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PR Current Controllers for Harmonics Generators to Test an Inductive Current Transformer

Anh-Tuan PHUNG, Vu Hoang Phuong*, Thuy-Nguyen VU

Hanoi University of Science and Technology – No. 1, Dai Co Viet Str., Hai Ba Trung, Ha Noi, Viet Nam

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Abstract

Current transformers are commonly used electrical devices to measure the current of electric loads. To assess the quality and accuracy of the current transformer, one of the necessary requirements is to evaluate the accuracy of this object under the condition that the primary current has a large distorted waveform and is composed of harmonics. This has led to the need to create a programmable current source capable of generating current that contains basic harmonic components and high harmonics according to present standards. The current source must accurately generate the desired amplitude and frequency values, which in turn requires the use of resonant modulation regulators. The parameters of the regulator greatly affect the quality of the above current source. Therefore, this article will present a method of calculating the proportional-resonant regulator parameter, corresponding to each generated harmonic component. Simulation results performed in MATLAB software have proven effective design methods when applying the generated harmonic components. Experiment results will be discussed in detail for such an advanced regulator.

Keywords: Current transformer, Fundamental current, Harmonic distortion, High frequency, Accuracy, Harmonics pollution

1. Introduction

A current transformer (CT) is an electrical device which is used to measure alternating current. It generates a current in its secondary side which is proportional to the current in its primary side. It is classified into the class of instrument transformers, which are used for measurement purpose and differentiated from power transformers, which are used to transfer electrical energy. Instrument transformers scale down the large values of voltage or current to small, standardized values that are easy to handle for instruments and protective relays [1]. They also isolate measurement or protection circuits from the high voltage of the primary circuits.

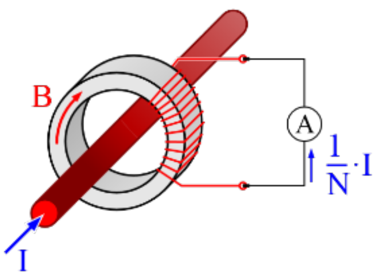

Fig. 1. Typical representation of inductive current transformers.

* Corresponding author: Tel.: (+84) 989258854
Email: phuong.vuhoang@hust.edu.vn

A current transformer has a primary winding, a core and a secondary winding. The alternating current in the primary produces an alternating magnetic field in the core, which then induces an alternating current in the secondary. The primary circuit is largely unaffected by the insertion of the CT. Accurate current transformers need closed coupling between the primary and secondary to ensure that the secondary current is proportional to the primary current over a wide current range. Assuming no leakage loss, the current in the secondary is the current in the primary (assuming a single turn primary) divided by the number of turns of the secondary [2].

Current transformer construction consists of a primary winding, secondary winding and a silicon steel ring core. The alternating magnetic field generated by the primary conductor will couple with the core to generate an alternating secondary current through this magnetic core. This core is frequently made by high grade silicon steel to ensure a perfect coupling between the two inherent circuits [1].

The equivalent circuit of this current transformer shares the same topology with a typical power transformer, in which, an ideal transformer is coupled with primary and secondary magnetic impedance. These magnetic components are subject to high frequency impact. In fact, the current transformer literally constitutes a low-pass filter which repels high frequency signals. The higher frequency content is in the primary current, the more reflection is. The quality of the magnetic core and its high frequency behavior are subject to studies. There were much research [3]-[5] which reported on high frequency behavior of current transformers. However, the frequency range of these studies exhibits kHz range up to MHz [6]. According to regulations [7], the harmonics content of primary current should not exceed a certain level.

The standard IEC 60044-1 [8] addresses CTs and gives requirements only under sinusoidal conditions and does not give any requirements in non-sinusoidal conditions. The standards about power quality measurements, IEC 61000-4-30 or IEC 61000-4-7 [9]-[12], suggest using the frequency response test to characterize the behavior under non-sinusoidal conditions. Manufacturers do not declare the frequency response as a specification for the CTs. It is possible to find the frequency response as a specification only if the CTs are tested with a power quality instrument.

