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Design of DC-DC Boost Converter with Digital Controller using State Space Averaging Technique

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ABSTRACT—A DC-DC converter is a circuit which contains electronic components like (Diode, PE switches and energy storage elements) which helps in converting the DC source voltage from one level to another. It is a class of switched mode power supply. The range of power levels can be changed from low to high level or vice versa. DPID controller is applied on voltage controlled DC-DC boost Converter. Due to fluctuation of source voltage, load side current and nonlinear state of power electronic switches, the designing of control system is challenging. DC-DC power converter is designed using State Space Averaging (SSA) technique which is a modern approach of analysis of control system. Due to the fact that digital execution of controller aims at better dynamic response makes it most satisfactory to explore the control method, providing more accurate value for voltage and current in view or as per there pulsating value, also it is more suitable for analyzing a converter having digital control devices. Without requiring any significant hardware change, scheme can be modified in the digital controller. MATLAB/Simulink is used to demonstrate the dynamic response and steady state response of controller (algorithm implemented using DSP system toolbox).

Keywords—DC-DC Boost Converter, State Space averaging, DSP system toolbox, Digital PID controller, ADC, PE Switch.

I. INTRODUCTION

To exercise and manage the electric energy flow providing voltage and current such that to befit for user side load. Initially transformation of energy is there in electromechanical converter (mostly rotating machine). Due to bulk manufacturing and growth of power semiconductors, there is widespread use of static power converters in diverse areas mostly in particle accelerators. Due to their minute weight and compact size, the static and dynamic state functioning is good. For example we can see that there is updation in the electromechanical devices (DC machine) itself that Commutator is replaced by the P.E. converter due to their high switching but there is a problem of harmonics in the conversion from AC to DC which cause time varying flux to flow in Yoke getting a little Eddy current loss. Power converters are built in a manner such that it increases productivity. But in the first method, assumption is made that power converter is lossless [1]. The commutation technique become more crucial with the fast development of controllable power semiconductor. Due to the chopping of losses and EMI disruption the frequencies are increased causing the converter functioning to improve. The correct turn-on and turn-off for switch has to be empowered by circuit topology. The most appropriate way to reach these goals is Soft commutation (using external circuit(generally forced resonant system) that prevents overlapping of the voltage and current wave forms during the time of transistor commutation). In forced resonant system what we do is taking the help of various inputs (input voltage, load, transistor voltages, currents etc.) for calculating the offset time for current and voltage waveform helping is coping up with the swittching losses. [2]. In advance control system is needed to improve the efficiency of the electrical power output which is generated by renewable energy resources [2, 3]. Solar cell, fuel cell and many renewable energy resources like it, creates DC components. And DC-DC power converter would be a fine medium to connect it straight away to the load with no use of inverter and energy storage elements [3].

Due to fluctuation of source voltage, load side current and non-linear state of power electronic switches, the designing of control system is challenging. Today's designers are focused to keep enhancing the technology of switching devices to decline the power bundle size and weight. Load voltage and current depends on the efficiency of the application. Some application have their particular power supply scheme. There is no easy method that exist for selecting the right topology. [4].

Switched mode power supply converters are used to convert unregulated DC supply into regulated DC voltage across load, and defending in opposition to over-currents and short circuits. Switched mode power supply converters present an innovative, highly systematic approach that has mnemonic, closed-form solution for the circuits. DC-DC Boost converter comes under switched mode power supply which is used for conversion of voltage and current it would be AC to DC, DC to DC and AC to AC converter. It can be used in automobiles such as heavy vehicles and in industrial equipments like telecommunication rack. In vehicle equipment a DC to DC switched mode power supply is used like conversion of 12V to 24V DC for cracking supply. Power can be equally divided at low voltage. Each equipment in vehicle areconnected with switched mode power converter through which equally divided voltage will be supplied due to which each equipment will have a voltage supply according to their need. The converter topology is a system which is a combination of power switches and energy storage elements that create a power scheme. It also comprises a control segment which regulate the power flow as too reach the required output voltage [4-5].

Normally, analogue controllers are used for controlling of DC-DC converters and help to reach the required output. An analogue control system (ACS) works in genuine time with high bandwidth and theoretically infinite resolution [7]. In past few years DC-DC converters have a great solution due to Digital control. There is also no cost-prohibitive aspect of digital control technology due to continuous declination in cost of Digital ICs [8]. The easy implementation of advanced control algorithm like adaptive control and non-linear control have made the Digital control of DC-DC converters dominant over analogue control [9].

