Adaptive and Fast-Response controller for Boost PFC Converter with Wide Range of Operating Conditions

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Abstract

This paper provides a manner to design adaptive controller for Boost PFC converter. An Adaptive controller can compensate variations in converter parameters and conditions then lead it to best and near ideal performance. We design an adaptive controller by use of Gain Scheduling techniques. To improve response of output voltage at encounter to load variations, we propose use of fast dynamic techniques and adaptive controller simultaneously. In addition, we choose a Boost converter to operate in wide range of load variations. In other word it coverage CCM, MCM, and DCM then has very near to unity power factor in all operating conditions.

Keywords: Adaptive Control, Boost Converter, PFC Converter, Gain Scheduling, CCM and DCM.

I. Introduction

Adaptive method not only use in controller design but also employed in wide filed of other sciences. In the nature, any things finally adapted with environment condition. The adaptive control is an important topic in adaptive literature. The control word means hold a system or things in reasonable condition or lead on to wanted way. If reasonable condition, wanted parameter or nature of system change and controller stay to fallow previous defined parameters, then system encounter with essential problem. The non-adaptive control is suitable only for systems that are time invariant on conditions and laws. The parameters and conditions are change in most systems and are unavoidable. Overcome to these problems is challenging of adaptive controller designers. In literature, explain different classifications in field of adaptive control [1], [2]. Any adaptive control method has advantages and drawbacks or disadvantages depend to system under control. Therefore, we must choose a suitable method of classical adaptive control or initiative manner, to control converters that operate as a Power Factor Correction (PFC) converter. Therefore, designer must investigates and good understands the essential operation of switching power converter. In this work, we will focus on Boost converter and then we can expand the methods to other converters. A PFC Boost converter ordinary constructed of two control loops. In other words, at least two specifications of converter must control with controller. The output voltage and input or inductor current of converter must be control by controller. The voltage control loop regulates output voltage on favored level. Voltage regulating is important necessary or is critical task of any AC-to-DC or DC-to-DC converter. Any unregulated voltage on the converter's output, can damage or harm to supplied circuits and devices. Thus the prior task in converters is providing best quantitative and qualities of output voltage. If this firs task does not confirm the converter is not converter. Another task in all AC-to-DC converters is providing unit or near unit Power Factor. This reasonable specification is a quality option in converters. The standards about power factor or Total Harmonic Distortion (THD) are at least amount must observe with PFC designers. The conventional PFC controllers such as Proportional–Integral (PI) Controller or Proportional–Integral–Derivative (PID) Controller usually design for its operating point exactly and utmost have reliable in narrow area around of operating point. The move converters operating point in most applications is normally. Thus, PFC with use PI and PID controllers has not reasonable performance in wide range of load also converter act well in one point. To overcome this problem we propose adaptive controller. That controller adapts itself not only by load variation but also by any change on other condition as same, as input voltage variation and switch between converter operation modes. Most efforts to design PFC converter focus on only one mode of converter operation modes [3]-[5]. Boost Converters can operate in several modes such as Continuous Conduction Mode (CCM), Discontinuous Conduction Mode (DCM), and Mixed Conduction Mode (MCM) depend to amount of load and other condition [6]. The CCM and DCM are different in behavior and structure, thus to operate in wide range of load need two separate controller on DCM and CCM, or an adaptive controller. This paper organized as follows: the next section first introduces adaptive control and review classification of adaptive control systems. Then it will explain reasons to choose Gain Scheduling. Section III discusses basic design adaptive controller with Gain Scheduling and introduce its structure. In section IV, we explain simulation result and propose fast-response adaptive controller then it investigate it by simulation results.

II. Choose an Adaptive Control Method

As mentioned above, any type of adaptive control system has advantages and disadvantages. To choose one method we have review classification of adaptive control systems.

Gain Scheduling is an approach to control non-linear systems. These types of adaptive control systems are suitable for systems have measurable variables. In this manner, the system has at least two loops, one loop consists of controller and plant and another loop provide controller parameters depend to plant variation. It is use of preloaded tables to map some plant parameters to controller parameters. Gain Scheduling adaptive system compensates move of operating point in plant. The whole width of operations area fractions to subintervals, then design controller for any subinterval particularly. In other word, obtain controller parameters for any subinterval separately. Thus, these parameters depend to that operating point and lean on amount of measurable plant variable directly. At final arranged all parameters in tables and employ lookup table technique such as interpolations to supply controller parameters [1], [2].

