Real time hardware implementation of discrete sliding mode fuzzy controlled buck converter using digital signal processor

Viji Karthikeyan[1], Anil Kumar Tiwari[2], Chitra Kandasamy[1]
[1]Department of Electrical and Electronics Engineering, CMR Institute of Technology, Visvesvaraya Technological University, Bengaluru, India
[2]Department of Electronics and Communication, Amity School of Engineering and Technology, Amity University, Lucknow, India

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ABSTRACT

This paper deals with the real time hardware implementation of discrete sliding mode fuzzy control (DSMFC) for buck converter using digital signal processor (DSP). Applications like electric vehicle suspension control, flight dynamic control, robot position control and engine throttle position control; sliding mode control (SMC) plays a major role. Hardware realization is difficult with SMC strategy due to the continuous gain change results in chattering problem and actuator or contact may break. To resolve this problem the fuzzy logic (FL) approach has combined with the robust technique discrete sliding mode control (DSMC) to develop a new strategy for DSMFC. The mathematical modeling of the controller is done using MATLAB/Simulink software and practical design of the converter is also realized. The robustness of the controller is proved by introducing sudden change in input voltage as well as load with the help of switching circuit in hardware realization. The obtained practical results are verified by comparing with the simulation output and reference value.

Corresponding Author:

Viji Karthikeyan
Department of Electrical and Electronics Engineering, CMR Institute of Technology
AECS Layout, Bengaluru-560037, India
Email: kvijiperumal@gmail.com

1. INTRODUCTION

Earlier proportional-integral-derivative (PID) controllers has been used which require precise linear mathematical model, but the performance is affected during non-linear conditions and load fluctuation. The DC-DC converters are inherently non-linear due to the switching requirement and hence they do not perform satisfactorily with PID controller. Although mathematical model has been acquired by state space averaging technique but it is possible only for small signals [1]–[4]. Another type of controller used in controlling the converters is adaptive controller. In this, the controller is designed to adapt the parameter variation or uncertainty. This type of controllers requires accurate mathematical model and they are sensitive to parameter variations. In addition they also suffer convergence and robustness issue [5]–[8].

In state feedback controller technique, the performance of the system is controlled by placing pole in a pre-determined location of a closed loop system. Even this method requires accurate mathematical modeling to implement the control technique and is applicable only for single input/single output systems. The control of this technique is based on the type of input and output and is independent on the inner characteristics of the plant [9]–[12]. In self-tuning systems the performance of the system is optimized by automatically changing the parameters in order to achieve maximum efficiency or to minimize the error. This method requires accurate mathematical modeling of the system and sensitive to parameter variation.

An alternate controller which does not require accurate mathematical model is sliding mode controller (SMC). Though the accurate mathematical model is not required for SMC, however knowledge about parameter fluctuation is important for stability studies. Irrespective of system order SMC is always designed for the first-order and its control algorithm can handle worse case dynamics resulting in chattering. So, a margin limit has been applied on either side of the sliding surface to reduce chattering problem. To control variable structure systems, SMC have been introduced which has major advantages like stability, robustness against uncertainties, flexibility in design and ease of implementation. This ensures its wide industrial application like furnace control and automotive control.

Discrete sliding mode controllers are used to control power converters. The implementation of DSMC has the following advantages like: i) flexible sliding surface, ii) same controller can control other power converter with small adjustment, iii) usage of simple hardware, and iv) ease of implementation with any digital controllers [13]–[17]. In case of fuzzy logic control (FLC) it does not require accurate mathematical model; the controller is designed on the basis of human experience. The input and output variables of the fuzzy systems are mapped with a set of membership functions called fuzzy sets. The fuzzy sets are framed based on human experience on that particular application. This controller has advantages like flexible control characteristics, insensitive to parameter variations, can handle non-linearity systems and ease of implementation.

A neural network control functions like a human brain. The performance of the controller is good for complex and non-linear systems; but training of the controller is a huge requirement. The system may become unstable under larger unknown problems. The theory used to assure the performance of the neural network is still under development.

