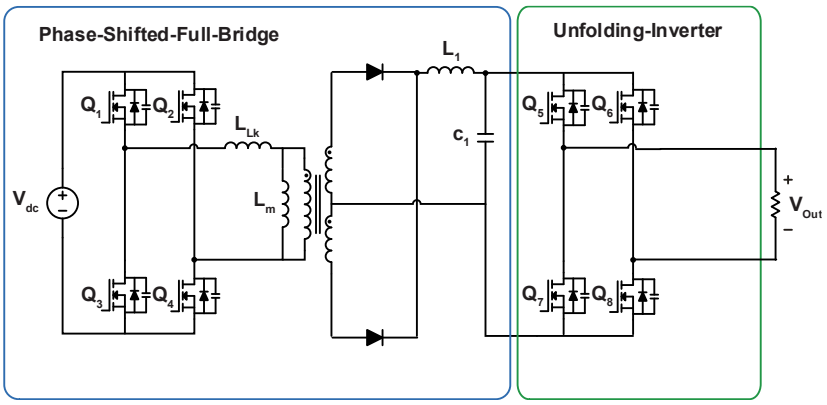
<PSFB-Unfolding Inverter>



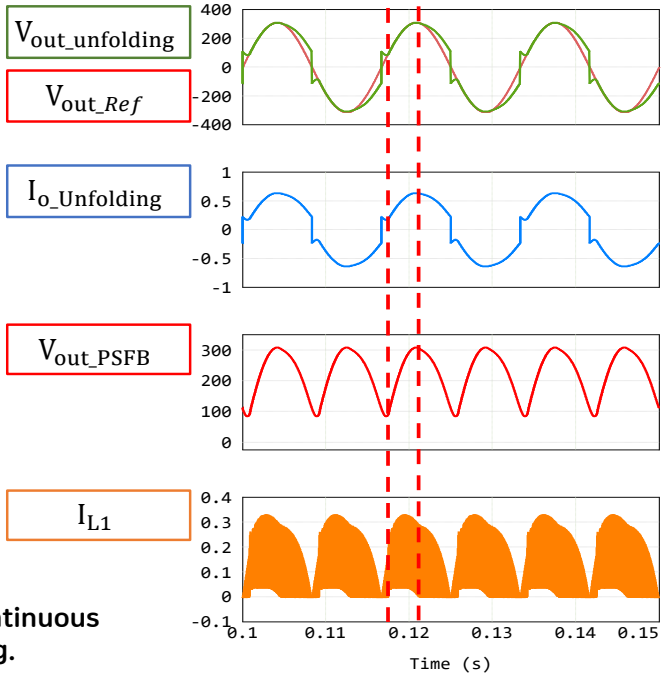
- The unfolding circuit inverts the absolute value of the sine wave to generate a pure sine wave.

Analysis of Output Voltage Waveform Distortion Causes

- Main Waveform Under Light Load Conditions

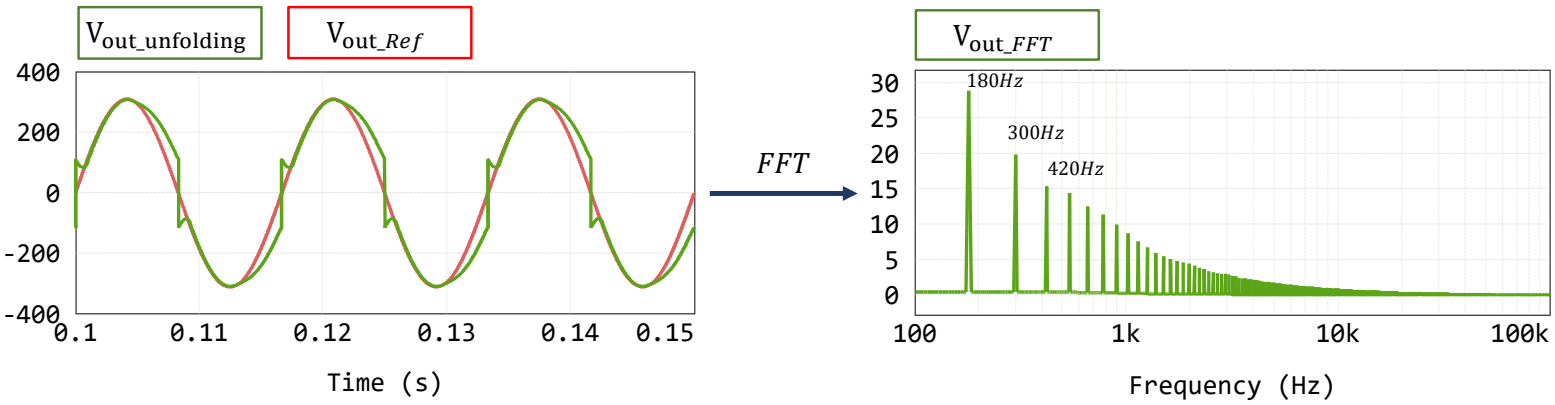


<PSFB-Unfolding Inverter>



- Under light load conditions, the L1 current enters DCM (Discontinuous Conduction Mode), preventing the C1 voltage from discharging.

- Output Voltage FFT Analysis



- It is confirmed that odd harmonic components appear in the output voltage FFT results.
- As the light load condition becomes more severe, the gain values of the odd harmonic components increase.
- Control is required for both the CCM region and the DCM region.