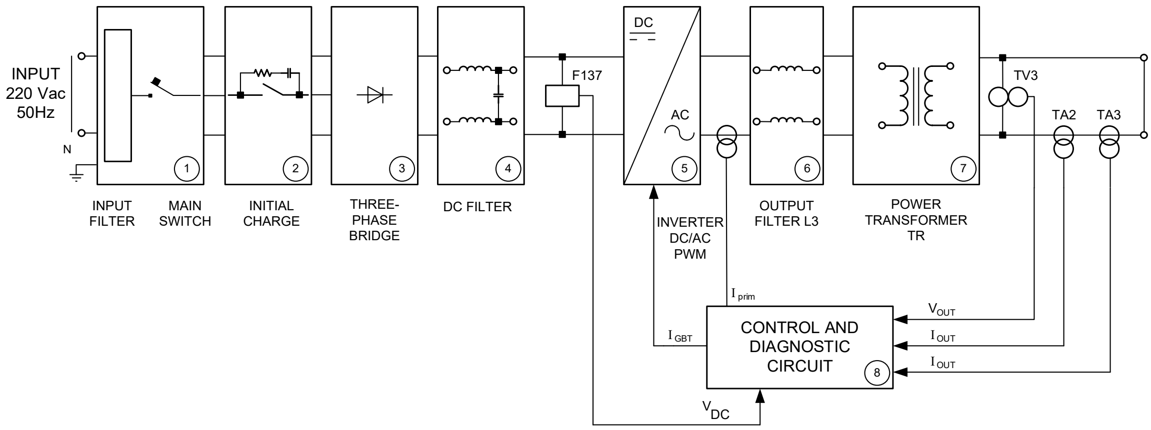

Fig. 2. Overall system of the inductive current transformer harmonic tester

One simple approach is to feed the primary conductor with a high harmonic content and to measure its secondary response.

To obtain a correct harmonics content of the current source, regulators are used. One of recent developments is Propositional – Resonant (PR) controller [13]-[17]. Recently, PR controllers have been suggested as an alternative option for PI controllers in grid-connected VSI applications. PR controllers have an infinite gain at a selected resonant frequency; thus, the zero steady-state error or the harmonic at this frequency can be eliminated. The parameters of the PR controller are designed in the frequency domain, considering the desired system phase margin and guaranteeing system stability [15], which is usually the fundamental frequency. So that, this paper proposes a generalized design method for PR current controllers containing multiple resonant components in an inductive current transformer to generate desired harmonics current.

2. Control scheme

2.1. Modelling of inductive current transformer

The equivalent impedance referred to the primary side of the transformer is given as follows:

$$Z_{eqS} = \left(r_p + N^2 r_s\right) + j\left(x_{\sigma p} + N^2 x_{\sigma s}\right) = R + j\omega_1 L_\sigma \quad (1)$$

where N is the turns ratio of transformer, r_p and r_s are the resistances of the primary and secondary sides, $x_{\sigma p}$ and $x_{\sigma s}$ are the leakage inductances of the primary and secondary sides.

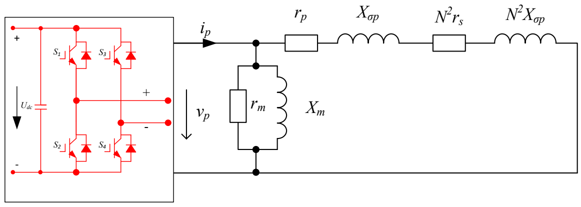

Fig. 3. Equivalent circuit of per phase and series connected transformer [13].