The response of the power electronic converters are affected by: i) the non-linear features of the switches like power diodes and power metal–oxide–semiconductor field-effect transistor (MOSFET), ii) the inductance may saturate and can cause non-linearity, and iii) the capacitance used for filtering purpose leads to clamping of voltage results in non-linear characteristics [18]–[20]. The non-linearity can be overcome with the help of SMC, which is a part of variable structure system (VSS). Even systems with unknown parameters can be model with the help of SMC which requires only approximate equivalent design. Such that all the higher order systems are reduced into first order for SMC design resulting in simplicity of the design. The system shows excellent robustness against parameter fluctuations, and hence the non-linearity issues in power converters can be overcome by this controller. One limitation of the algorithm is the chattering phenomenon, which due to controller switching across the sliding line in order to track the path.

Recently FLC are most widely used due to its robustness, it needs only rough mathematical model, can perform well with less accurate inputs and with non-linear devices. Thus fuzzy logic has been used along with sliding mode controller to suppress chattering phenomenon [21]–[23]. The discrete sliding mode fuzzy control (DSMFC) has been introduced in order to eliminate the need for analog to digital converter (ADC). It has flexible control algorithm, ease of implementation and reduced ripples in the output which overall improves the efficiency of the system. Figure 1 illustrates the block diagram representation of hardware for DSMFC buck converter.

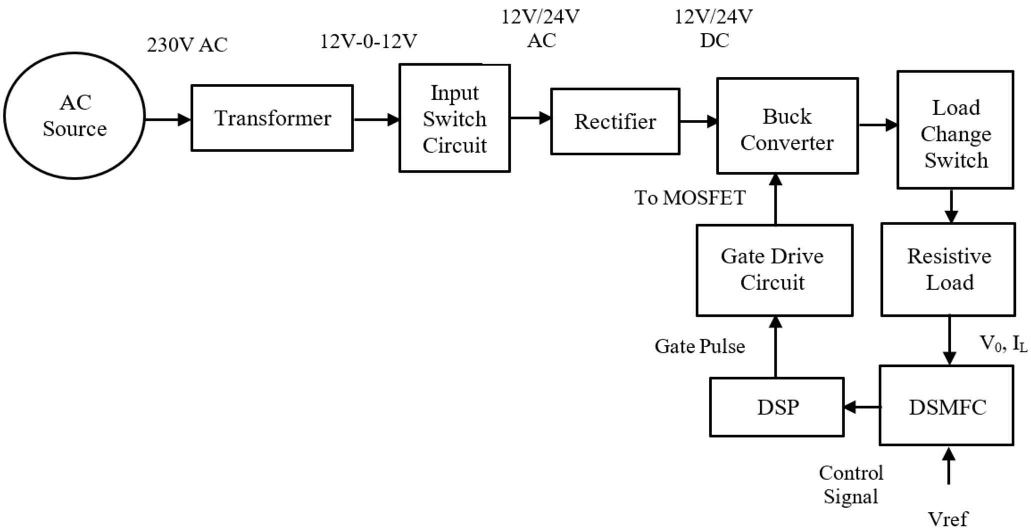

Figure 1. Block diagram representation of DSMFC based buck converter hardware

The input supply is taken from the 230 V AC source, with the help of step-down transformer 230 V is reduced to the rating 12-0-12 V AC. The output voltage of step-down transformer is connected to the switch circuit to get the output voltage of 12 or 24 V AC. The 12 or 24 V supply is connected to the switch circuit through the relays. By pressing the push button, we can switch voltage from 12 to 24 V and vice-versa. This is used to introduce a sudden step change in supply voltage when the program is running [24]. With the help of rectifier AC is converted into DC of 12 or 24 V and it is given to the buck converter as input. MOSFET is used as a switch for buck converter [25], the resistances of 25, 75 and 100 Ω of 50 W each are connected in parallel with the help of relays to the converter as loads. The resistances can be selected with the help of push button together constitutes the trip circuit for load change.

