Modeling & Simulation of Digital Current Mode Controller for Buck Converter

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Abstract: *From almost Last two decades Power electronics has been one of the most interesting and challenging topic of study and till date demanding efforts and research is going on to improve the comprehensive characterization and overall efficiency of Power converters as they are used in wide range of applications of engineering like, Electrical power Systems, Electrical & Electronics equipment and appliances and one of the most important converter is DC-DC Buck Converters and Due to its use in several applications, its efficiency needs to be enhanced by using a suitable controller. In this Paper, An Average current mode controller is proposed and implemented for Buck converter. Proposed CMC control technique is simulated in MATLAB/SIMULINK and its results are very much authenticated. Simulation analysis of designed model reflects the efficacy of the proposed controller.*

Key Words: *Buck converter, Average current mode controller, Steady-State response, PI controller.*

1. INTRODUCTION:

Power Electronics converters has become an interesting subject of study in technical field in which lot of research is going on for its component's configuration. There are mainly four types of converters namely AC to AC (Cyclo-converters), DC to DC (Choppers), DC to AC (Inverters) and AC to DC (Rectifiers). These converters are used in wide range of applications [1, 2] and configured in two types Linear & Switch mode where switch mode can be configured in two techniques, Isolated or non-isolated and there are also other sub classified configurations of both, In Isolated Technique Isolation is provided by means of a nonphysical connection between the converter and source such as transformer. In Non-Isolated Switch mode the power switches are used (normally MOSFETS, IGBTs) which have a sensitive terminal, hence require an opto isolator to provide the external high frequency signal [1, 3]. Switch mode controllers for power electronic converters operate according to the switching pulses on power switches at high frequencies. The controlling prospect and the reduced size are obtained at higher frequency operation thus overall cost is reduced. Real time switching in the power converter produces some nonlinearity these nonlinearities are considered in designing a controller. Due to the absence of a closed loop controller (open loop) DC-DC converters cannot achieved Voltage regulation for very long time, To overcome this issue Controllers are designed and few of factors must be considered like high overshoot and settling time , (Raymond B. Ridley 1991) presented the continuous-time model for current mode control. One of the latest control models which had demonstrated to be very precise at half of the switching frequency. But there were many difficulties with designing and implementing such a model due to the complex mathematical modeling [1].

Some of the last decades, Engineers are designing controllers with aimed to improve the efficiency of the digital signal processors (DSPs), microcontrollers, and field-programmable gate arrays (FPGAs) used for some wide-ranging applications like high & low frequencies operating drives and motors. In designing these kinds of controllers, the low frequencies are specially scrutinized, therefore some limitation must be in consideration when dealing with these types of controllers.

Continuous research has leaded the digital controller technology to the development of highly integrated, least cost and upgraded performance models. In these types of controller, such as these are integrated on Very Large-Scale Integration(VLSI) Chip IC, there are some provisional blocks within those, Advance Analog to Digital Converter's(ADCs); Digital I/Os; flash ROM; CPU for programming, communication, diagnostics, power management, etc, because these blocks are extensively used for most of the digital applications. Digital controller not only provides the fitted output voltage regulation but improved performance than the analog controllers [2, 3]. Work done in [2] uses a CMC that is adaptively controlled by digital circuits for buck converter which was somewhat impractical when it comes to the implementation in a hardware model. Digital PWM based controller based on time domain analysis was designed and tested in [5], which shows decent response but complex circuitry was a major de-merit of the proposed controller.

Cascaded controller is designed and suggested in [6] and implemented through analog operational-amplifier circuits. Performance & Efficiency of the controller was based on critical damping condition and thus shows no overshoot but need more settling time.

2. BUCK CONVERTER:

The buck converter implements the process of stepping down the output voltage from the high input voltage; an equivalent to the step-down transformer in AC systems. It is the modest converter in DC-DC power converters designed with the help of static switch (e.g. MOSFET), diode, inductor and capacitor. The buck converter has two modes of conduction called as Continuous Conduction mode (CCM) and Discontinuous Conduction Mode (DCM). Working of buck converter depends upon switching of MOSFET. When MOSFET is in ON condition, inductor current is increasing thus having a positive going ramp. When MOSFET is in OFF condition, inductor current decreases thus having a negative going ramp. In CCM inductor current start a positive going ramp without falling to zero while in DCM, it falls to zero and rests there for a time period and then starts positive going ramp [4]. Figure 1 represents simple circuit for the DC voltage step down converter using a switch where switching signal will be applied.