Model Reference Adaptive (MRA) control is an important and power full manner in adaptive systems, if we able to provide a suitable model of plant. In this approach compare outputs of actual system with like output or signals of model and product errors signals, and then exert mathematical acts and theories such as MIT or Lyapunov's laws. The results are supply to controller that leads error signal to minimum value and stable system [1], [2], [7], [9].

Dual Adaptive Control is base on dual control theory. It is a branch of control theory for system deals with characteristics are initially unknown. These systems call "dual" because controller uses two kind's information in control process, current system knowledge and experimental information about its behavior [2].

Self Tuning Regulator is an approach adaptive control. It is use PID, pole-placement or other conventional control methods with adjustable parameters in controller that adjusted by measurable parameters on plant. It has Estimation unit and controller design unit. There are several methods to estimation plant's parameters and depend to that estimation results directly apply to controller or by use of "Design Controller Unit", it is called direct or indirect adaptive control respectively [2], [10], [11].

As comparison all adaptive control methods and look at PFC converters we propose Gain Scheduling approach to design adaptive PFC. We select this method because, moving of operating points is essential challenge of PFC converter. In addition, Gain Scheduling techniques are use to compensate moving of operating points and others variations in system under control. Finding variables that specify operating point or operation condition is important problem in Gain Scheduling. On the other hand the load or inductor current, output voltage and input voltages of PFC converters are measurable. When PFC converter operates in wide range of load, it is as same as change operation's points only. In addition switch between CCM and DCM can consider as change operating points. When we are implement Gain Scheduling for complete range of load it has consist of light load refer to DCM and heavy load refer to CCM. Means design separate controllers for CCM and DCM or in other words use an adaptive controller. We Must attentions that important variables of converter are involve with unwanted change slowly or rapidly. input or inductor current is depend to load current and input voltage is depend to line voltage of power distribution system. Therefore these converter variables are predictable and they variance in specific range. We can have compute controller parameters and gather all parameters in several tables then switch to appropriates parameters rapidly. Gain Scheduling is not need complicate calculation or estimation, because controller parameters stored in tables based on plant parameters. It is as same as memory that plant's variables or plant's parameters provide or made memory's addresses and controller's parameters store in memory cells. Then it act as fast as read of a memory. For more explain, Gain Scheduling tables are as same as read only memories that designer wrote those and then all time it reads only. Therefore, an important advantage of Gain Scheduling is higher operating speed as analogues by other adaptive manners. Gain Scheduling is simple in design stage and implementation, because Gain Scheduling systems do not involve with complicates algorithms and calculation.