2. RESEARCH METHOD

2.1. Real time implementation of DSMFC buck converter

Design of practical buck converter is given below and the specification for the design is given in Table 1. DSMFC for buck converter has been designed, which is software in loop with the hardware converter is shown in Figure 2. The input to the controller is inductor current and output voltage or capacitor voltage of the buck converter and output of the controller is the control signal [10]. The inputs and output are connected to the controller through universal serial bus (USB) cables. COM11 and COM13 are input ports and COM12 is an output port. The output of the controller is given to the digital signal processor (DSP) where the change in control signal is converted into a train of pulses using pulse width modulation (PWM) technique. These generated pulses are given to the gate drive circuit to drive the MOSFET of the buck converter.

Table 1. Design parameter specification

Parameter	Value
Input voltage	12-24 V
Output voltage	5 V
Switching frequency	20 KHz
Load current rating	5 A

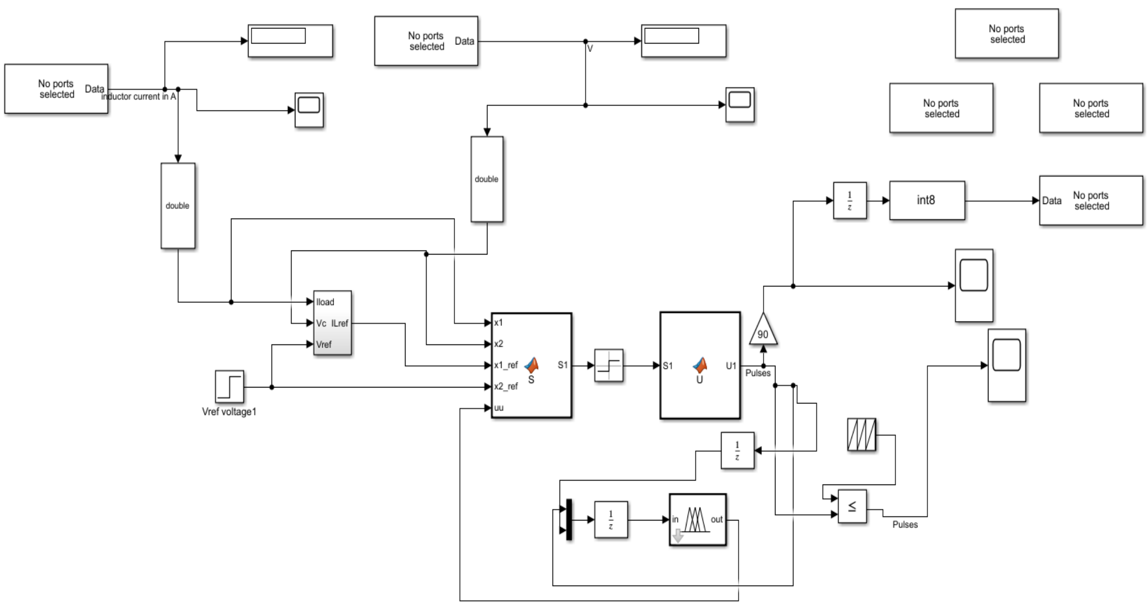

Figure 2. Simulink model of DSMFC for hardware realization

The DSMFC uses fuzzy logic, which can be implemented by Sugeno inference engine of MATLAB/Simulink library. The input1 of the fuzzy membership functions are in1mf1, in1mf2, in1mf3, in1mf4, in1mf5, in1mf6 and in1mf7, these fuzzy sets are taking values from 0 to 1. Gbell type membership functions are used for input1. The input2 of the fuzzy membership functions are in2mf1, in2mf2, in2mf3, in2mf4, in2mf5, in2mf6 and in2mf7, these fuzzy sets are taking values from 0 to 1. The fuzzy sets used for input2 are Gbell type membership functions. In order to introduce smoothness in the corner of fuzzy sets and its performance can be better for nonlinear inputs.