The analogue technique has drawbacks of large number parts, complex hardware configuration, and sensitivity to environment in terms of thermal and ageing. Due to the fact that digital execution of controller aims at better dynamic response makes it most satisfactory to explore the control method. Time optimal response is also a remarkable field of interest for converter application. Due to the less sensitivity to parametric discrepancy in Digital controller, auto detecting and monitoring in operation are possible. There is a sequence of control actions as a result for time optimal response that takes minimum time against exterior disruptions. So, for DC-DC converters it is a sequence of precisely timed pulses [10, 11].

Switching converters are nonlinear systems (i.e., systems which may be designed using sequential but not simultaneous equation). Even though the system is modeled by a set of simultaneous equations, there should be at least one non-linear equation among the equations. The reason behind non-linearity in equation is because they generally entail the manipulation of nonlinear quantities. The sate-space averaging method, different from the circuit averaging technique (circuit averaging approach involves manipulation of circuits rather than equations), is a mainstay of modern control theory. An advance modern technique is used to produce small signal transfer function of a DC-DC converter which is known as state-space representation, using the transfer function the closed loop response can be created by varying the modelling parameter. Using transformation technique an open loop response is produced in discrete time. [12].

Power management integrated circuit huge amount of digital circuit, but it is still remain hidden from the consumer. All power management integrated circuits perfectly withstand analogue response, doing analogue calculations and accepting analogue controllers. Digital execution of the power converters helps in creating an advanced technology for future advancement in power supply, so that it can be more efficient and can be used in more application [13].

In this paper modelling and simulation of boost converter and execution of digital controller take place. State space analysis is used to model non-ideal DC-DC boost converter which are necessary for effective controller design. A tuned PID controller was applied to the model for improving the response characteristics of the model. The model took in to consideration the parasitic parameters of circuit elements in order to obtain improved dynamic model for effective controller design. And further to improve output more that is making the output waveform more smooth and improve the dynamic response the application of digital filter is there. The effectiveness of controller make the converter output response fast with improved dynamic performance which is necessary for eliminating voltage changes which are associated with highly variable voltage source like solar photovoltaic system.

- MODELING OF BOOST CONVERTER

DC- DC converters includes a variety of topologies to convert voltage level including buck-boost SEPIC and PUK.

When we talk of DC-DC boost Converter which is a non-isolating power converter that performs the task of stepping up the voltage (as from input to output). There are two basic mode i.e. voltage mode and the current control mode. Voltage control mode is a voltage control with single loop having only output voltage and control signal.

The Current control mode is a multi-loop control which is having a feedback loop for inner current and also a feedback for outer voltage with inner current feedback loop in addition to the outer voltage feedback.

Figure 1 shows the power circuit module for boost converter which is voltage controlled. First, the switch is open for the time T according to the Duty cycle given to Gate terminal of Power MOSFET. The capacitor now charged nearly equal to input voltage (as diode drop is very less) through inductor. Now, for the remaining cycle of duty cycle the MOSFET is closed and now also the current pass through inductor and MOSFET, still the capacitor is charged due to unavailability of discharge path. After some time the MOSFET is open there is sudden oppose for inductor but the conductor oppose the sudden change in current due to its nature. So it responds by creating a voltage of opposite polarity due to which diode gets forward biased again and charging capacitor again making the capacitor voltage (output voltage) greater than input voltage.

V_o= Output voltage (serve as a feedback)

ADC= Output voltage is transformed to discrete value.

Error signal (e) = V_{ref} - V_o

The detected error is then further processed using a compensator block to determine the duty cycle for PWM technique.

Further we have used the DSP system Toolbox blocks such as ADC-Quantizer and Digital fiiter to check whether it will improve result or not.

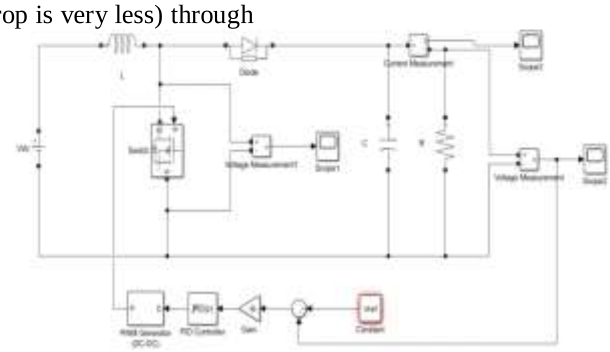

Fig 1. Basic model for Boost Converter with DPID.