The plant transfer function of the current control loop in inductive current transformers is determined as follows:

$$G_{iv}(s) = \frac{i_p(s)}{v_p(s)} = \frac{1}{L_\sigma s + R} \quad (2)$$

2.2. Parameters of PR controller

The proportional resonant (PR) controller provides gains at a certain frequency (resonant frequency) and eliminates steady-state errors [13]-[17]. Therefore, the PR controller can be successfully applied to inductive current transformers. The transfer function of an ideal PR controller is given as follows:

$$G_{PR}(s) = K_{ph} + \frac{K_{rh}s}{s^2 + \omega_h^2} \quad (3)$$

where K_{ph}, K_{rh}, and ω_h are the proportional gain, resonant gain, and frequency for the h-order harmonic, respectively.

Examples of Bode diagram of several PR controllers with the fundamental resonant frequency are shown in Fig. 4. In this practice, K_{ph} is set to 1, K_{rh} is set to 100, 1000, and 10000, respectively.

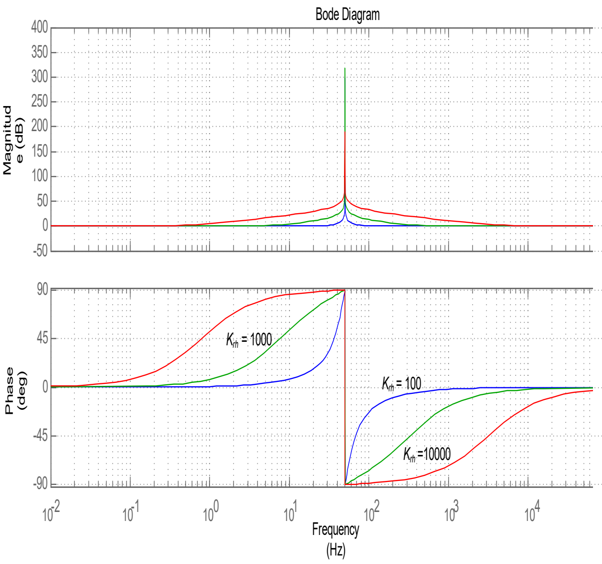

Fig. 4. Bode diagrams of PR controllers with the fundamental resonant frequency.

The frequency response characteristics of the PR controller at the selected resonant frequency are calculated as follows:

$$|G_{PR}(j\omega)| = \frac{\sqrt{K_P^2\left(\omega_h^2 - \omega^2\right)^2 + K_{rp}^2\omega^2}}{\left(\omega_h^2 - \omega^2\right)} \quad (4)$$

$$\angle G_{RP}(j\omega) = \arctan\left[\frac{K_{rh}\omega}{K_P\left(\omega_h^2 - \omega^2\right)}\right] \quad (5)$$

A simple transfer function of the HC and PR controller which allows to control specific could be rewritten as follows:

$$G_{PR}(s) = G_{PR1}(s) + G_{PR3}(s) + G_{PR5}(s) + G_{PR7}(s) = \sum_{h=1,3,5,7,...} K_{ph} + \sum_{h=1,3,5,7,...} \frac{K_{rh}s}{s^2 + \omega_h^2} \quad (6)$$

The magnitude-frequency response of the system is unity at the cross-over frequency (f_c), and f_c is higher than the fundamental frequency (50Hz). As a result, according to Fig. 4, the magnitude-frequency response of PR controller simplifies the calculation of controller gain K_{ph} of PR as follows:

$$\left(\sum_{h=1,3,5,7,...} \left|G_{PRh}(j\omega)\right|_{\omega=\omega_C}\right)\left|G_{vi}(j\omega)\right|_{\omega=\omega_C} = 1 \rightarrow \sum_{h=1,3,5,7,...} K_{ph} \approx \frac{1}{\left|G_{vi}(j\omega)\right|_{\omega=\omega_C}} \quad (7)$$

The unity gain of the PR controller can be divided among harmonic orders. According to IEC61000-3-4, if the tracking for the fundamental current is given a higher priority compared to other harmonic orders, $\left|G_{PR1}(j\omega)\right|_{\omega=\omega_C}\left|G_{vi}(j\omega)\right|_{\omega=\omega_C}$ is given the highest value while the corresponding quantities for tracking 2nd, 5th, and h^{th} can be set to smaller values.

