

REVIEW OF A HIGH PERFORMANCE CONTROL OF AC SIGNALS BASED ON A PROPORTIONAL PLUS RESONANT COMPENSATOR

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Abstract

This article reviews a high performance control of alternative current (AC) signals based on a controller called the Proportional plus Resonant (P+Resonant) compensator. Recently, this type of compensator has been considered as a high performance controller and it can be applied to the AC control system, particularly in the field of power electronics. Applications of P+Resonant Compensator have been proposed including the design consideration. When compared with the traditional controllers such as Proportional + Integral (PI) controller, an accurate control of a high frequency AC signal can be obtained with this type of compensator. The characteristics and merits of the P+Resonant controller are analyzed and illustrated including the controller design in the discrete domain. Another major advantage is the ability to eliminate external disturbance having the same frequency as the tuned resonance frequency.

Keywords: AC system, current control system, proportional + integral (PI) controller, proportional plus resonant compensator

Introduction

Recently, in the field of power electronics, attention has been paid to the performance of the control system used in a circuit. In order to obtain high efficiency of power electronic devices, a very accurate control system is required. However, one of the main control problems in the field of power electronics, particularly when the system is connected to the main, is that the reference signal appears as AC signals to the controller. For example, the controller of a pulse width modulated (PWM) controlled rectifier (Wu *et al.*, 1991; Rim *et al.*, 1994) must track the AC

reference current at the fundamental frequency. Also, for a shunt active filter which is used to improve the power quality of the supply network, the control must be very fast and accurate to inject currents which cancel the harmonic currents drawn by non-linear loads (Akagi, 1996). These harmonic currents have a frequency at least 5 times that of the fundamental frequency. This causes difficulty in the control design to track these AC reference signals with the lowest possible error.

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From knowledge of the control system design, a very high bandwidth controller is required to reduce the tracking error for higher frequency AC signals. However, due to the bandwidth limitation of conventional Proportional + Integral (PI) or Proportional + Integral + Derivative (PID) compensators, these controllers are normally suitable for DC input. But they cannot completely eliminate the steady-state error when the input is AC signals with very high frequency as shown in Figure 1, i.e. a phase difference between the reference and response signals exists. A control system design to achieve such a high bandwidth requires a very small sampling time (very high sampling frequency) (Franklin *et al.*, 1998; Franklin *et al.*, 2002). For a power electronic system, the sampling and switching frequency of the system depends on the kVA level required, and this therefore limits the current control sampling frequency. In practice, a high switching frequency causes a number of problems, such as the device heating due to switching losses at a high power level. Additionally, the components, such as a very fast processor, a high speed analogue to digital converter, and also a high speed switching device, all of which are required for the implementation, will increase the system costs.

The P+Resonant compensator has been proposed in literature for the current control of a power electronic system. A zero steady-state error can be achieved at resonant frequencies using this type of compensator with a proper design. When it is applied to signals at its resonant frequency, it can be considered to be closely related to the PI compensator for a DC signal. As a result, it is very effective in almost

eliminating the steady-state error when tracking an AC reference signal. The characteristics of the P+Resonant controller and the control application based on this controller are discussed in this article. Simulation results are presented and confirm the effectiveness of this alternative controller.

Proportional Plus Resonant Compensator

The transfer function of a conventional PI controller which achieves zero steady-state error for a DC reference input is given in (1) where K_p is the proportional gain and K_i is the gain of the integral term:

$$C(s) = K_p + \frac{K_i}{s}. \quad (1)$$

In the 3-phase system, the popular control scheme is based on the coordinate transformation of the 3-phase system to 2-phase (dq) system (Bose 2001). The transformed signals will be appeared as DC values and are then easily controlled by using PI compensator with zero steady-state error. The P+Resonant compensator performs similarly to the PI compensator in the dq reference frame in that it controls signals alternating at the resonant frequency with quasi-zero steady-state error. It can be derived mathematically by transforming a PI compensator in dq frame of reference to the 3-phase system frame of reference. The full derivation has been presented by Zmood *et al.*, 2001 which has been cited mostly in papers relating to this type of controller. From a survey, there are two main different transfer functions for a

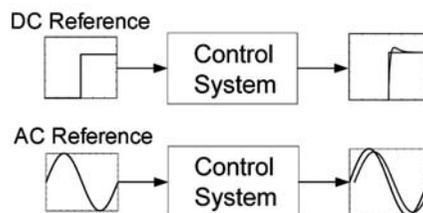


Figure 1. Control system responses of conventional low bandwidth PI or PID controllers