- Steady State Design

As we study the versatile nature of dc-dc converter we
need to study firstly the steady state and secondly the dynamic modelling for the operation of continuous current mode that for a non-ideal converter.

Table 1 & 2 represents the steady state parameters which were used in the modeling.

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TABLE 1 Steady state parameters for 12/24 V boost converter

Variable	Symbol	Value
Input (Volts)	V_{in}	12 V
Output (Volts)	V_o	24.26 V
Output Ripple (Volts)		571 mV
Mean Output Current	I_o	2.426 A
Resistance (Switch ON)	R	0.1 ohm
Resistance (Parasitic Inductor)	r_L	0.01 ohm
Resistance (Parasitic Capacitor)	r_C	0.01 ohm
Load Resistance	R_L	10ohm
PWM Time Period	-	2.5e-5 sec
Duty Cycle	d	0.5%

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Inductor	L	19.57uH
Output Capacitor	C	25uF
Switching Frequency	f_s	40kHz

TABLE 2 Steady state parameters for 12/48 V boost converter

Variable	Notation	Value
Input (Volts)	V_{in}	12 V
Output (Volts)	V_o	62 V
Output Ripple (Volts)		411 mV
Mean Output Current	I_o	10.17 A
Resistance (Switch ON)	R	0.1 ohm
Resistance (Parasitic Inductor)	r_L	0.01 ohm
Resistance (Parasitic Capacitor)	r_C	0.01 ohm
Load Resistance	R_L	1.1 ohm
PWM Time Period	-	2.5e-5 sec
Duty Cycle	d	75%
Inductor	L	3.66 uH
Output Capacitor	C	0.8 uF
Switching Frequency	f_s	40kHz

The details of steady state design equation for DC-DC boost converter have been presented in [4, 5]. A 54.40 W, 24 V boost converter and 573.738 W, 48 V boost converter was designed with 12 V nominal inputs and no input variation. The switching frequency of pulse width switching control is 40 K-Hz to ensure low switching losses.

- Dynamic state model

Firstly, we discuss a switching converter which is basically a periodic time system. It can be modelled using circuit averaging or state space averaging technique. As we make comparison between the dynamic model and continuous model, we have found that the dynamic model has certain advantages over continuous model which are:- providing more accurate value for voltage and current in view or as per there pulsating value, also it is more suitable for analyzing a converter having digital control devices[14,15].

SSA i.e. State space averaging which is being used for calculating small signals transfer function e.g. DC-DC converter from where we can derive ideal closed loop responses which is obtained on substituting the designing parameters. Further, the open loop response for discrete time is obtained using transformation method. For an average continuous time model consider switching of the duty cycle as its input and further describing the slower dynamic of system avoiding hardships faced because of the system's hybrid nature. As we conferred a mathematical depiction for a boost converter in continuous conduction mode (CCM) by utilizing the SSA method. A digital controller, DC-DC PWM generator, power stage, ADC quantizer all these comprised together forms a digitally controlled DC-DC converter[16-18].
The differential state variables for boost converters are derived in [1].
Fig-2 and Fig-3 shows step response of simple and with tuned PID controller of a 12/48 V boost converter.

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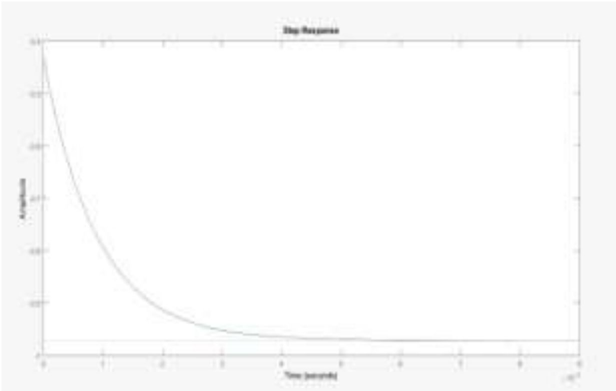