III. Design Adaptive Controller

We select a Boost converter that coverage DCM and CCM operation modes to have comprehensive investigate and extensive controller design. The inductor value and switching frequency are important parameters that specify boundary between two operations modes and amount of power can provide at output in Boost converters. We consider the switching frequency and inductor value are constant. Because the PFC converters involve with current controller and voltage controller we propose adaptive controller for two loops. The conventional PID controllers are simple and have reasonable response in PFC, thus we propose PID controllers that parameters obtain of Gain Scheduling techniques. In this approach, we provide independent Gain Scheduling adaptive controllers for voltage and current loops. Indeed, we arrived that PI controllers are sufficient for voltage and current loops, also construct simulation with PID controllers with lookup tables in virtual environment of MATLAB simulation. The controller design divided to several steps. In first step, we select a Boost converter with wide range of load. Then on second step, we must fraction load range to subintervals and design suitable PID controllers for any of subintervals. In the first step, we envisage with several questions. How operation areas divide to subintervals? Where are suitable boundaries? We think reply to questions such as; these questions are an independent research topic. To answer above questions we explain, as a point of view that controller's parameters in any subinterval must satisfy wanted aim and credit during it subinterval. If the system's variants are rapidly then the length of subintervals must choose smaller than a system with slowly variant. It is better Boost converters load range, fraction in to several subintervals in any operation mode. Therefore, any subinterval can sits in CCM or DCM absolutely or in MCM. At third step, we must design PID controllers for any subinterval. We have a special output's power and special input's effective voltage for any subinterval. We consider that other elements and parameters of Boost PFC converter such as inductor value and switching frequency are constant. We will find PID parameters for any subintervals of load range by trial and error. However, the trial and error is not a time save approach but it is useful because Boost PFC has two dependent control loops and cannot use of ordinary design method readily. Fig. 1 shows a Boost PFC converter, that its circuit parameters are show in Table 1. We design adaptive controller for Boost converter the basic parameters has mentioned in Table 1. From zero to 80 watts this Converter operates in DCM absolutely. Then appear CCM mode on during times that input sinusoidal voltage is near the peak, by increase output load. This PFC converter has CCM and DCM in one period of line voltage or in other words, it is in MCM, during 80 to 150 watt of power load. Converter goes to CCM absolutely for output power above 150 watt. We divided load power variation area in into five sections and consider input voltage that basic is 110 volts root mean of square (rms) decrease to 90 volts or increase to 130 volts. Thus the tables in Gain Scheduling have two dimensions, one dimension input voltages and other dimension output power. In other word, we consider five subinterval in output power and three subintervals in input voltage. Therefore whole operation area divides in to 15 subsections. Then must obtain PID coefficients for any subsection and gather coefficients in tables as use as lookup tables. The tables that use as lookup tables in simulation for voltage and current loops are separately. In addition, we make special table for any PID coefficient separately. Table 2 contains Proportional coefficients of PID controller in current loop. Integral coefficients of current loop PID controller gather in Table 3. Table 4 and Table 5 are containing proportional and integral coefficients of voltage loop PID controller respectively. Derivation coefficients of PID controller in this paper are equal to zero. However, to provide a comprehensive comprehend of Gain scheduling that easily developable to other converters we emphasize to PID in seated of PI controller.

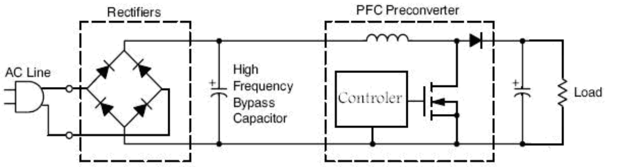

Fig. 1 Boost PFC converter

Table 1 Boost converter circuit parameters

Parameter	**Value**	**Unit**
Input voltage	110	Volt (rms)
Output voltage	200	Volt
Inductor	400	μ H
Capacitor	470	μ F
Load power	0 – 250	watt
Diode feed forward voltage	0.7	Volt
Switching frequency	40	KHz

Table 2 Proportional coefficients of current loop PID

Volt(rms) \ Watt	**50**	**100**	**150**	**200**
90	0.001	0.001	0.0001	0.00005
110	0.001	0.001	0.0001	0.00005
130	0.001	0.001	0.0001	0.00005

Table 3 Integral coefficients of current loop PID

Volt(rms) \ Watt	**50**	**100**	**150**	**200**
90	10000	10000	1000	1000
110	10000	10000	1000	1000
130	10000	10000	1000	1000

Table 4 Proportional coefficients of voltage loop PID

Volt(rms) \ Watt	**50**	**100**	**150**	**200**
90	0.9	0.15	0.15	0.2
110	0.9	0.1	0.15	0.2
130	0.1	0.1	0.15	0.2

Table 5 Integral coefficients of voltage loop PID

Volt(rms) \ Watt	**50**	**100**	**150**	**200**
90	1.2	3	7	16
110	1.3	3	7	19
130	1.4	3	8	20