P+Resonant compensator. One is based on a sinusoidal transfer function as in (2); similarly, the other is based on a cosinusoidal transfer function given in (3):

$$C_{\sin}(s) = K_p + \frac{K_r \omega_0}{s^2 + \omega_0^2}, \quad (2)$$

$$\text{and } C_{\cos}(s) = K_p + \frac{K_r \omega_0 s}{s^2 + \omega_0^2}, \quad (3)$$

where K_r is the gain of the resonant term and the resonant frequency is ω_0 . It should be noticed that the ideal P+Resonant controller provides an infinity gain at the resonant frequency. It is obvious that $C_{\cos}(s)$ in (3) has the phase margin (PM) higher than that of $C_{\sin}(s)$ in (2) (90 degrees higher), thus for a stability concern, $C_{\cos}(s)$ is more preferable for the design. In a

control system design, a system with positive phase margin is considered stable since a phase margin quantifies a safety margin that the system has to the parameter variations. PM is the most widely used measure of relative stability when working in the frequency domain. A system with poor phase margin can lead the system to instability or even have highly oscillation behavior. Figure 2 compares two frequency responses of the PI controller and P+Resonant controller having a resonant frequency at 50 Hz.

From Figure 2(a), it can be noticed that the magnitude response of the PI controller tends to decrease when the input frequency increases. On the other hand, the P+Resonant compensator provides a very high gain (theoretically infinite) at its resonant frequency. This means the controller will react rapidly to the input or error at this frequency due to its high gain. As a result,

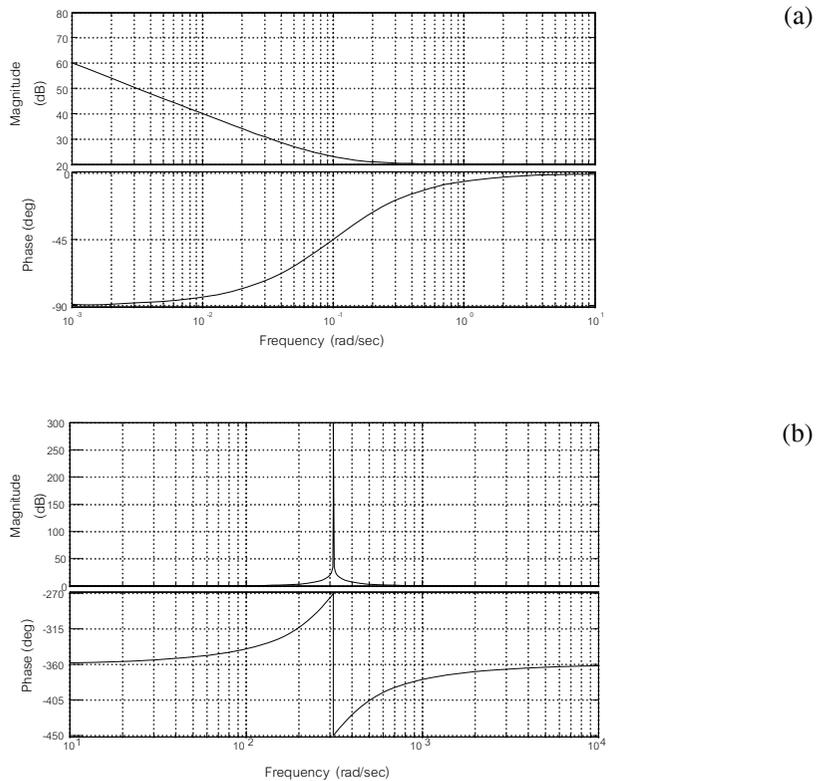


Figure 2. (a) Bode plot of PI controller $C(s) = 10+1/s$ (b) Bode plot of P+Resonant controller $C(s) = 1+2\pi 50.s/(s^2+(2\pi 50)^2)$

the steady-state error can be almost completely removed for a closed-loop control system. For the PI controller, the steady-state response is determined by the DC gain of the system. The DC gain can be designed to be high as the steady-state error is satisfied. However, a very high gain controller is not preferable in some systems in practice, because of the limitation in the rating of the hardware used in the circuit. Additionally, the control will amplify noises.