In this hardware two Arduino microcontrollers are used; one for receiving inductor current signal through current sensor and another is to receive output voltage signal through voltage sensor. Arduino with controller; through which the analog signals are given as input to its serial port. This block should be downloaded from MATLAB/Simulink library to receive the analog input signals else MATLAB cannot able to support the hardware. Figure 3 illustrates the hardware board of buck converter. This includes input side transformer with trip circuit, regulators for relay energization, driver unit, power supply transformer, Arduino uno microcontrollers, buck converter, output side tripping circuit, Input and output tripping switches and parallel connected load power resistors. All the parts used in hardware are marked in the Figure 3.

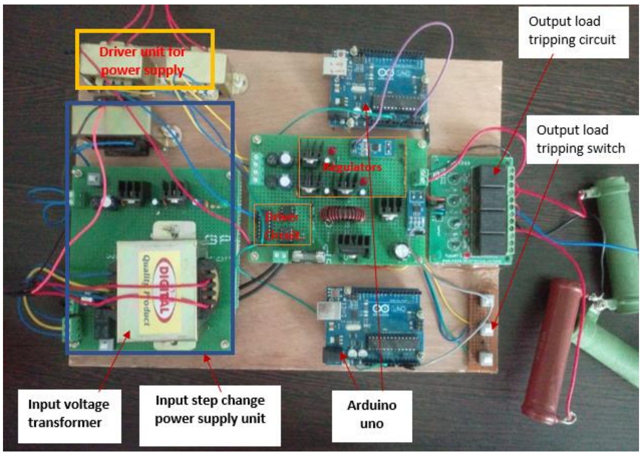

Figure 3. Hardware board for buck converter

3. RESULTS AND DISCUSSION

Figure 4 illustrates the different components used for hardware along with their interfacing. It consists of laptop with 2017 MATLAB, where DSMFC are developed using Simulink model is running. It is taking inputs from buck converter using USB cables through current and voltage sensors and Arduino Uno microcontrollers. The output of the controller is given to the DSP board. In that the change in control signal is converted into PWM signals and is given to the driver circuit. From MOSFET gate to source oscilloscope (CRO) probe is connected to the digital storage oscilloscope to plot the gate pulse. There is a provision to introduce a sudden step change in input and output by switch circuits. On the input side voltage can be changed from 12 to 24 V DC and output side load variations can be introduced by selecting different power resistors.

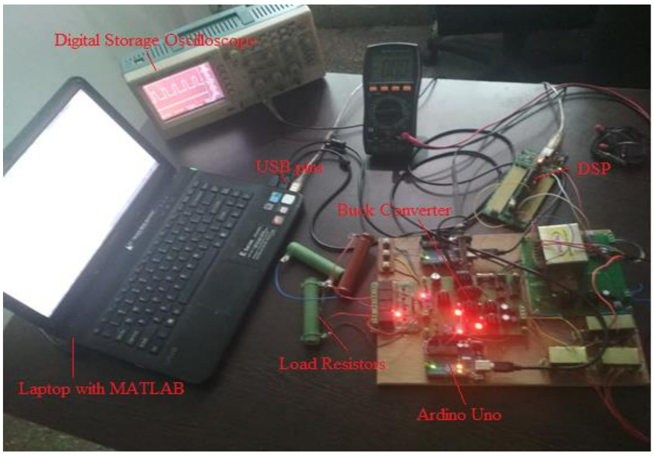

Figure 4. Hardware components with interfacing

Figure 5 illustrates the hardware realization of DSMFC based buck converter with 12 V input voltage and 100 Ω/50 W load and the output voltage is displayed in the multimeter. Figure 6 illustrates the generated MOSFET gate pulse signal for 12 V input voltage and 100 Ω/50 W load for the reference voltage of 5 V. The generated gate pulse has the switching frequency of about 20 KHz and ON duration of the pulse is about 14.71 µs.