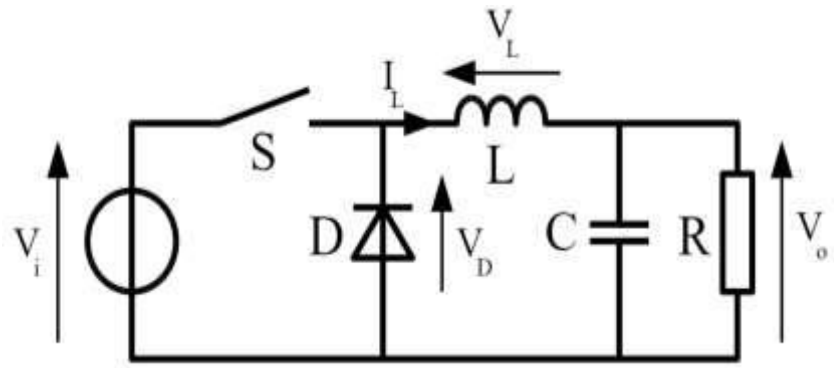

Figure 1: Circuit Diagram of Buck Converter

As per the mathematical model, the duty cycle can be determined using Equation (1)

$$D = \frac{t_{on}}{t} = \frac{V_o}{V_{in}} \qquad (1)$$

As buck converter work on two modes their equation can be determined using Kirchhoff's law for Voltage and current. Equation (1) shows conduction mode where, The MOSFET starts current conduction to load at the outset through a inductor (which is used for energy storage), capacitor (which filter out the ripples of output voltage), and the diode is used reverse biased,

$$\begin{bmatrix} i_L \\ V_o \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_o \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{in} \qquad (2)$$

Equation (3) is for Non conduction mode where the inductor is fully charged and the MOSFET will not conduct; the inductor current then get discharge through the diode and capacitor.

$$\begin{bmatrix} i_L \\ V_o \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_o \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} V_{in} \qquad (3)$$

Complete operation of the step-down buck converter for both modes can be evaluated by mathematically multiplying the right-hand sides of Equation (2) and Equation (3) with the addition of Duty cycle D and (1-D) Respectively, Equation (4)

$$\begin{bmatrix} i_L \\ V_o \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_o \end{bmatrix} + \begin{bmatrix} \frac{D}{L} \\ 0 \end{bmatrix} V_{in}. \qquad (4)$$

The simulation model buck converter Diagram is shown in Fig 2

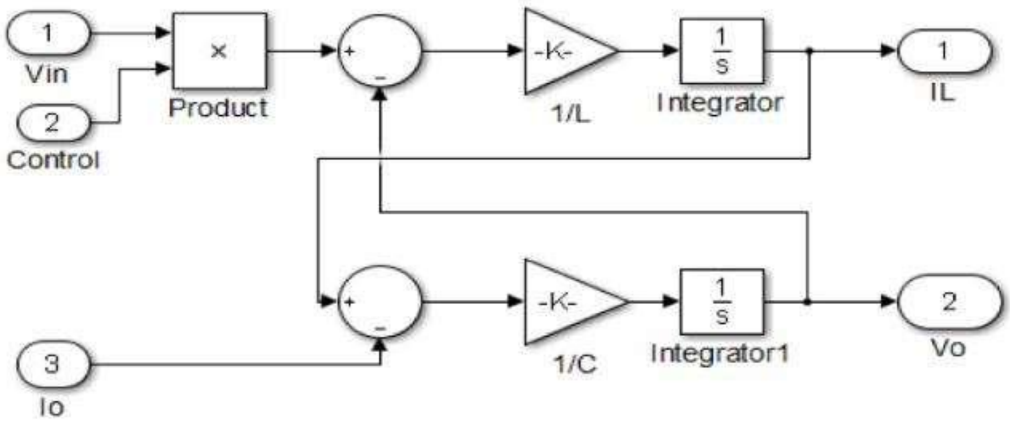

Figure 2: Buck converter state space Model in Simulink

3. CLASSIFICATION OF SWITCHING CONTROLLERS:

There are different control methods for switching that can be functioned in many methods by means of diverse topologies involved in the feedback loop for the DC-DC converters [5]. Classification of controllers differ with the requirements of applications. Universally used switching controllers are, (CMC) current mode control, (VMC) voltage mode control (SMC) sliding mode control and V2 mode control. Each of them has some merits and de-merits over the others [3] and the designer have to select according to applications requirements second order nonlinear controller is used in [4] to improve the transient Response of DC-DC converter.