As mentioned, a very high gain is not always necessary in a control system because it tends to reduce the phase margin causing difficulty in practical work. If the phase margin is insufficient, the system is potentially sensitive to external disturbances that can lead to instability. For the P+Resonant controller, the gain of the resonant term must high enough to achieve a zero or quasi-zero steady-state error. The quality factor Q , is introduced in (4) to change the gain at the resonant frequency. This parameter also affects the band-pass region. The definition of Q is shown in Figure 3. Q represents the ratio of the centre or resonant frequency, f_0 , to the -3 dB bandwidth which is $f_H - f_L$. The upper and lower frequencies, f_H and f_L , are defined as the frequencies where the gain has dropped to 0.707 of the gain at a centre frequency. The transfer function of the compensator is therefore modified to (5) and is chosen for the control of the AC reference in this article. Higher values of Q result in higher gains at the resonant frequency and narrower band-pass regions near this frequency. On the other hand, lower values

of Q will result in lower gains, hence some steady-state errors will be present:

$$Q = \frac{f_0}{f_H - f_L}, \quad (4)$$

$$\text{and } C_{\cos}(s) = K_p + \frac{K_r \omega_0 s}{s^2 + \omega_0 / Q + \omega_0^2}. \quad (5)$$

Design of P+Resonant Compensator

The stability of the current control system should be considered with this type of compensator according to the configuration of the resonant term, which provides a considerably high gain in the closed loop system. Moreover the compensator has a complex conjugated pole, which may cause a resonance in the system. Clearly, to choose the appropriate parameters of the P+Resonant compensators is not straightforward. Quality factor, resonant gain, and proportional gain all need to be carefully selected taking into account many different factors, especially system stability and robustness. Unlike the tuning of the PI compensator, there is no principle to tune parameters of this compensator. However, design methods have been introduced by some researchers. Fukuda and Imamura 2005 obtained controller gains empirically through their experiment. This is based on the rule of trail and error. Lenwari *et al.* 2006 proposed the controller design by using the root locus technique but the design much depends on the designer experiences. The criteria for choosing the proportional gain,

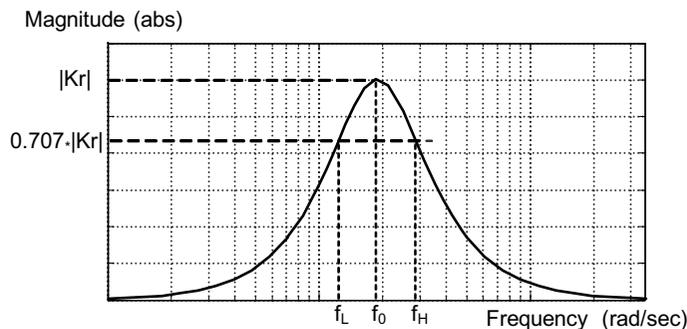


Figure 3. The definition of quality factor(Q)

K_p , the resonant gain, K_r , and the quality factor, Q , is discussed as following. It should be noted that the resonant frequency (ω_b) is designed to match with the frequency of a sinusoidal reference input.

Quality Factor

A higher Q will result in a higher peak and narrower band-pass region around the resonant frequency. However, if the peak magnitude is too high, the system is potentially sensitive to external disturbances and can lead to instability. On the other hand if the peak magnitude is too low, the steady-state error cannot be completely removed at the chosen harmonic frequency. In addition, the quality factor alters the complex-conjugated pole location which needs to be positioned inside the stable region. Too high Q will bring this pole toward the stability boundary.

Resonant Gain

K_r determines the magnitude response of the controller at the resonant frequency. The change of resonant gain K_r will change the numerator of the resonant term which the position of the zero is determined. In general, some distance between the zero and its pole should be adequate to provide sufficient gains at the resonant frequency. For example, in case of K_r is 1, the zero is located near to the pole and this provides insufficient gain.

Proportional Gain

It should be noted that the resonant term provides only a very small gain outside its band-pass region. Therefore, in order to obtain a decent transient response an additional proportional gain K_p is required. K_p plays a very important part in overall dynamic responses of the system including a transient response. The control bandwidth is mainly determined by this gain. Clearly a high proportional gain will result in a faster transient response, but a value must be a compromise between system stability and steady-state error.