Distortion Reduction Methods or Control Strategies

▪ Reference Paper 1

2488 IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 69, NO. 3, MARCH 2022

Feasibility Study of Model Predictive Control for Grid-Connected Twisted Buck–Boost Inverter

Oleksandr Matiushkin, *Graduate Student Member, IEEE*, Oleksandr Husev, *Senior Member, IEEE*, Jose Rodriguez, *Life Fellow, IEEE*, Hector Young, *Member, IEEE*, and Indrek Roasto, *Member, IEEE*

***Abstract*—This article studies the model predictive control (MPC) for a twisted buck–boost inverter based on unfolding circuit. The focus is on the practical implementation of the MPC algorithm for the microcontroller designed for application in power electronics. Selection of proper cost function parameters along with a continuous control set reduced prediction horizon, at the same time keeping good quality of the grid current. The results showed that simplified differential equations and a multicore microcontroller contribute to the sample time reduction, which in turn increases the sampling frequency with the corresponding increase in the output current quality. The simulation and experimental results confirmed theoretical predictions. In conclusion, the MPC technique suits for reducing zero-crossing distortion and in applications based on unfolding circuit.**

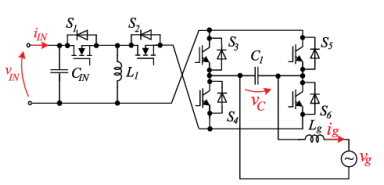
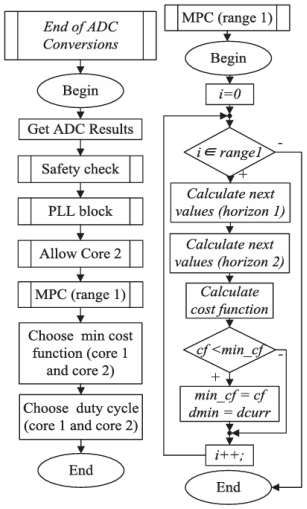


Fig. 1. Buck–boost twisted dc–ac converter based on unfolding circuit.



< MPC algorithm >

- Because the complex calculation process takes place inside the MCU(Model Predictive Control), a high-performance MCU must be used.
- Compared to the basic control method, there are drawbacks in that the number of sensors increases and the model accuracy is sensitive.

- Reference Paper 2

Precise tracking of highly nonlinear phase-shift full-bridge series resonant inverter via iterative learning control

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ARTICLE INFO

Keywords:
Nonlinear dynamics
Wide operating range
Grid voltage disturbance
Iterative learning controller
First harmonic approximation
Global convergence

ABSTRACT

This paper presents iterative learning control of the phase-shift full-bridge series-resonant inverter (PSFB-SRI). It has the merits of high conversion efficiency, medium-to-high power capacity, compact size, and low current–voltage stress on components, but the demerits of highly nonlinear dynamics that varies in a wide range depending on the operating points. The PSFB-SRI also suffers from a grid-voltage disturbance when it operates in grid-connected environment. To overcome these control problems, an iterative learning controller (ILC) supplemented with a proportional controller is developed and applied to the PSFB-SRI. Conventional proportional controller is used to improve the output current tracking performance. The ILC makes use of both previous-cycle and current-cycle learning terms which help the system output to converge to the reference trajectory. It is also simple in structure and easy to implement in practical applications. First-harmonic approximation of the PSFB-SRI model has been conducted and the resulting nonlinear large-signal model was used to construct the developed ILC. A detailed design guideline of the control parameters is provided. Numerical simulations validate the proposed control scheme, and experiments using a 500-W prototype demonstrate its feasibility.

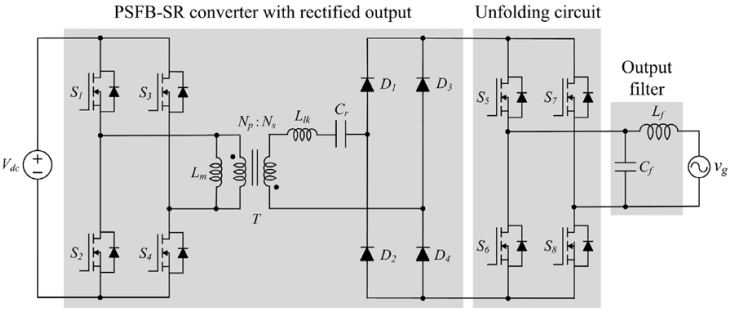
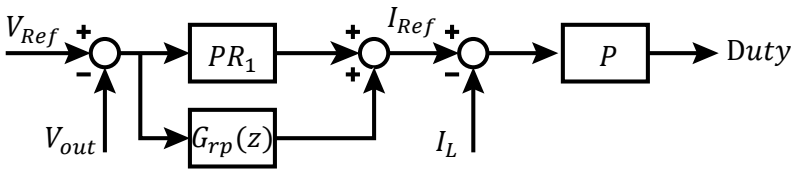


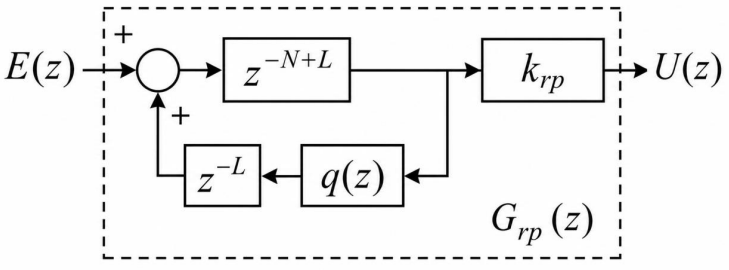
Fig. 1. Circuit diagram of the PSFB-SRI. Components and processes are described in the text.

- This paper uses ILC (Iterative Learning Control), a nonlinear controller, which requires complex calculations to be performed within the MCU.
- A typical unfolding inverter uses complex control to reduce THD.

- Proposed Control Method



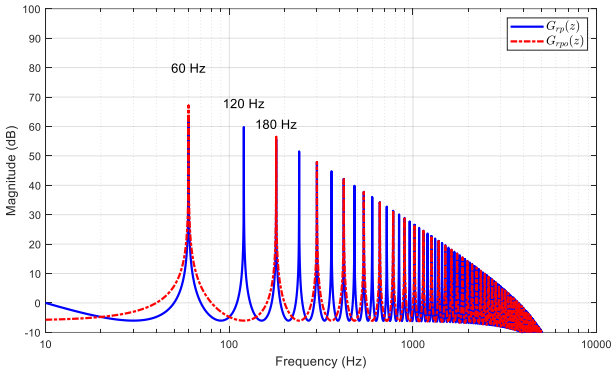
< Proposed Block Diagram >



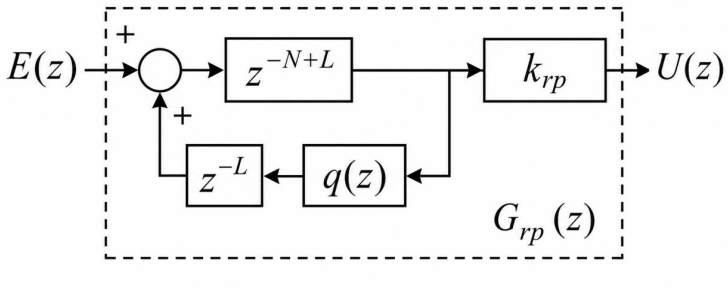
< Block Diagram of Grp(z) >

- PR control is used to directly regulate the AC voltage.
- A repetitive controller is used in parallel to compensate for the gain values of harmonic components.
- P control is used as the current controller.