IV. Simulation Results

For simulation we use of MATLAB/SIMULINK. In the beginning, we design necessary models of Boost PFC converter in SIMULIK environment. The models must have true function in all operation modes. As mention before we construct Gain Scheduling adaptive controller with use of PID structure that coefficients supplied from pre stored lookup tables. Fig. 2 shows block diagram of this adaptive controller, with three lookup tables. The input voltage value and amount of load power select suitable coefficients from tables. We examined the above PFC, encounter to variations of input voltage, and load power value. Fig. 3 shows response of adaptive PFC to change load power from 50 watt to 200 watt and vs. it is shows that converter have reasonable power factor and compensate output voltage in short time. For more details, we show zoomed figure of Fig. 3 during increase and decrease load value in Fig. 4 and Fig. 5 respectively. As see in Fig. 5, converter output voltage has an overshot that raise to near 350 volts. This overshot is a failure or inability to succeed. In actual, overshot on output voltage of converter can damage or harm to devices and circuits supplied by converter. Limited bandwidth of voltage loop is the reason why occur overshoot and undershoot in output voltage during suddenly change load value. Beside the voltage controller must have limited bound width (e.g. 10 Hz) that filters and stops output voltage’s ripples. Output voltage’s ripples order is twice of line voltage frequency. There is a trade off between voltage loop low bandwidth and high-speed response to load variations. Many efforts current in literatures for overcome this problem [12]-[17]. Therefore, by use some techniques we can have PFC converter with high-speed voltage response and eliminate effects output voltage's ripples simultaneously. We decide to improve the above adaptive PFC converter by supplement a ripple elimination technique to it. The output voltage's ripple $\tilde{v}_O$ is [13]

$$\tilde{v}_O = \left(\frac{-V_O}{2\omega C_O R_O}\right)\sin(2\omega t) \qquad (1)$$

Where, V_O , R_O , C_O , ω , t are output voltage, load resistance, output capacitance, sinusoidal input voltage's radian frequency and time respectively. In any trial to achieve PID coefficients, we measure domain of voltage's ripple. We propose a method to eliminate output voltage's ripple that its simulation block diagram depicts in Fig. 6. it shows that a section on Block diagram generate a signal, as same as out put voltage ripple and add with negative sing to ripple, to delete it before reach to voltage controller. In this case, the output voltage's ripples completely removed of output voltage before reaches to controller. Therefore, we can use controller with higher bandwidth in voltage's loop now. We repeat trials and obtain PID coefficients in the extended converter operation area. We gather voltage's controller coefficients in Table 6 and Table 7. The coefficients current's controller not change and have before values. Fig. 7 shows responses of propose adaptive PFC converter with fast dynamic to change load from 50 watt to 200 watts and vs. it shows that output voltage has a very little overshoot as compare as Fig. 3. In addition, input current followed the shape of sinusoidal input voltage in worst case during increase load to 300 percent. For explain, more details of recent PFC responses, we depict zoomed in of during load change of Fig. 7 at Fig. 8 and Fig. 9. Therefore, we propose a comprehensive Boost PFC converter, whit use adaptive control, and fast dynamic technique simultaneously.

V. Conclusion

This paper has outlined and illustrated a method to obtain an adaptive and fast-response controller for power converters. The proposed methods are simple, robust and easy to design and simulate. The methods are easy to develop to other converter types. Adaptive Gain Scheduling is easy to comprehend. Simulation times are a few tens of second, by use models of converter that obtain by averaged techniques. The proposed methods have not needed complicate equations that describe converter or complicate calculations. Using adaptive and fast-response technique in converter controller simultaneously and coverage wide range of operating conditions together are reasons that proposed methods are suitable for extensive field of converters used.

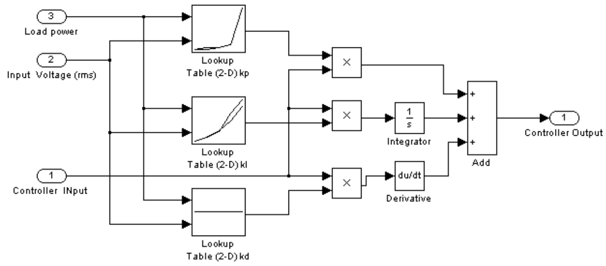

Fig. 2 PID controller model that coefficients supplied from lookup tables in MATLAB/SIMULINK