There are two types of disturbance to measure the control loop:
Load regulation: when sudden increase in Load current, the transient response of output voltage;
Line regulation: When sudden increase in Line Voltage, the transient response of output voltage.
The improved the loop designed, the minor the output overshoot, the smaller the output settling time.
Considering different sampling method at output node, there are basically two control methods: voltage control and current control.

In voltage mode control, the sampled output voltage is matched with a reference voltage and generates an error signal. Through the comparator, duty cycle will change as the error changes. Assume that output voltage is greater than the reference, a negative error is generated. This will decrease the duty cycle to close MOSFET Switch longer time. As Duty cycle becomes smaller, output voltage will be reduced and error will become smaller.
Current mode control technique includes voltage sampling and current sampling, it is based on two-loop control. Voltage sampling is same as voltage mode. Current sampling is used to sample the voltage across a sensing resistor. In that manner, the inductor ripple current will interpret into ramp voltage and served back to the comparator Due to increase in control action of current loop it is well suited for cascaded controllers.

4. SYSTEM DESCRIPTION:

In this research, an Average current mode controller is designed for Buck converter. As discussed earlier there are two loops in current mode controller; an outer voltage loop and the inner current loop. Voltage signal for outer voltage control loop is taken from the output capacitor and the current signal from the inductor in the power stage PI controller is used for comparing and compensating of these signals in order to achieve the desired output; the ADC Quantizer in the circuit takes the signal and delivers to the power switch after the modification. The model was successfully tested using the MATLAB/SIMULINK.

The Simulink model of Average current mode controller for buck converter is shown in fig.3, The parameters of the converter are: Vs=50V, Vref=20V, f=350kHz, R= 5ohms, L=350uH, C=10uF, the actual output signal is matched with the reference signal voltage and the resulting signal is transformed into the controlled PWM signal by means of current compensator. Signal from the voltage error amplifier is managed by the PI Controller in current loop, the Pulses produced is inserted to the MOSFET in buck converter. Results obtained for inductor current and output voltage are observed at various operating parameters like Line & Load Variation of the Simulink model.

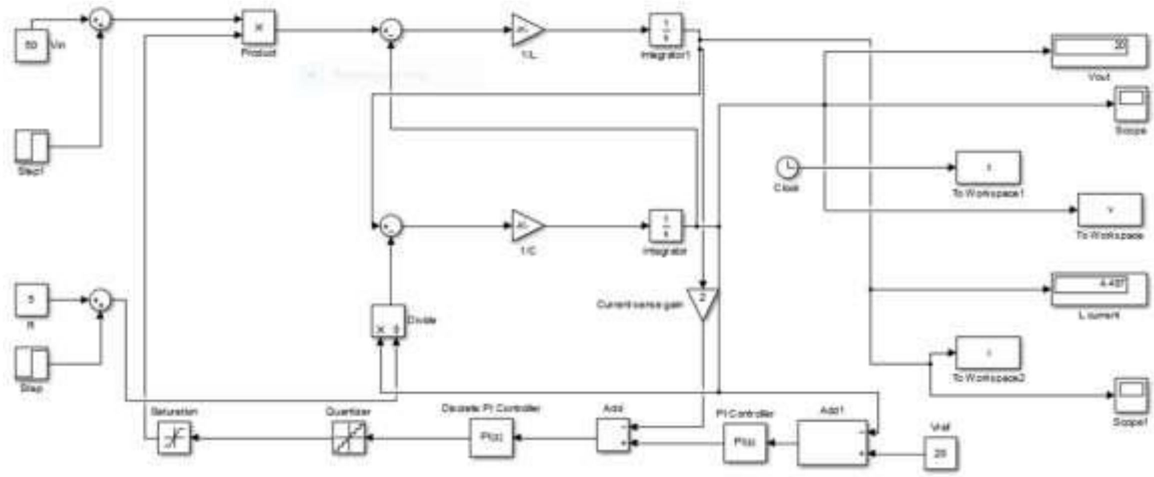

Figure 3: Simulation Model of Current Mode Controller for Buck Converter

5. RESULT AND DISCUSSION:

Developed simulation model of the Average current mode control for Buck converter scheme are analyzed under varying operating conditions. Figures 5 and 6 show Current for inductor and resulting voltage response for initial transient at start of the buck converter with proposed Average current mode controller. There is an Overshoot of 1.34 A, which is then settled after 0.2 ms and gained the stable state at 4 A. The Output Voltage has an Overshoot of 2.5V and settling time of 0.02 ms