- Characteristics of the Repetitive Controller



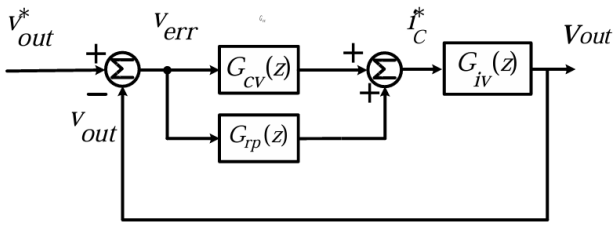
<Bode Plot of the Repetitive Controller >



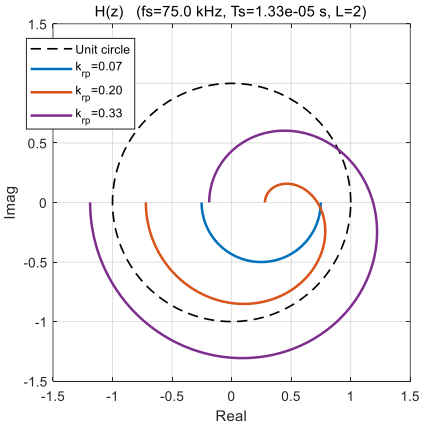
< Block Diagram of Grp(z) >

- The repetitive controller is a method that generates an error model and adds it to the existing controller.
- Repetitive errors are stored in digital memory and output over time during the controller computation process.

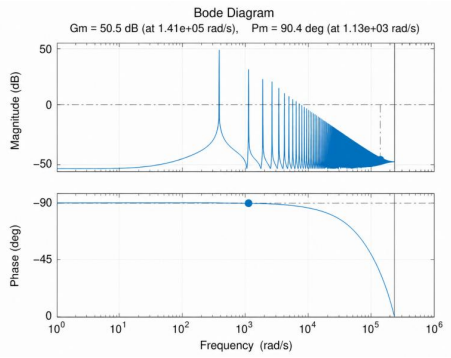
- Krp Gain Selection Method



< Parallel Structure of Voltage PR and Repetitive Controller >



<Overall System Stability Evaluation>



<Bode Plot of the Configured Repetitive Controller>

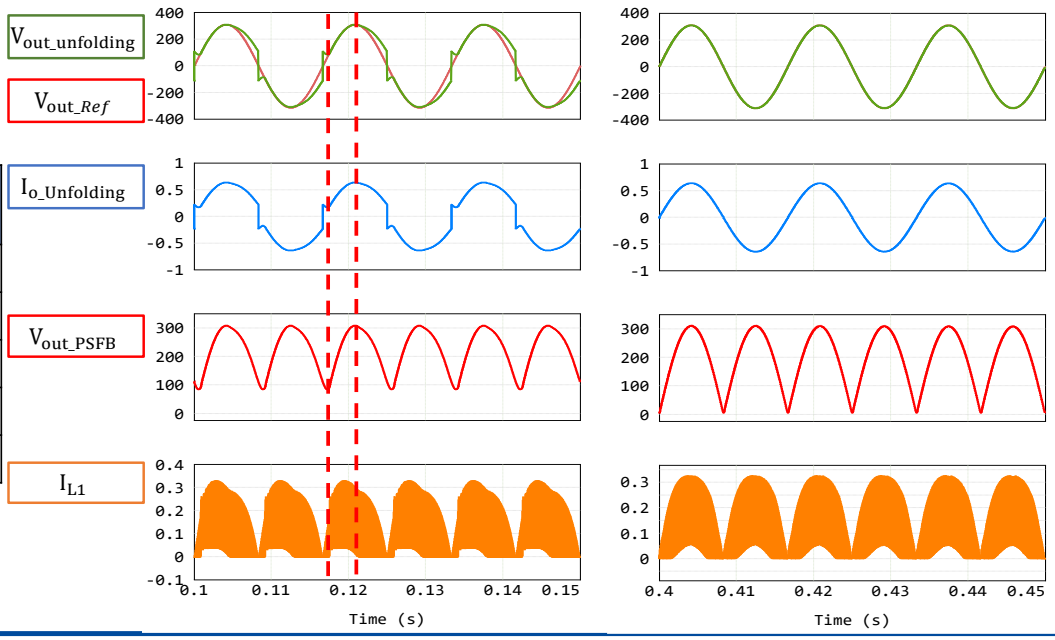
- $G_e(z) = \frac{V_{out}}{V_{out}^*} = \frac{\left(G_{cv}(z)+G_{rp}(z)\right)G_{iv}(z)}{1+\left(G_{cv}(z)+G_{rp}(z)\right)G_{iv}(z)}$
- $G_{rp}(z) = K_{rp} * \frac{-z^{-L}}{\frac{N}{z^2}+q(z)}$
  - $\left(L = 2,\ q(z) = \frac{z+2+z^{-1}}{4},\ N = 1250\right)$
- $G_{cv}(z) = \frac{0.00066z^2-0.00066}{z^2-2z+0.9997}, G_{iv} = 0.036$

- Stability requires all poles to be located inside the unit circle.
- L, N, and q(z) are generalized in the repetitive controller.