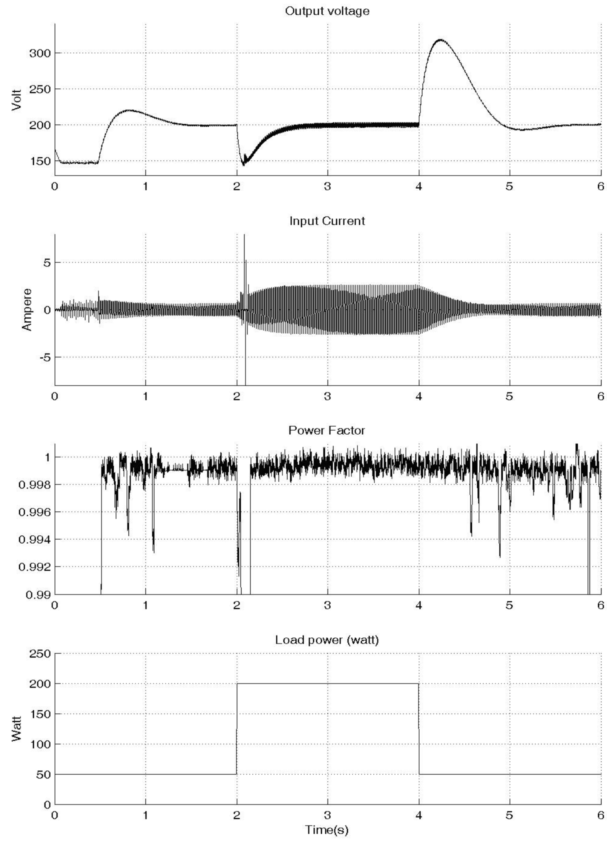

Fig. 3 Responses of Boost PFC with adaptive controller to load power variation from 50 to 200 watt and versa; Signals from top to down are output voltage, input current, power factor and load value of converter respectively.

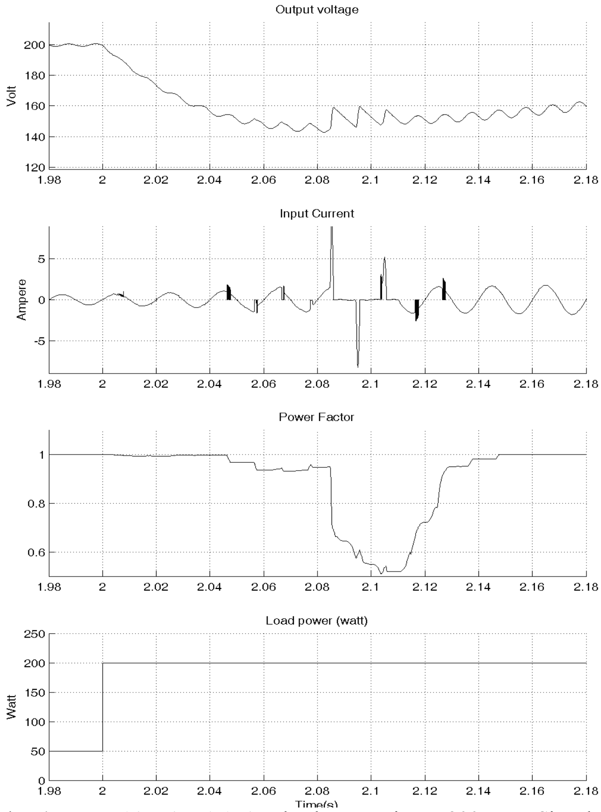

Fig. 4 Zoomed in Fig. 5 during load power rise to 200 watt; Signals from top to down are output voltage, input current, power factor and load value of converter respectively.