The parameter K_{rh} of the PR controller is determined based on the desired value PM of the system's open-loop transfer function the cross-over frequency ω_c, which is given as follows:

$$PM = \angle G_{PRh}(j\omega)\big|_{\omega=\omega_C} + G_{vi}(j\omega)\big|_{\omega=\omega_C} + 180^\circ \quad (8)$$

Therefore, the parameter K_{rh} of the PR regulator is determined as follows:

$$\arctan\left[\frac{K_{rh}\omega_c}{K_{ph}\left(\omega_h^2 - \omega_c^2\right)}\right] = A_c \rightarrow K_{rh} = \frac{\tan(A_c)K_{ph}\left(\omega_h^2 - \omega_c^2\right)}{\omega_c} \quad (9)$$

where $A_c = PM_c - \left[G_{vi}(j\omega)\big|_{\omega=\omega_C} + 180^\circ\right]$.

The relation between the cross-over frequency f_c and the sampling frequency f_s is $f_c \le \frac{f_s}{10}$.

3. Simulation and analysis

The simulation of the proposed design method for PR current controllers for inductive current transformers is carried out in Matlab/Simulink/Simpower. The parameters of the test system are shown in Table 1.

Table 1. Parameters of a inductive current transformer

DC-link voltage	300 Vdc
Switching frequency	10 kHz
Parameters of transformer	N = 1 $R = 0.5\Omega$ $L_{\sigma} = 0.3mH$
Harmonic current limit expressed as a percentage of the fundamental frequency current (According to IEC61000-3-4)	2nd is 2% 3rd is 30% 5th is 10% 7th is 7% 9th is 5% 11th is 3%

Table 2. The parameters of the designed PR controller for each harmonic order

K_{ph}	K_{rh}	PM	f_c
K_{p1} = 0.0036	K_{r1}= 13.75		
K_{p2} = 2.23e-4	K_{r2} = 0.85	30.6^0	964Hz
K_{p3} = 0.0018	K_{r3} = 6.74		
K_{p5} = 8.93e-4	K_{r5} = 3.23		
K_{p7}= 2.23e-4	K_{r7}= 0.76		
K_{p9} = 2.23e-4	K_{r9} = 0.69		
K_{p11} = 2.23e-4	K_{r11} = 0.6		