▪ Simulation Results

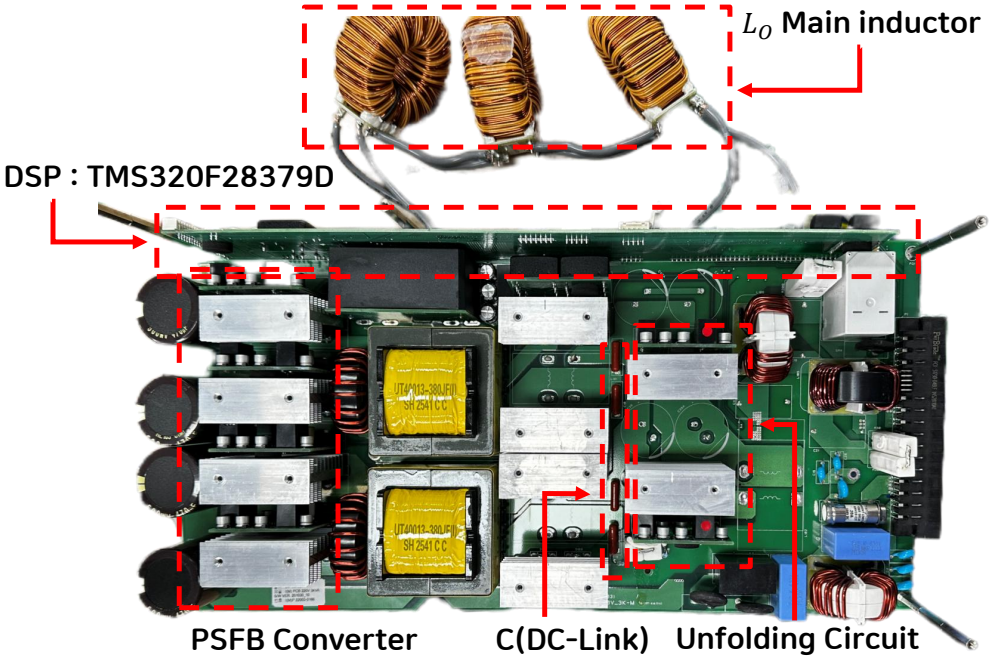
Open Loop THD : 19.3%
Close Loop THD : 0.41%

Harmonic Order	Frequency (Hz)	Open Loop Magnitude	Closed Loop Magnitude
3	180	34.01	0.166
5	300	25.02	0.118
7	420	20.06	0.115
9	540	18.30	0.099
11	660	15.56	0.088



Experimental Results and Verification

▪ Plant and parameters



Parameter	
V_{in}	$380V$
L_{lk}	$15\mu H$
L_m	$400\mu H$
L_o	$1.5mH$
C	$40nF$
R	16.13Ω(**Rated Load**) **3kVA**

▪ Experimental Main Waveform(5% Load 150W)

C1 : DC Link Voltage, C2 : Output Voltage , C4 : Duty

<Close Loop THD 0.8%>

<Open Loop THD 14.2%>

▪ At 5% load, THD was reduced from 14.2% to 0.8%.

▪ Experimental Results and Verification

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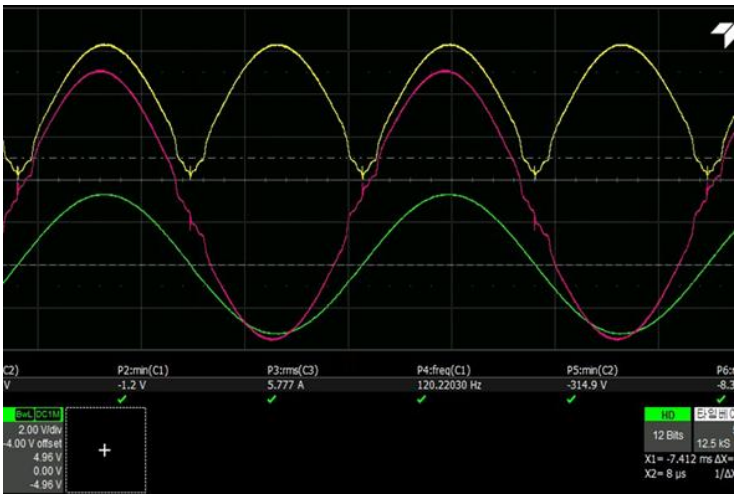
- Experimental Main Waveform(40% Load 1300W)

C1 : DC Link Voltage, C2 : Output Voltage , C4 : Duty

<Close Loop THD 0.9%>



<Open Loop THD 5.5%>

- At 40% load, THD was reduced from 5.5% to 0.9%.

▪ Experimental Results and Verification

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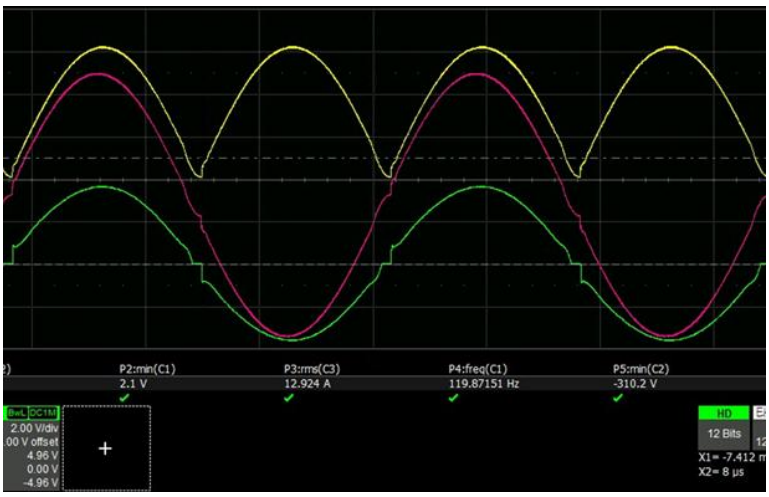
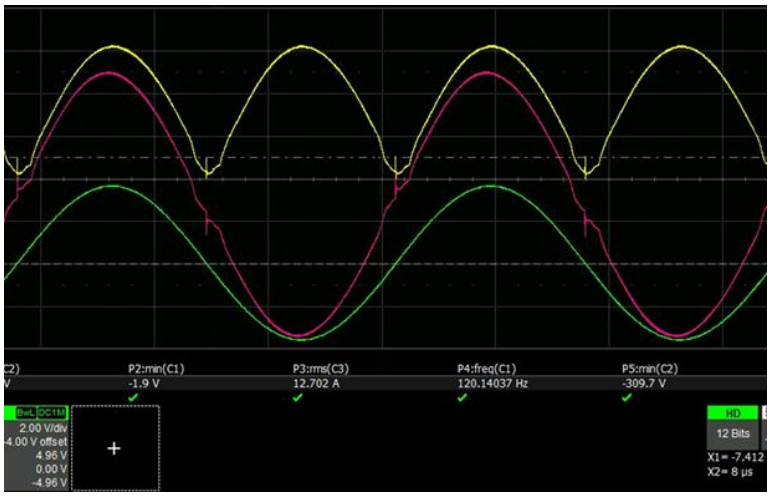
- Experimental Main Waveform(100% Load 3000W)

C1 : DC Link Voltage, C2 : Output Voltage , C4 : Duty



<Close Loop THD 1.1%>



<Open Loop THD 4.2%>

- At 100% load, THD was reduced from 1.1% to 4.2%.