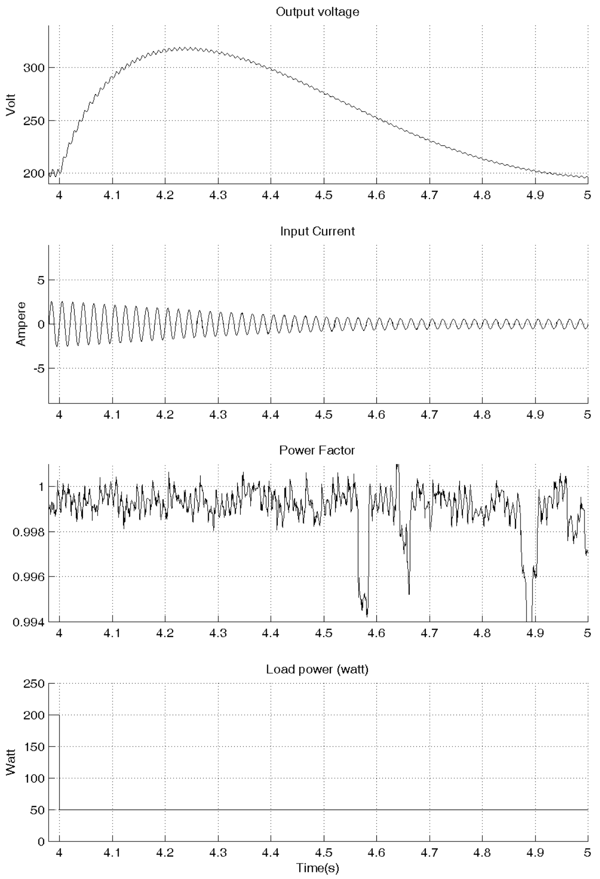

Fig. 5 Zoomed in Fig. 5 during load power fall down to 50 watt; Signals from top to down are output voltage, input current, power factor and load value of converter respectively.

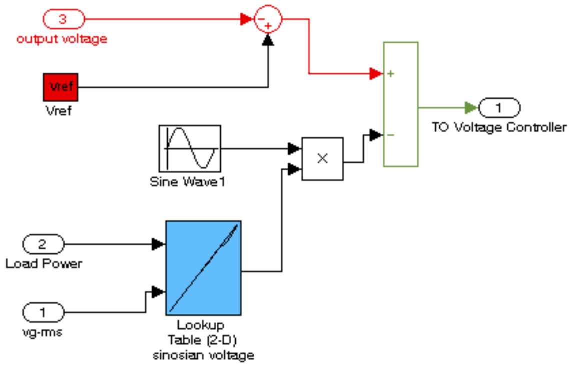

Fig. 6 Block diagram that generate a signal, as same as out put voltage ripple and add with negative sing to ripple, to delete it before reach to voltage controller.

Table 6 Integral coefficients of voltage loop PID with fast response

volt(rms)\watt	**50**	**100**	**150**	**200**	**250**	**300**	**350**
90	20	45	60	75	105	126	140
110	21	50	62	78	165	200	210
130	30	40	55	90	180	250	300

Table 7 Proportional coefficients of voltage PID with fast response

volt(rms)\watt	**50**	**100**	**150**	**200**	**250**	**300**	**350**
90	3.5	5	7	7	9.8	9.8	10
110	3.6	5.5	7	12	13	14	14
130	9.8	10	11	14	14.5	16	16

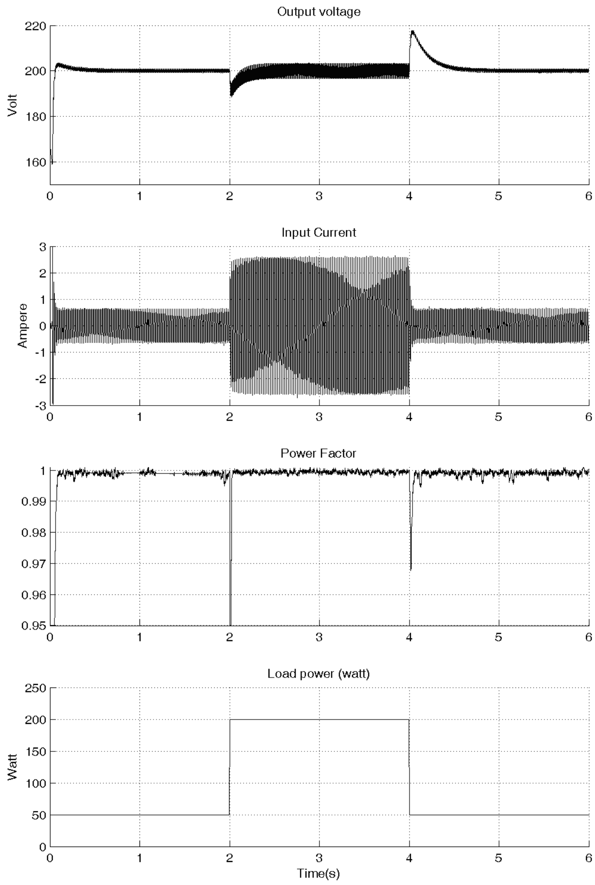

Fig. 7 Response of Boost PFC with adaptive controller and fast voltage control loop, to load power variation from 50 to 200 watt and versa; Signals from top to down are output voltage, input current, power factor and load value of converter respectively.