Nowadays, the optimization techniques

have been employed to automatically design the controller. These approaches range from the use of the Nelder-Mead method (Dell'Aquila *et al.*, 2006) to the Naslin polynomial technique (Dumitrescu *et al.*, 2007) and the Genetic Algorithm (Lenwari *et al.*, 2007). These techniques can reduce the time commissioning spent in the design process. The optimized controller was obtained with the excellent performance.

Applications of P+Resonant Compensator on AC Current Control System

As mentioned, the popular control scheme of the 3-phase system is based on the coordinate transformation of the 3-phase system to 2-phase system. However, the main drawback of the coordinate transformation based methods is that it requires a burden of complex computations leading to difficulty in real implementation. As a result, it can not be implemented with less computation resources and this is not favorable, particularly for commercial system. In the single-phase system where the transformation theory is not applicable, a popular control is based on PI compensator due to its simplicity. The PI based control is relatively easy to implement but a known disadvantage is the presence of tracking error. Although, a high bandwidth PI or PID controller can be designed by increasing a gain, mentioned earlier it is not preferable in some systems in practice. In addition, the system stability is another concern due to the bandwidth limitation of these types of compensators. With given merits of the P+Resonant controller, this type of controller can mitigate these problems. Therefore, it can be applied to the control schemes of either single-phase or 3-phase power electronics system, i.e. control of power converter of various topologies such as current control of single-phase and 3-phase inverters). It is a simple addition and can replace a traditional PI controller to obtain fast control of the AC reference input. Examples of application of the P+Resonant control in the field of power electronics are presented as following:

Active rectifiers: Active rectifier is widely used as the interface circuit for power electronic devices such as ASD (Adjustable Speed Drive)

because a unity input power factor can be obtained. The active rectifier typically consists of a 3-phase inverter for the PWM and an inductor-capacitor-inductor (LCL) filter for energy coupling and switching frequency harmonic reduction as shown in Figure 4. Control of the active rectifier must be designed to obtain a near sinusoidal line current (fundamental frequency) which results in low harmonic contents. The famous control topology for a 3-phase rectifier employs a vector control theory (Bose 2001) but coordinate transformation adds a complexity to the control. Therefore, Sato *et al.* 1998 proposed a new control based on (2). Zmood and Holmes 2003 and Fukuda and Imamura 2005 have introduced a control based on (3). They obtained satisfactory results with zero steady-state error. Li *et al.*, 2008 compared two current control techniques, P+Resonant and PI control, for single-phase voltage-source PWM rectifiers. A comparison shows the

superiority of the resonant based approach. In addition, it is able to eliminate the disturbance of the fundamental supply voltage completely. Recently, a resonant based approach is applied for the control of multilevel active rectifiers as presented by Dell'Aquila *et al.* 2008.

Uninterruptible power supplies (UPS): The P+Resonant control has been applied to current control algorithms for UPS systems which are applicable to both single-phase and three-phase systems. For example, Loh *et al.*, 2003 developed a high performance UPS control algorithm by adding a P+Resonant compensator into the outer voltage regulation loop to achieve zero steady-state error.

Active power filters: The harmonic problems in electrical power systems have sparked research in the field of active filtering and led to the development of the shunt active filter shown in Figure 5. The active filter is a power electronic device and is controlled to