Fig. 2:- Converter step response with unity feedback for 12/48 V

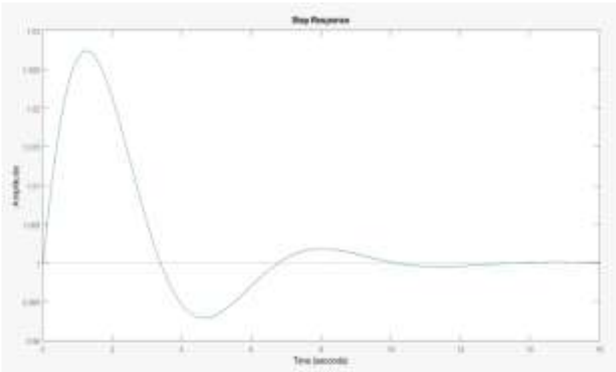

Fig.3:- Converter step response with unity feedback (tuned PID applied) for 12/48 V

- Digital Compensator Design

A PID controller was designed in time domain using Zeigler Nichols technique.

PID controller was digitalized using DSP system toolbox blocks.

A model of 12/24 V boost converter having DPID controller is shown in figure 4.

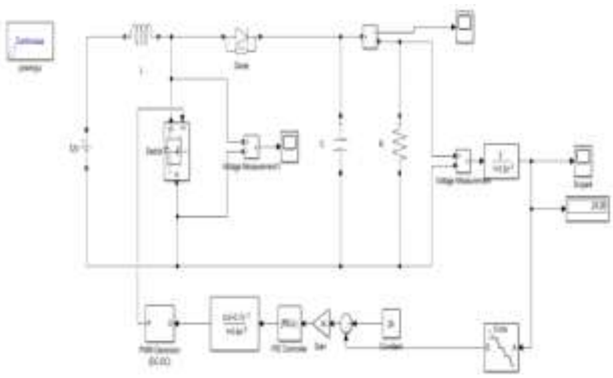

Fig.4:- 12/24 V boost converter with digitalized PID controller

A model of 12/48 V boost converter having DPID controller is shown in figure 5.

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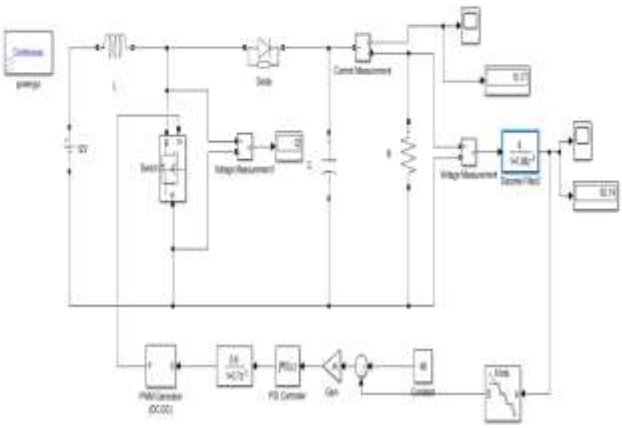

Fig 5:- 12/48 V boost converter with digitalized PID controller

II. RESULTS & DISCUSSION

Time response for 12/24 V boost converter having DPID controller is shown in figure 6. The response takes 10.945 to rise till 90% of its final value from initial value, + overshoot of 24.545%, takes 19.992ms to settle to its final value and a peak to peak steady state voltage of 0.571 V.

The figure shows that the first peak in transient period is near to 80V which is a very steep rise in voltage and as soon as the process goes on the system itself settles to the steady state value with a voltage variation of 0.571 V.

The waveform smoothness is a little bit less because of the harmonic effects in PE switch.

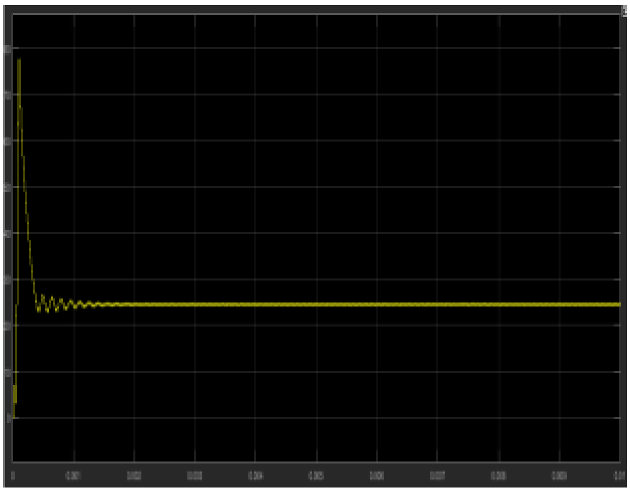

Fig. 6:- Time response for 12/24 V

Time response for 12/48 V boost converter having D-PID controller is shown in figure 7. The The response takes 6.2 to rise till 90% of its final value from initial value,

+ overshoot of 0.806%, has Undefined settling time which indicates that the system is never settling in the tolerance band of 2%. and a peak to peak of 0.411 V.