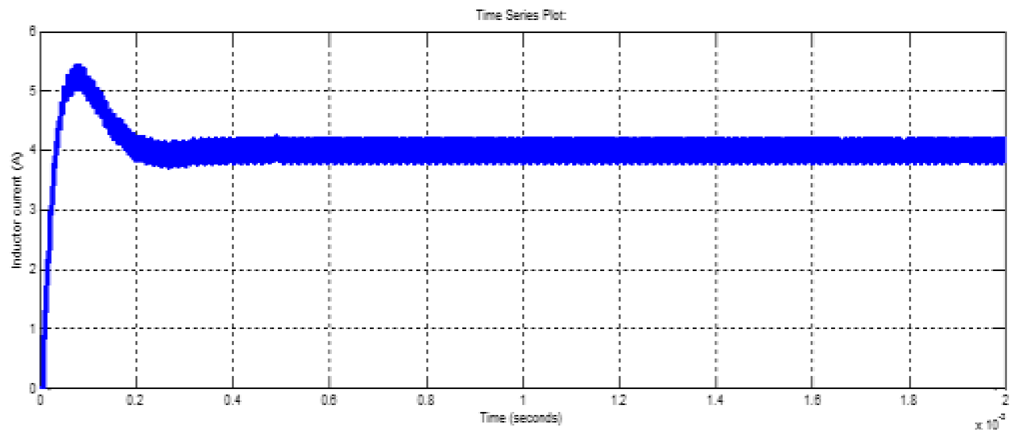

Figure 5: Simulation Graph of Inductor Current

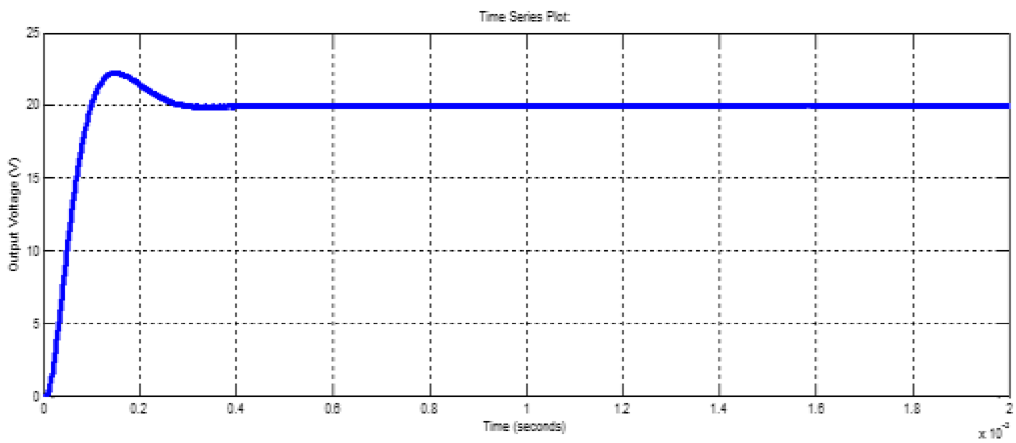

Figure 6: Simulation Graph of Output Voltage

Figures 7 and 8 show resulting voltage and response of current of inductor for Line deviation from 50 to 65 V. The Resulting voltage has no major difference and remains same as for line voltage of 50V. For inductor current there is an Overshoot of 1.5 A, and same settling time of 0.2 ms as for line voltage of 50V and gained the stable state at 4 A but DC component was less smooth as compared to Inductor Current for line voltage of 50 V.