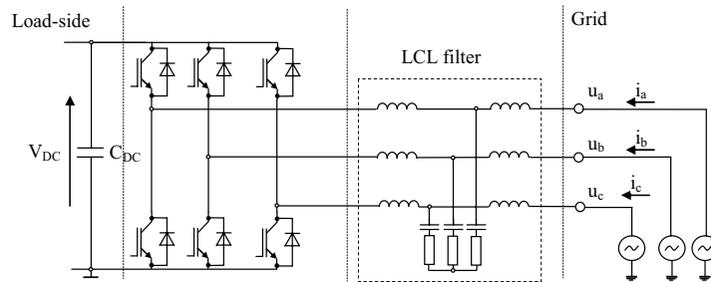


Figure 4. 3-phase active rectifier

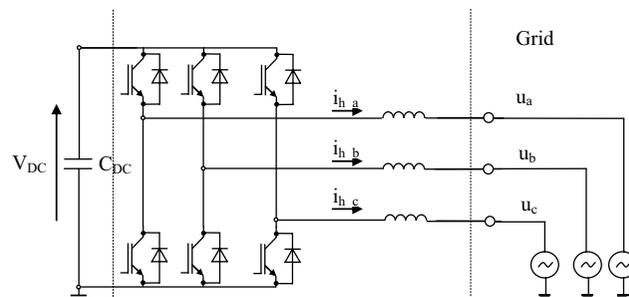


Figure 5. 3-phase shunt active filter

inject current (i_h) into the grid, which cancels the harmonic currents caused by disturbing non-linear loads. The 5th, 7th, 11th, and 13th are the frequencies which are of the most concern since they are commonly the main harmonic frequencies generated by the non-linear load. The difficulty is that the frequencies of these harmonics are considerably high. If the control is not fast enough, a shunt active filter may actually exacerbate the grid harmonics problem. The standard PI controllers can be applied with vector control topology but they cannot control harmonic current injection accurately, particularly for high order harmonics. The P+Resonant controller was applied and obtained an excellent control of harmonic currents (Mattavelli 2001; Yuan *et al.*, 2002; Fukuda and Imamura 2005; Liserre *et al.*, 2006; Lenwari *et al.*, 2006; Lascu *et al.*, 2007). Some controllers were designed to have more than 1 resonant frequency.

Harmonic reference generation: Since the resonant terms provide high gains at resonant frequencies, they can be modified to use as harmonic voltage or current extraction method for generating harmonic reference for the active power filter. These applications have been reported, for example, by Newman *et al.*, 2002.

Photovoltaic (PV) system: In a PV system, the control of grid-connected inverter can be designed with P+Resonant controllers, for example, reported by Ciobotaru *et al.*, 2005 and Xiaoqiang *et al.*, 2006. The control was improved in the performance and achieved zero steady-state error. It is not limited only to PV system applications but also in different power generation systems in the future such as hydropower, wind power, etc.

Distributed generation system: Another application is on the power quality improvement along the distributed line. For example, to improve the power quality of a grid-connected system, the control based on the P+Resonant were proposed by Liserre *et al.*, 2006 and Li *et al.*, 2006. In the latter, the P+Resonant controllers were used to maintain the grid-connected inverter and compensate both positive and negative sequences components in a micro-grid system. The results show the improvement of voltage control and power quality on a micro-grid system.

Future application: Nowadays, research trend in renewable energy has become more popular particularly with the focus on energy efficiency improvement. Renewable energy technologies have been growing rapidly for many forms of renewable energy. A power converter plays a very important part on the system efficiency including the utility interfacing. The high performance control of power converter circuit will therefore enhance the system performance and if resonant control is applicable to parts of the control system, it will be possible to boost a system performance with a precise control.

Digital Implementation

Nowadays, the control strategy is digitally implemented using microcontrollers or a digital signal processor. To design the P+Resonant controller, the simple current control loop in discrete domain is shown in Figure 6. A computation delay to represent the processor delay is included and set to be a 1 interrupt period. The digital controller is shown in the dotted area of Figure 6. The continuous-time controller (5) is discretized by the forward rectangular rule approximation (Franklin *et al.*, 1998) given in (6) where T_s is the sampling time. The digital controller parameters are then derived as in (7):

$$s = \frac{z - 1}{T_s} \quad (6)$$

$$A = K_r \omega_0 T_s, B = -K_r \omega_0 T_s, \quad (7)$$

$$\text{and } C = (\omega_0 / Q) T_s - 2,$$

$$D = 1 + \omega_0^2 T_s^2 - (\omega_0 / Q) T_s. \quad (8)$$

In order to evaluate the control performance based on the P+Resonant controller, it is compared with a simply designed PI controller. A control loop in Figure 6 is modeled by MATLAB/Simulink. The plant is an inductor with little resistance, a common type in the field of power electronics. In this paper, the plant inductance and resistance used in the design were 7.5mH

and 0.4Ω respectively. The sampling frequency is 5kHz. A P+Resonant compensator was designed to have a resonant frequency at 250 Hz and a PI controller was designed with a zero cancelling the plant pole. The control responses are compared as shown in Figure 7. The reference (green color) is an AC signal of 250 Hz with a magnitude of 1A and the feedback signal is blue. Figure 7 clearly shows that the P+Resonant controller (bottom) even with a lower gain (1) has a better performance when compared with

the PI controller (top) with a higher gain (5) as the phase error is almost perfectly eliminated. Further investigation was under taken when the gain of the PI controller was increased to 37 (just before the loop is unstable at the gain of 38). A small phase error can be seen in the result. This clearly shows the superiority of the P+Resonant controller and strengthens what the author mentioned earlier about the merit of the resonant compensator in practice.