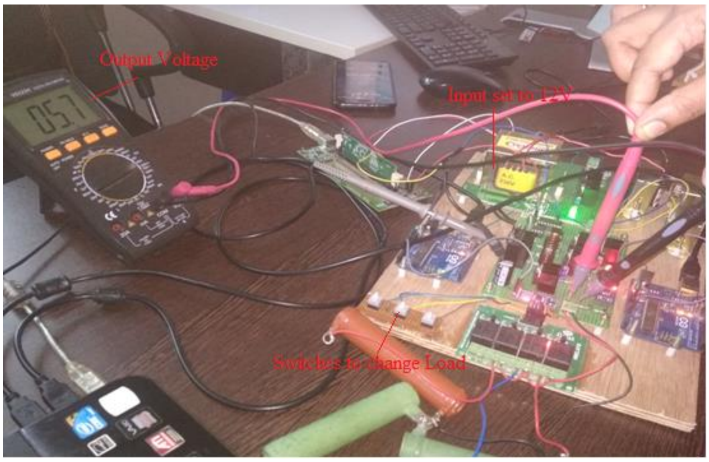

Figure 5. Hardware realization with output for 12 V input and 100 Ω/50 W load

Figure 7 illustrates the generated MOSFET gate pulse signal for 24 V input voltage and 100 Ω/50 W load for the reference voltage of 5 V. The generated gate pulse has the switching frequency of about 20 KHz and ON duration of the pulse is about 7.18 µs. Table 2 shows the hardware response of DSMFC buck converter for different loads and reference voltage of 5 V. Comparative analysis of practical and simulated output voltage for DSMFC buck converter is shown in Figure 8.

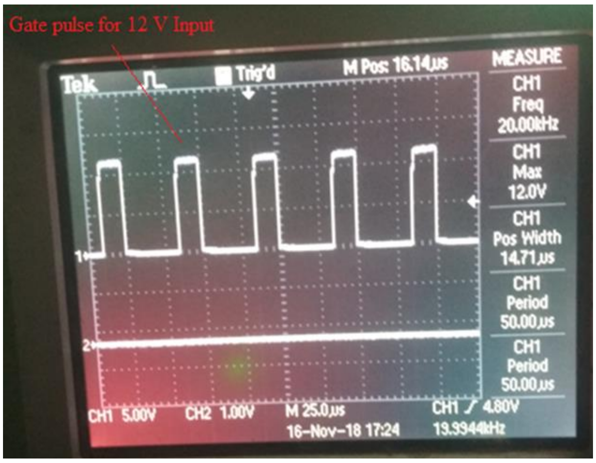

Figure 6. MOSFET gate pulse for 12 V input voltage

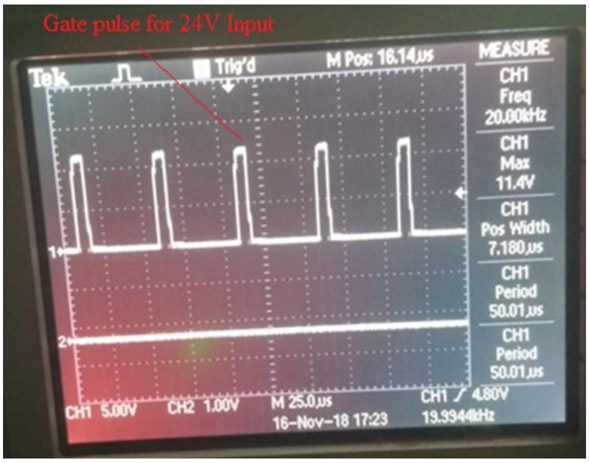

Figure 7. MOSFET gate pulse for 24 V input voltage

Table 2. Hardware response DSMFC-buck converter for V_{ref}=5 V

Input Voltage (rms) 12 V	24 V	Load-1 75 Ω, 50 W	Load-2 100 Ω, 50 W	Load-3 25 Ω, 50 W	Output Voltage (V)
yes		yes			5.1
yes			yes		5.7
yes				yes	4.8
	yes	yes			5.5
	yes		yes		5.5
	yes			yes	5.1