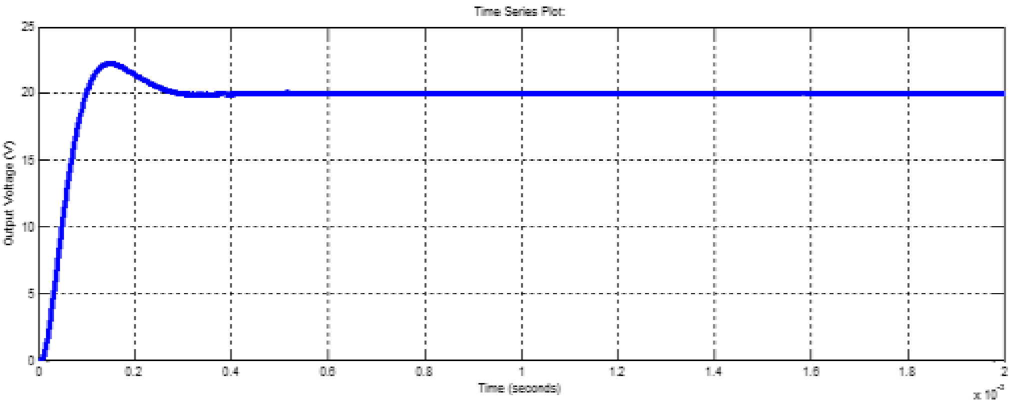

Figure 7: Simulation Graph of Output Voltage at Line variation 50V - 65V

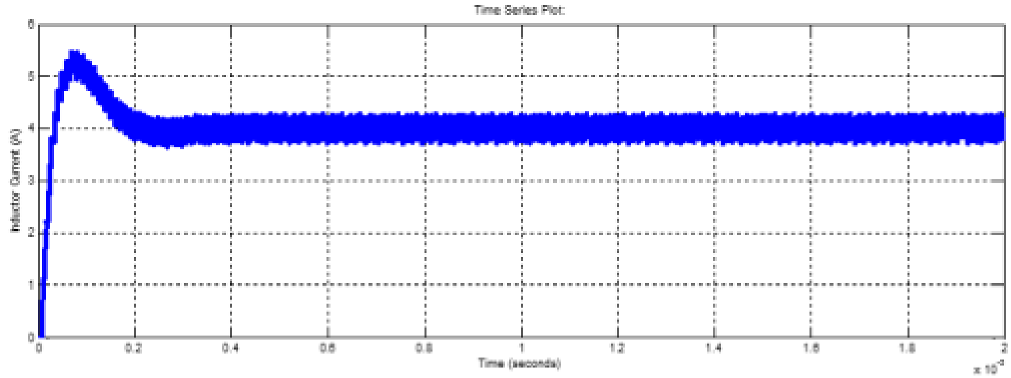

Figure 8: Simulation Graph of Inductor Current at Line variation 50V - 65V

Figures 9 and 10 show output voltage and inductor current response for supply variation from 50 to 35 V. Again The Resulting voltage has no major difference and remains same as for line voltage of 50V. For inductor current there is same Overshoot of 1.5 A, and same settling time of 0.2 ms as for line voltage of 50 V and gained the stable state at 4 A but DC component become more smoother than for line voltage of 50 V.