▪ Experimental Results and Verification

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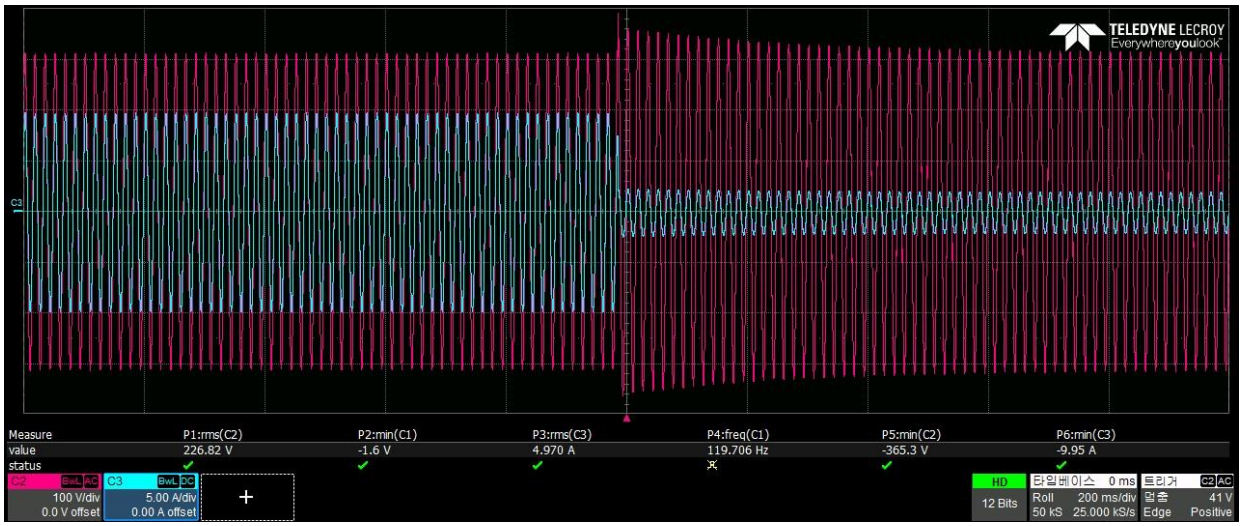
- Load variation test

C2 : Output Voltage, C3 : Output Current



- 50%(1500W) -> 10%(300W) Load variation test
- Steady-state tracking takes more than 30 cycles

▪ Simulation Results and Control Method Comparison

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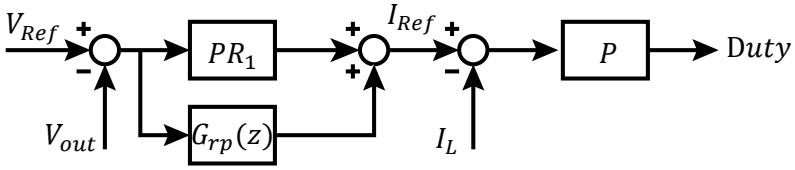
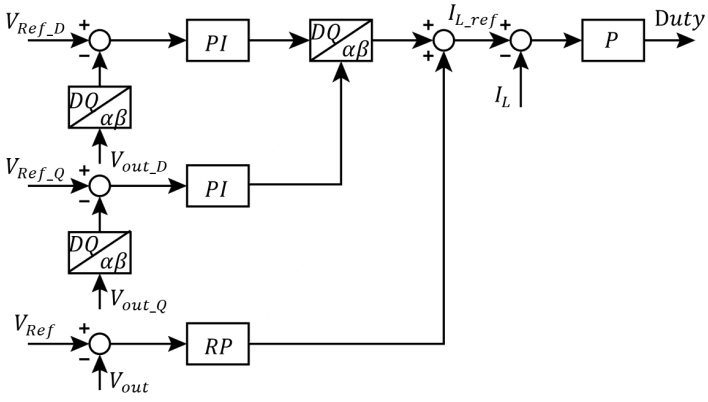
- Control Method Change



< Proposed control method >

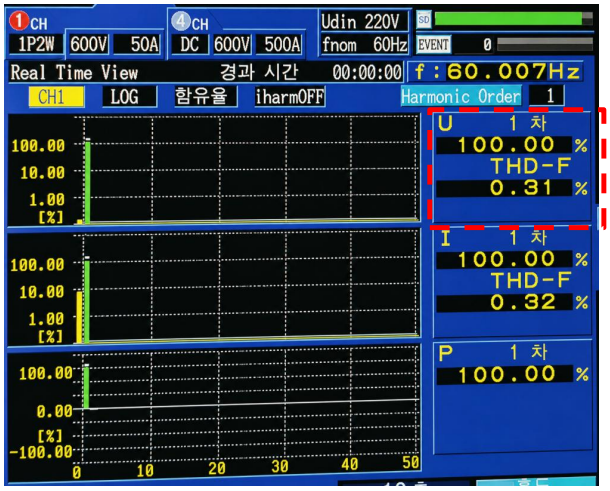


< A control method that compensates for load variations >

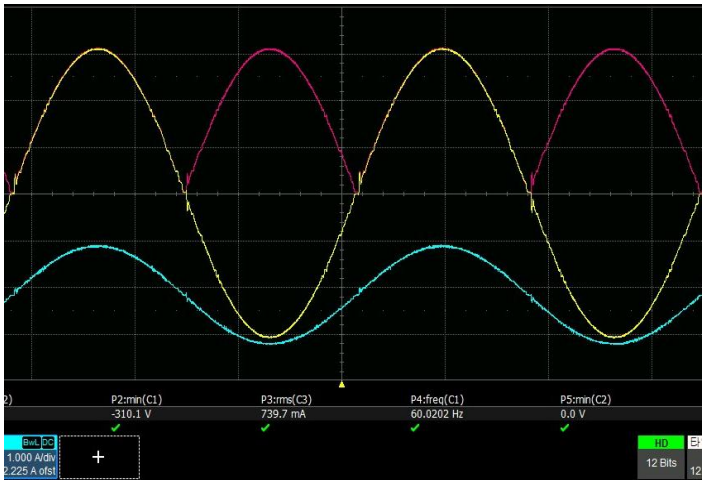
- The PR control was changed to single-phase DQ control to improve transient response during load variation.
- Since single-phase DQ control regulates DC quantities, it has lower control complexity, making gain tuning easier compared to PR control.
- In the proposed method, using RP on the DQ axis doubles the system memory capacity.