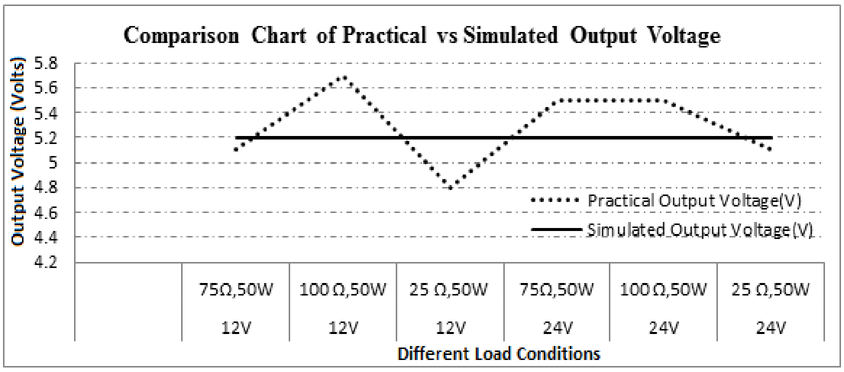

Figure 8. Comparative analysis of practical and simulated output voltage for DSMFC buck converter

4. CONCLUSION

In this paper the hardware realization of DSMFC for buck converter is explained and the results are tabulated. Power resistors are used as loads, 75 Ω, 50 W (load-1), 100 Ω, 50 W (load-2) and 25 Ω, 50 W (load-3) are connected in parallel and with the help of push button any one load is selected. For the reference voltage of 5 V, Input of 12 V the output voltages are 5.1 V for load-1, 5.7 V for load-2 and 4.8 V for load-3. For the same reference voltage, 24 V input the output voltage values are given as 5.5 V for load-1, 5.5 V for load-2 and 5.1 V for load-3. The chattering problem faced by the DSMC is overcome by the usage of DSMFC, such that the hardware realization is achieved. This is impossible earlier because of breakage of actuators or contacts. The robustness of the controller is also established by introducing sudden step change in input and reference voltage as well as by introducing sudden variation in load.

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BIOGRAPHIES OF AUTHORS

Viji Karthikeyan has completed her Ph.D. in Visvesvaraya Technological University, India; currently she is working as an Assistant Professor, in Department of Electrical and Electronics Engineering, CMR Institute of Technology, Bengaluru, India. She completed her B. E. (Distinction) from Manonmaniam Sundaranar University India, M.E. (Distinction) from Anna University India. Her area of research is advanced control systems, power electronics and renewable energy sources. She is a Life Member of ISTE and member of IEI. She can be contacted at email: kvijiperumal@gmail.com.

Anil Kumar Tiwari completed his B E (Hons) from Thapar University Patiala India, M.E. (Distinction) from Pune University, India, PhD from Motilal Nehru National Institute of Technology Allahabad India. A passionate teacher and researcher he has been Head, Faculty of Electronics and is currently Director of AMITY School of Engineering and Technology AMITY University Uttar Pradesh Lucknow Campus. His current area of research is advanced nonlinear control theory, sliding mode control theory, intelligent control, aerospace control, microwave and radar, photonics sensors and devices. He can be contacted at email: akumar3@lko.amity.edu.

Chitra Kandasamy completed her PhD in Electrical Engineering and ME in Power Electronics and Drives from Anna University; She received the B.E degree in Electrical and Electronics Engineering from Bharathiyar University. She has 16 years of teaching experience. She is currently working as Professor and Head of the Department in EEE department, CMR Institute of Technology, Bengaluru. She published more than 30 research papers in reputed journals. Her research interests include inverters, UPS systems, power converters and renewable energy sources. She can be contacted at email: hod.eee@cmrit.ac.in.