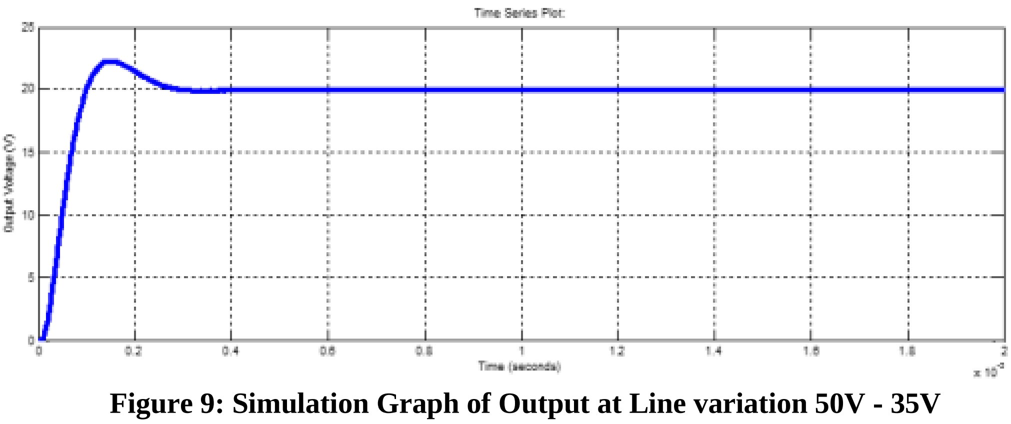

Figure 9: Simulation Graph of Output at Line variation 50V - 35V

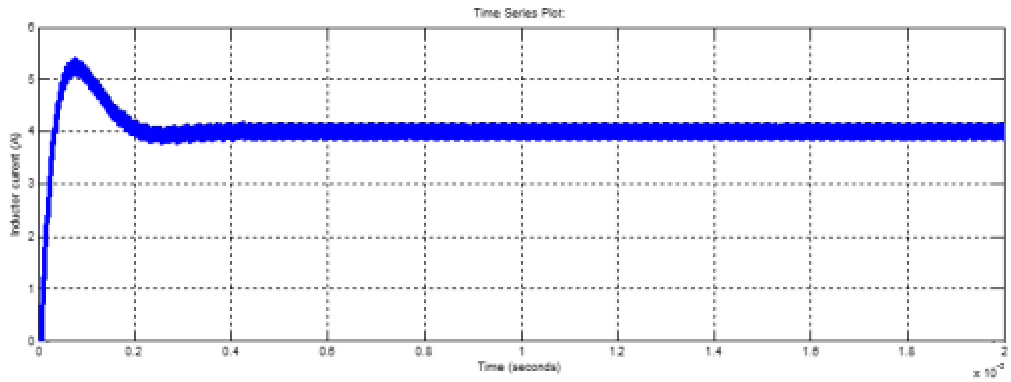

Figure 10: Simulation Graph of Inductor at Line variation 50V - 35V

Figures 11 and 12. The Output resulting voltage has no overshoot and settling down to required voltage of 20 V at 0.2 ms, for current waveform there is also no overshoot observed and settles down in 0.09 ms and gain stable state at 6.8 A which shows drastically best results for load Deviation from 5Ω to 3Ω.