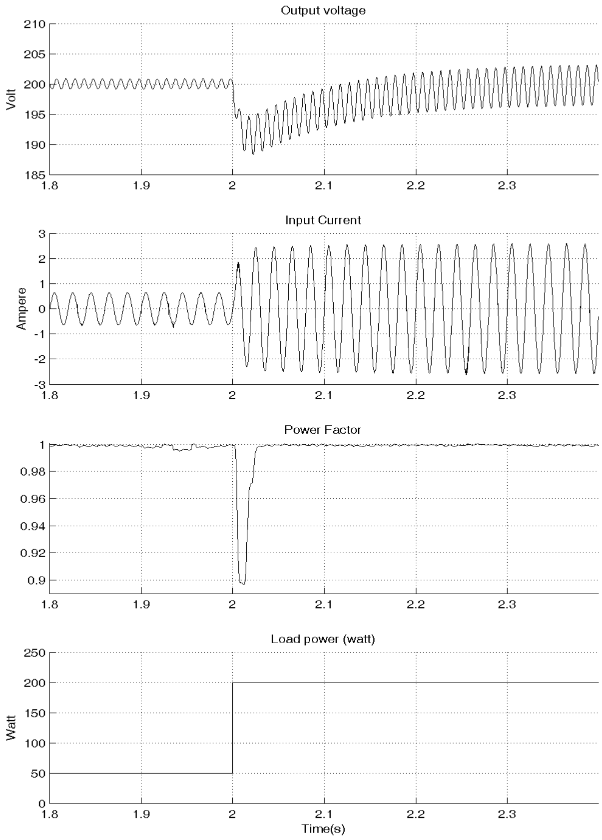

Fig. 8 Zoomed in Fig. 7 during load power rise to 200 watt; Signals from top to down are output voltage, input current, power factor and load value of converter respectively.

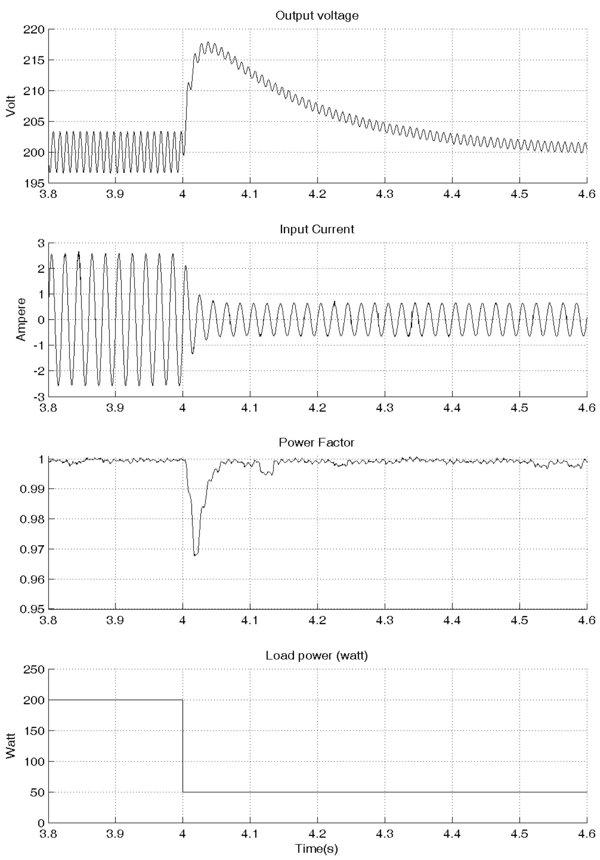

Fig. 9 Zoomed in Fig. 7 during load power fall down to 50 watt; Signals from top to down are output voltage, input current, power factor and load value of converter respectively.

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