▪ Control method change(DQ-RP parallel)(5% Load 150W)

C1 : Output Voltage, C2 : DC Link Voltage , C3 : Output Current



<Power Quality Analyzer>

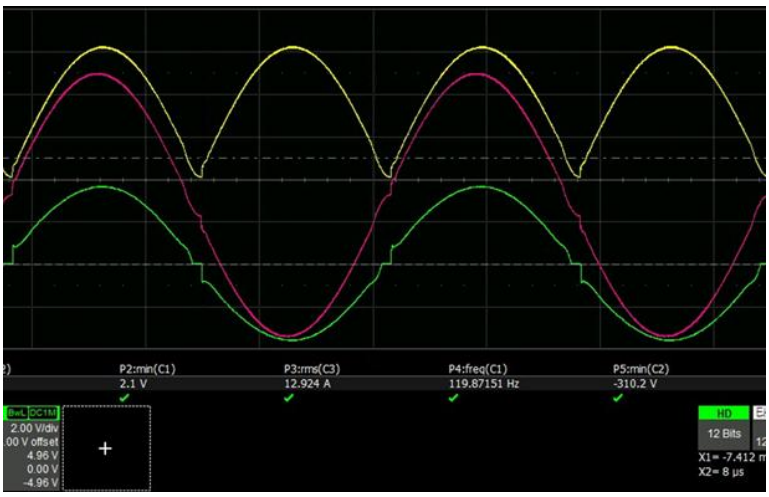


<DQ-RP THD 0.31%>

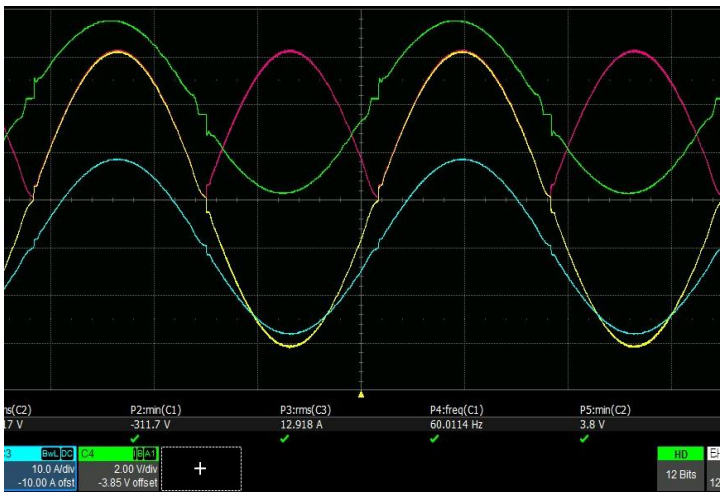
▪ Achieves THD of 0.31% at 5% load (Open-loop THD: 14.2%)

▪ Control method change(DQ-RP parallel)(100% Load 3000W)

C1 : DC Link Voltage, C2 : Output Voltage, C3 : Output Current, C4 : Duty



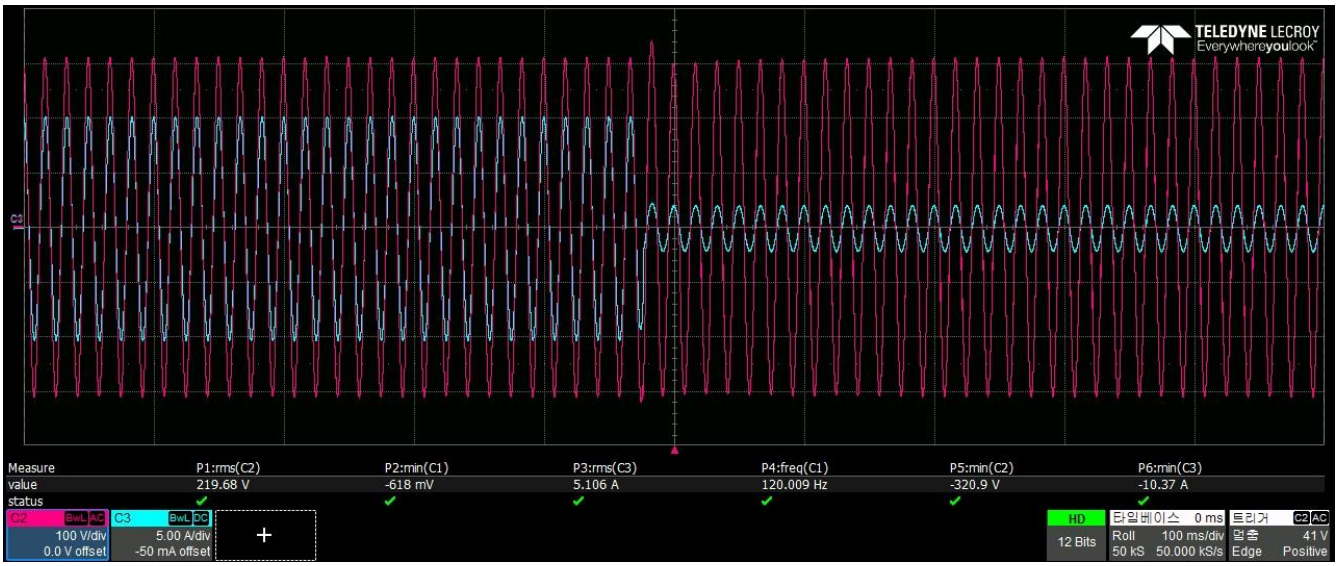
<PR-RP THD 1.1%>



<DQ-RP THD 0.69%>

▪ Achieves 95.1% efficiency at rated capacity

▪ Load variation test(DQ-RP parallel)



- 50%(1500W) -> 10%(300W) Load variation test
- Steady-state tracking takes more than 3 cycles