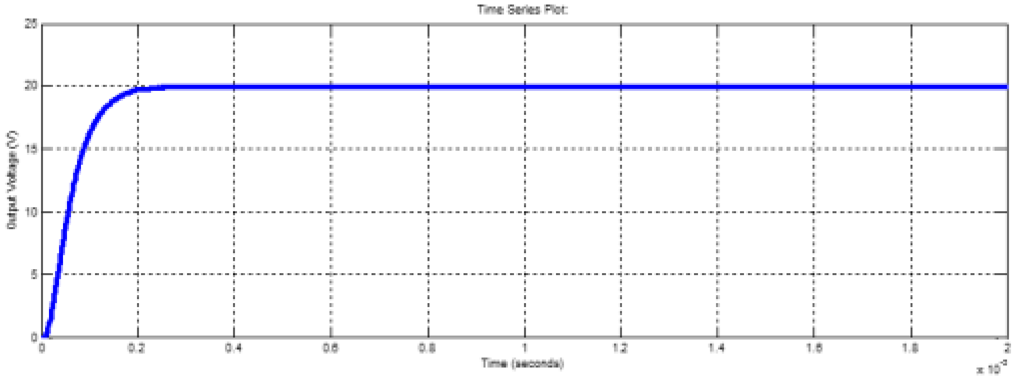

Figure 11: Simulation Graph of Output Voltage at Load variation 5Ω - 3Ω

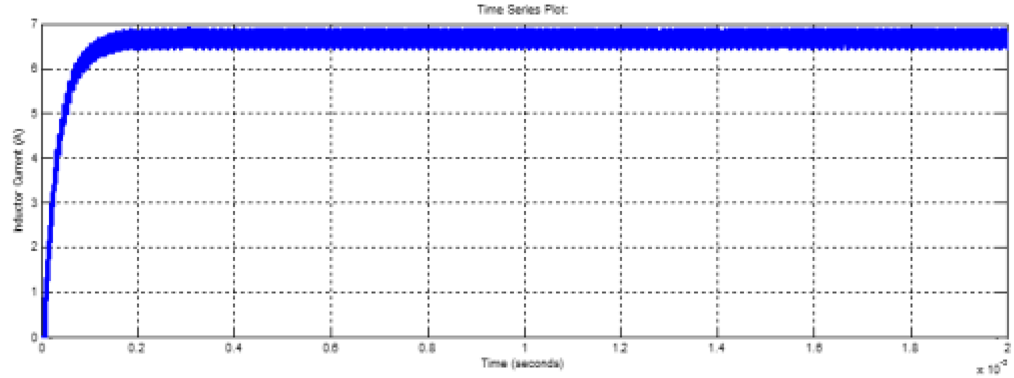

Figure 12: Simulation Graph of Inductor current at Load variation 5Ω - 3Ω

Figures 13 and 14 show output voltage and inductor current response for load variation from 5Ω to 10Ω. The Output voltage has an overshoot of 6V and then undershoot of 1 V and gain stable state at settling time of 0.4 ms. For current of inductor there is an Overshoot of 2.5 A and then undershoot by 1.8 A, and gained the stable state at 2 A at 0.4 ms.

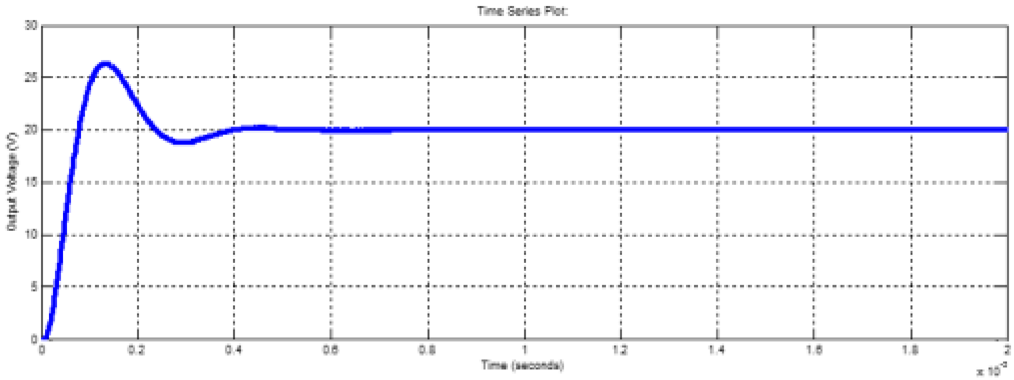

Figure 13: Simulation Graph of Output Voltage at Load variation 5Ω to 10Ω

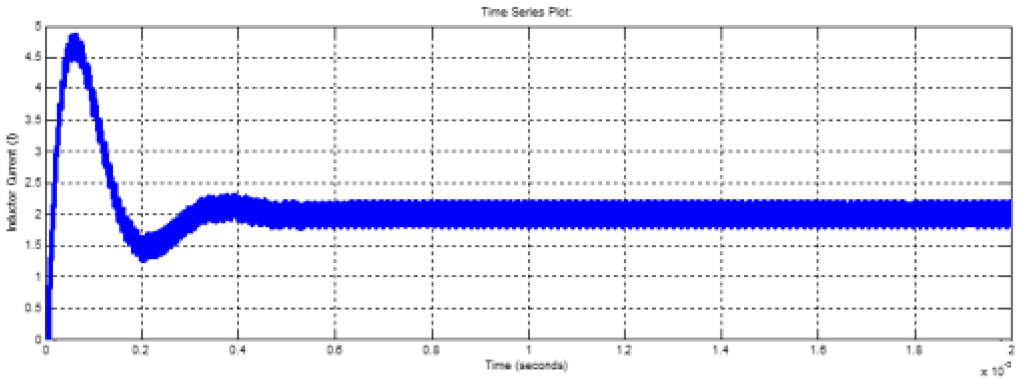

Figure 14: Simulation Graph of Inductor current at Load variation 5Ω to 10Ω

6. CONCLUSION:

This paper has detail study of unique method to apply the Average Current mode controller for Buck converter using Simulink by analyzing of results. It is seen that (PI controller) for Voltage loop gain can be configured with respect to the Voltage error signal value to impressively improved the Buck converter steady state response. The implementation involves MATLAB/Simulink based digital compensator which is well suited for practicing high-frequency power switching controllers. The Average Current mode controller is designed for buck converter and its steady state characteristics are observed very much authentic. Simulation and new results are shown for Line variation of 50V-to-20V point-of-load Buck converter to show the improved steady state response.

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