The figure shows that the first peak in transient period is near to 80V which is a very steep rise in voltage and as soon as the process goes on the system itself settles to the steady state value with a voltage variation of 0.4111 V.

The waveform smoothness is a bit less (from 12-24V converter) because the duty cycle in this converter is more as compared to the previous converter so more turn ON of converter more the the harmonic effects in PE switch

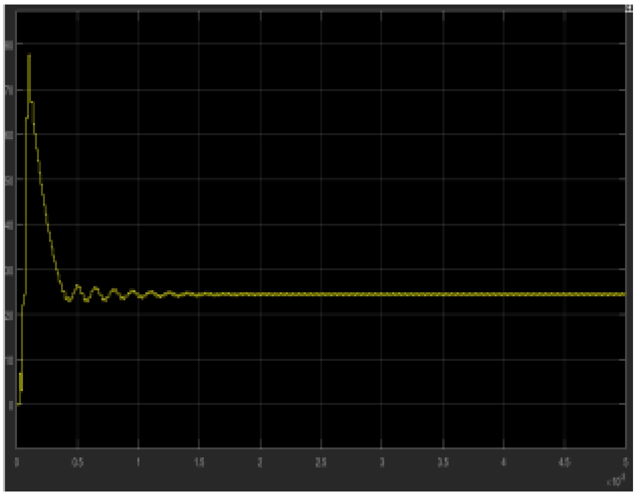

Fig. 7:- Time response for 12/48 V

The comparison of the response parameters for 12/24 V and 12/48 V boost converters having different system models is shown in table 3 & 4 respectively. It is observed from the tables that as we apply more and different updated techniques to the circuit the transient response become more faster and the steady state response become more stable. And finally improving the converter performance.

TABLE 3 Parameter comparison for 12/24 V

System	**Response parameters**		
	Rise time ()	**+Overshoot ()**	**Peak to peak ripple voltage**
Simple 12V-24V boost converter	1.229	13.366 %	86.94
12V-24V boost converter with Tuned PID	48.388	10 %	4.064
12V-24V boost converter with Digital PID		24.545 %	0.571

TABLE 4 Parameter comparison for 12/48 V

System	**Response parameters**		
	Rise time ()	**+Overshoot ()**	**Peak to peak ripple voltage**
Simple 12V-48V boost converter	1.230	13.068 %	86.93
12V-48V boost converter with Tuned PID		12 %	45.35
12V-48V boost converter with Digital PID	6.2	0.806 %	0.411

As the PID is added to system and got digitalized the response parameters becomes better.
Table 5 shows the comparison of parameters with the base paper.

TABLE 5

Comparison of Parameters with Base Paper [1]

Response Parameters	**Our Observations**	**Base Paper Results**
Rise time ()	6.2	15
+Overshoot ()	0.806%	6%
Output Power (P_o)	630.54 W	500 W
Output Voltage (V_o)	62 V	48 V
Voltage ripple	411 mV	500 mV

The rise time and the overshoot are very low (6.2 & 0.806% respectively) which makes the transient response fast and stable.
The peak to peak ripple voltage is low (411mV) which make the steady state response stable. The output voltage observed was 62 V at 40 K-Hz switching frequency which means the system efficiency is good.
The transient response is faster and the steady state response is more stable than the base paper. The overall system is fast, stable and efficient than the base paper response.

III. CONCLUSION

The modelling of non-ideal DC-DC boost converter is done using State Space Averaging (SSA) technique and DSP system toolbox blocks are used in designing digital controller. The controller used is PID controller due to its superiority over other controllers. The proposed Boost converters with DPID controller provides better voltage regulation, overshoot reduction and improves the converter performance compared to the conventional Boost converter. It offers advantages like improved response parameters, robustness. Digital implementation of controllers is most suitable due to adaptive and non-linear control which targets better dynamic response.

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