▪ Analytical Loss Analysis of Transformer and Inverter

		Loss Types	One	Total
PSFB Q1	Body Diode	Conduction Loss	1.64E-03	6.54E-03
	MOSFET		1.9615	7.846
	Body Diode	Switching Loss	6.67E-04	2.67E-03
	MOSFET		1.64983	6.59932
PSFB Q3	Body Diode	Conduction Loss	1.11E-03	4.44E-03
	MOSFET		2.04787	8.19148
	Body Diode	Switching Loss	1.80E-03	7.19E-03
	MOSFET		1.59156	6.36624
Diode 1		Conduction Loss	1.53	6.12
Diode 2		Conduction Loss	1.53	6.12
Unfolding Q1		Conduction Loss	2.59	10.36
		Switching Loss	2.73E-06	1.09E-05
			Total Loss	51.62W

Loss Items	Value
Transformer Core Loss P_{fe}	31.5W
Transformer Copper Loss P_{cu}	14.1W
Total Transformer Loss	45.6W
Two Transformers	91.2W
Inductor Core Loss P_{fe}	199.8mW
Inductor Copper Loss P_{cu}	505mW
Six Inductors	4.23W
System Total Loss	147.05W
Rated System Efficiency(25℃)	95.1%

Conclusion

▪ Conclusion

- The output voltage waveform distortion characteristics of a single-phase inverter based on an unfolding circuit were analyzed.
- It was confirmed that the zero-crossing interval is the primary distortion occurrence region, with switch transition and inductor current mode transition identified as the key causes.
- The proposed distortion reduction method (application of repetitive controller) was applied to improve the sinusoidal quality of the output voltage.
- By using RC (Repetitive Control), a simpler linear controller than the previously studied THD reduction techniques MPC and ILC, THD was effectively reduced.
- Through simulation and experimental results, a THD of less than 1% was achieved across the entire load range.
- The proposed isolated single-phase inverter achieved an efficiency of 95.1% under rated operation, confirming its performance and practical feasibility as a high-efficiency inverter.

Q & A

Appendix

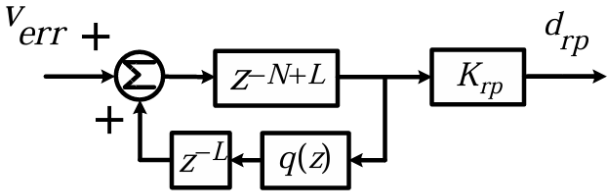
- Repetitive Controller Components

- The repetitive controller variables mainly consist of N, L, q(z), and Krp.

- $N = floor\left(\frac{fs}{fo}\right)$ ← floor(x) returns the largest integer less than or equal to x.
  - When N is a non-integer (decimal) value, the performance of the repetitive controller degrades.

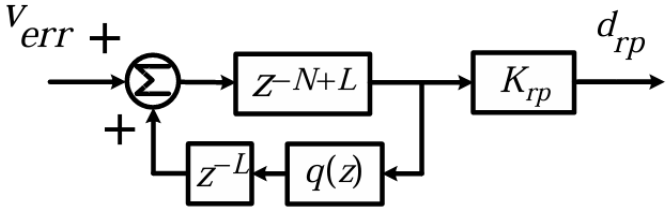
➢ $N = floor\left(\frac{fs}{fo}\right) = floor\left(\frac{75k}{60}\right) = 1250$
  - ➢ $(fs = 75kHz, f_o = 60Hz)$

- 1.5 sampling delay caused by the controller and PWM in digital control.
- L is a value that accounts for the sampling delay factor.
- Due to the 1.5 sampling delay, L is typically generalized as L = 2.

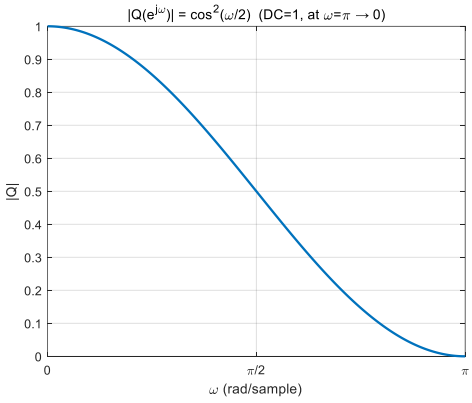


< Block Diagram of Grp(z) >

- q(z) Configuration



< Block Diagram of Grp(z) >



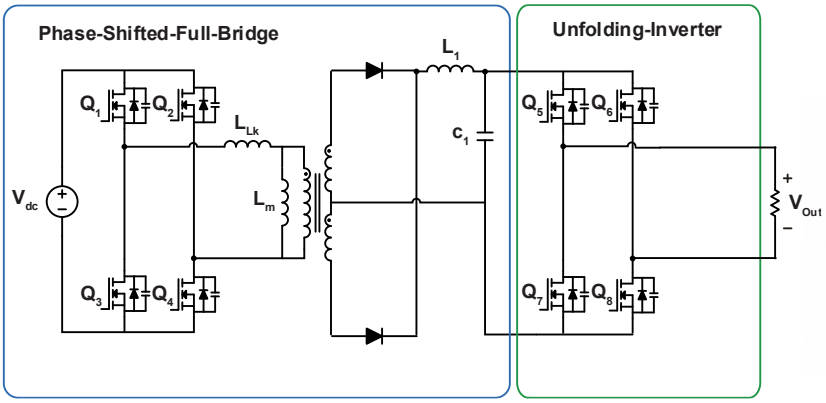
< Frequency Response of q(z) >

- $q(z) = \frac{z+2+z^{-1}}{4}$ or $0 < q(z) \leq 1$
- $(q(e^{jw}) = \frac{e^{jw}+2+e^{-jw}}{4} = \frac{1+\cos(\omega)}{2} = \cos^2(\frac{\omega}{2})$

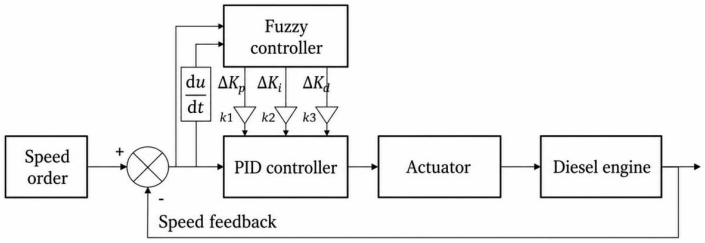
- A filter that attenuates the high gain of the repetitive controller in the high-frequency region.