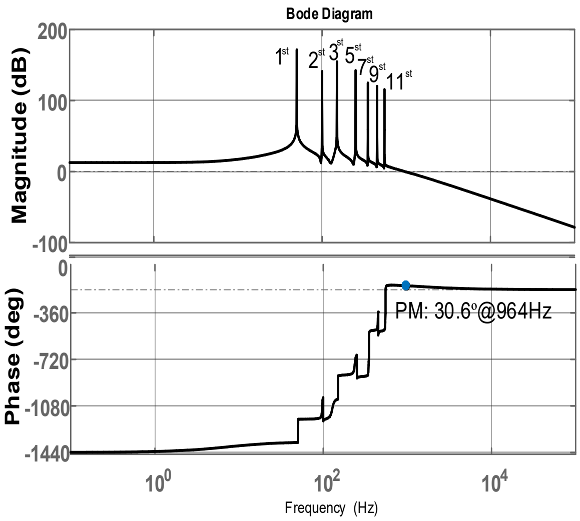

Fig. 5. Bode diagrams of open-loop transfer function

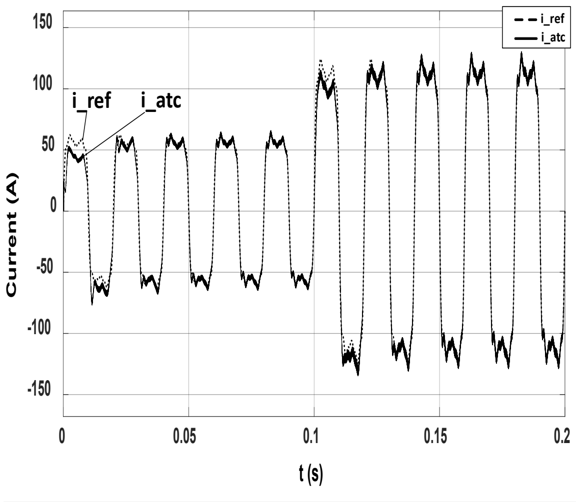

Fig. 6. Performance of the system

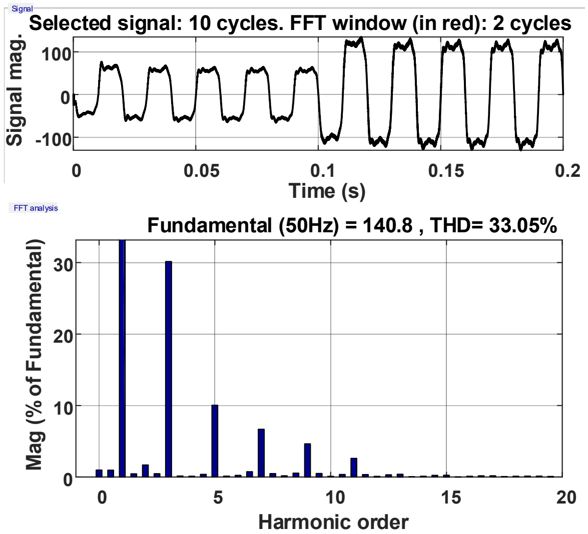

Fig. 7. FFT analysis waveform of actual current

With the filter parameters shown in Table 1, the desired phase margin (*PM*) is 30^0, and the cross-over frequency (f_c) is 1000 Hz. According to IEC 61000-3-4 standard, the reference current generates harmonic current in Table I. So that, the fundamental frequency, $\left|G_{PR1}(j\omega)\right|_{\omega=\omega_C}\left|G_{vi}(j\omega)\right|_{\omega=\omega_C} = 0.4$, while the corresponding quantities for tracking 2nd, 7th, 9th, and 11th are set to 0.025, 3rd is set to 0.2, 5th is set to 0.1, respectively. The parameters of the PR controllers are calculated using the method described in Section 3, and the calculated parameters of PR controller for each harmonic order is shown in Table 2. The Bode diagram that represents the characteristics of the current control loop with the implementation of the PR controller are shown in Fig. 5. The current loop is shown to be stable.

Table 3. List of actual current harmonics in 0.04s – 0.08s

Harmonic order	ercentage of the 50 Hz input current (%)	Phase
2	2.08	171.4^0
3	29.96	179.3^0
5	10.06	179^0
7	6.67	166^0
9	5.15	149.8^0
11	3.03	126.7^0

Table 4. List of actual current harmonics in 0.14s – 0.18s.

Harmonic order	Percentage of the 50 Hz input current (%)	Phase
2	1.94	175.7^0
3	29.95	179.7^0
5	10.03	179.3^0
7	6.81	172.9^0
9	5.16	164.2^0
11	3.12	150.9^0

Unipolar pulse-width-modulation technique is also implemented to control the switching of the IGBT switches of the single-phase VSI [21]. The reference root mean square current (i_{ref}) is changed from 50A to 100A at 0.1s. Simulation results in Fig. 6 show that the response of the current (i_{act}) tracks the reference in one power grid cycle (20ms). Besides, the efficiency of the proposed control scheme of the inductive current transformer is proven, and the ability of generating the correct content of current source compatible with the selective harmonics satisfies international standards in Fig. 7, Table III and Table IV.

4. Conclusion

In this paper, we have successfully implemented PR current controllers for the selective harmonics generator. This technique has been tested on a testbed to test the current transformer with different harmonics content.

Acknowledgments

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