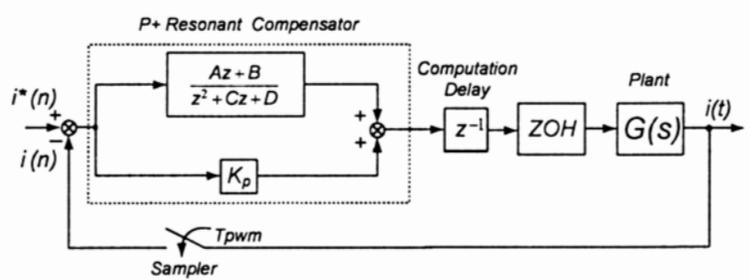


Figure 6. A simple current control loop in z-domain

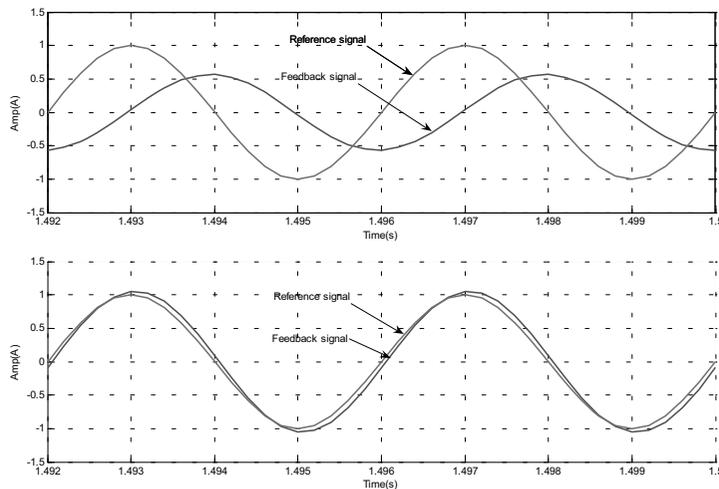


Figure 7. Comparison of control response between PI controller and Resonant controller: (Top) $5(z-0.9894)/(z-1)$; (Bottom) $(z^2-1.545z+0.6396)/(z^2-1.844z+0.9391)$

Disturbance Rejection Property of P+Resonant Control System

One of the most important concerns in a feedback control system is the effect of the disturbance signals. A disturbance signal is an unwanted input signal that affects the system output. It is introduced by any distorted voltages or currents in the system such as the harmonics in the main supply. Some control systems are subject to disturbance signals that cause the system to provide an inaccurate output or even make the system unstable (Franklin *et al.*, 2002). The disturbance rejection property of the current control system based on a P+Resonant compensator was investigated in this paper with both the simulation and experimental methods. Since the P+Resonant controller provides a very high gain at the resonant frequency, it is able to rapidly respond to any disturbances at this frequency

and eliminate them. Theoretically, the overall closed loop gain is high enough to eliminate these main disturbances. This excellent property can also be applied to the drive system to improve the system performance (Mihalache, 2004).

To begin, the current loop with respect to the presence of a disturbance (Figure 8) is modeled by MATLAB/Simulink. The voltage disturbance is an AC signal 50 Hz with the amplitude of 10 V. It is applied to the current control loop at the time 0.5 second. Simulation results presented in Figure 9 shows the feedback signal (blue), the output of the delay block in Figure 8, and the input voltage disturbance (green). It is clearly seen from Figure 9 that the current control quickly reacts to the voltage disturbance. At the steady-state, the voltage disturbance is controlled.

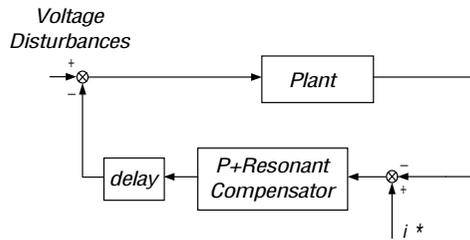


Figure 8. Current control loop with respect to disturbance

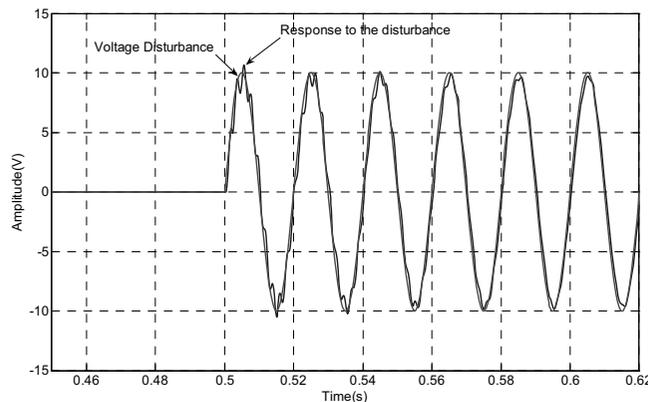


Figure 9. Simulation of the current control loop with respect to the voltage disturbance showing the disturbance rejection property