▪ Parallel Structure of Fuzzy-PI Controller

Parameter	
L_1	$1.5mH$
C	$40nF$



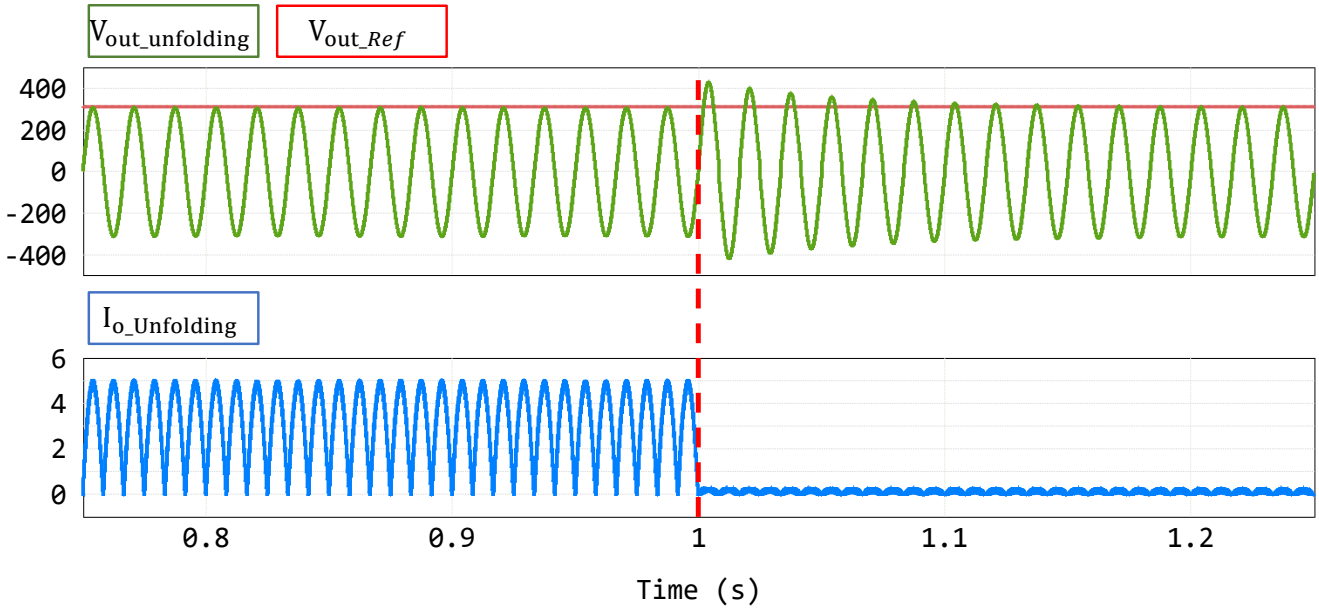
<PSFB-Unfolding Inverter>



<Block Diagram of Fuzzy-PI Control>

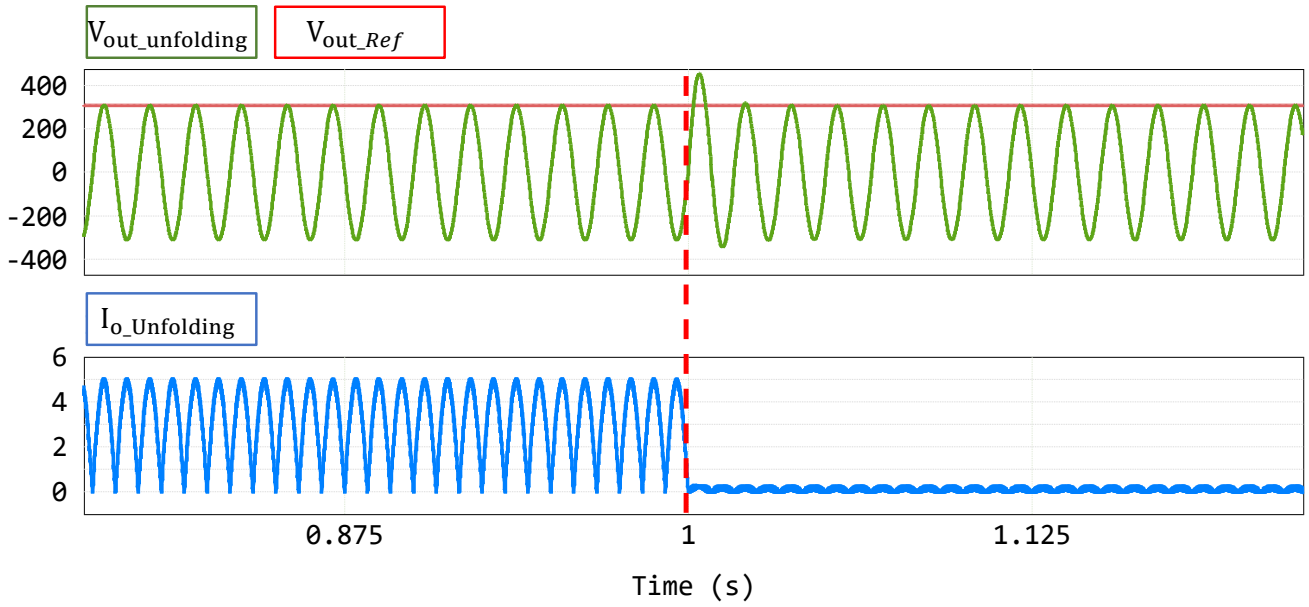
- $G_C(s) = K_P + \frac{K_I}{s} \rightarrow (K_P = K_{P0} + \triangle K_P \cdot k_1),\ (K_I = K_{I0} + \triangle K_I \cdot k_2)$
- $\triangle G_C(s) = K_{P0} + \triangle K_P \cdot k_1 + \frac{K_{I0} + \triangle K_I \cdot k_2}{s}$
- The Kp and Ki values are varied according to the magnitude of the error.

▪ Load Variation Simulation(PR-RP)(100 %Load -> 10% Load)



- Steady-state tracking takes more than 8 cycles

▪ Load Variation Simulation (DQ-RP)(100 %Load -> 10% Load)



▪ Steady-state tracking takes more than 2 cycles