In practice, the current control system can be seriously impaired by external disturbances, particularly the background harmonics on the supply voltage, and the effect of non-linearities in the power electronic converter such as deadtime and even the PWM algorithm itself. The deadtime has a considerable effect on the inverter output voltage. The distortion in the output voltage at the current zero crossing results in low order harmonics such as 3rd, 5th, 7th and so on, of the fundamental frequency in the inverter output. Similar distortions occur in the line-to-line output voltages of the 3-phase PWM inverter where low-order harmonics are of the order $6m \pm 1$ ($m = 1, 2, \dots$) of fundamental frequency (Mohan *et al.*, 1995). The main voltage disturbances corresponding to the supply harmonics, and deadtime effects inevitably exist in the system.

To experimentally verify the disturbance rejection property, the comparison had been made with the fundamental current control using the simple PI controller and the P+Resonant controller having resonant frequencies at 5th, 7th, 11th, and 13th of the fundamental frequency

as shown in Figure 10. In Figure 10(a), the PI controller is unable to reject the disturbances introduced by the supply voltage harmonics, and the inverter non-linearities, and significant 5th and 7th harmonic distortion can be seen. By contrast, the operation of the P+Resonant controller is illustrated in Figure 10(b) and the harmonic reduction in the presence of the same external disturbances is obvious. This confirms the exceptional property of the resonant based control system.

Conclusions

This article has reviewed a high performance control of AC signals by using the P+Resonant controller. The characteristic of the suggested controller has been described in detail. Recently, research trends favor fully digital control. Thus, a modified transfer function of the P+Resonant controller is proposed and discretized, which allows digital implementation. In order to show the advantage of using this type of controller, applications to an AC current control system are presented showing the precise control of the AC

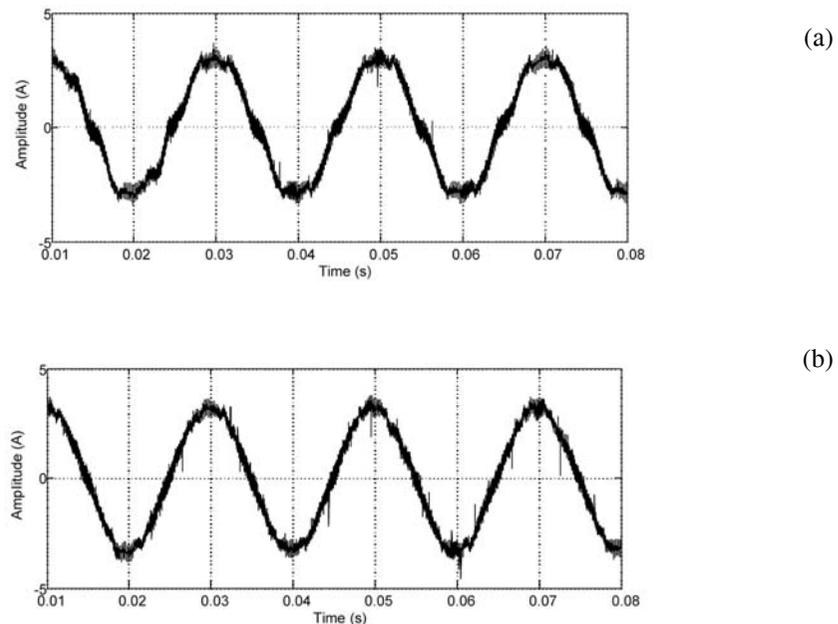


Figure 10. Fundamental Current Control (a) PI controller (b) P+Resonant controller

reference having a frequency at the resonant frequency. As the zero steady-state error can be achieved at resonant frequencies, this controller is very fascinating and the author believes that such an advantage may be of interest to a control system designer, particularly in field of power electronics where the AC control system is widely used.

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