



Fuzzy Logic Control of DC-DC Buck Converter in DC Distribution System with Constant Power Load

Ummaleti SaiSangeeth^(✉) and N. K. Arun

Department of Electrical Engineering, National Institute of Technology Calicut,
Kozhikode 673601, India

saisangeeth_m200379ee@nitc.ac.in

Abstract. Fuzzy Logic Control as an alternative approach for the control of Buck Converter with Constant Power Load for DC Microgrid application is proposed. Electric power system connected with point-of-load converter behave as Constant Power Load (CPL). The system will consist of two buck converters connected in cascade. CPL will have inherent negative resistance characteristics and injects a destabilizing nonlinear effect to main distribution bus. The system under consideration is very sensitive to parameter variations due to the negative resistance characteristics of CPL. Hence it is very important to design robust nonlinear controllers to ensure stability of closed loop system. Fuzzy Logic Controller (FLC), an inherently nonlinear controller shows robust behaviour for supply voltage and parameter variations for dc-to-dc converter (single stage). In this paper, a FLC is designed to ensure stabilization of buck power converter with CPL (two stages). The robust behaviour of FLC is verified by performing various simulations in MATLAB SIMULINK.

Keywords: Fuzzy Logic Controller (FLC) · Constant Power Load (CPL) · Microgrid · Buck Converter

1 Introduction

Advancements in power converters lead to many improvements in power systems, vehicular technology, renewable energy conversion systems. Buck power converters have applications like Low Voltage Direct Current (LVDC) microgrid. Cascaded buck power converters that incorporate point-of-load converters will have power conditioning and regulation characteristics. Point-of-load behave as CPL because of regulation capability [1]. Figure 1 shows a typical dc distribution system with first stage buck converter as line regulating converter and second stage buck converter along with load act as CPL.

The system under consideration turns out to be a 2nd order nonlinear system when modelled from first principles. Further, the model will be linearised around an operating point to design conventional linear controller like PID. However, these controllers work well only for small perturbations. To ensure large signal stability, controller using intelligent techniques need to be designed. From the literature it can be seen that FLC is one

such intelligent technique which ensures robust stability of dc-dc buck converter [2]. One main advantage of FLC is the non-requirement of exact mathematical model of the system. The necessary knowledge of the system is captured in the form of fuzzy set and rule base [3]. In [4] the authors have developed and implemented FLC for buck converter system in closed loop. It was observed that FLC can be realised in hardware and works well for various operating points. A simpler, faster and robust fuzzy controller [5] was developed for a system with boost converter. The advantages of FLC are retained with lower computational burden.

In [6] fuzzy PI controller design methodology for dc-dc buck, boost and buck boost converters is presented. It was observed that fuzzy controller is nonlinear controller and gives better performance over linear PI counterpart. Mathematical models of fuzzy PI controller were presented in [7]. The models can be easily realised using digital hardware like FPGA, introduce less computational delay and work well for nonlinear systems. FLC shows better transient performance when compared to linear PID controller for system with buck converter. Further FLC ensures desired output voltage even when external perturbations are present [8]. Upon critically investigating the above mentioned works the following observations are made.

1. FLC with low computational complexity are necessary for hardware realization in power converter applications
2. FLC provides robust behaviour in terms of supply voltage and system parameter variations for power converter applications

So, in this paper design of two fuzzy controllers for the two dc-dc buck converters (PC1 and PC2 shown in Fig. 1) connected in cascade is presented.

1.1 Paper Organisation

In Sect. 2, system details are explained. In Sect. 3, design of FLC is explained. In Sect. 4, simulation results of DC distribution system given in Fig. 1 are presented by considering perturbations in supply voltage and converter parameters.

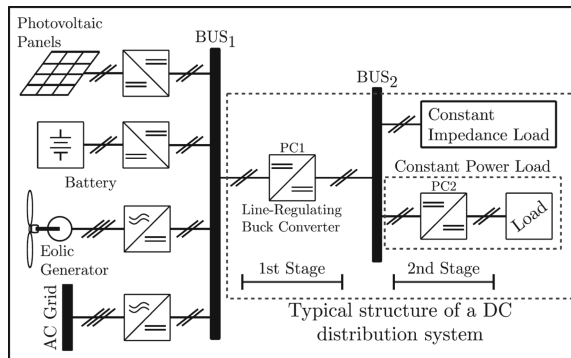


Fig. 1. DC distribution system [1]

2 System Details

System under consideration is divided into subparts i.e., DC Microgrid, Buck Converter and Constant Power Load.

2.1 DC Microgrid

As shown in Fig. 1, various type of energy sources, namely solar photovoltaic, battery wind turbine, and others interfaced together using power converters forming a DC bus (Bus 1) is called as DC Microgrid [9].

2.2 DC-DC Buck Converter

As shown in Fig. 1, a line regulating buck converter (1st stage) named as PC1 is connected between Bus1 and Bus 2. Circuit diagram of buck converter is given in Fig. 2.

Buck Converter transforms output voltage to level that is less than input voltage. Mathematical relation between input voltage and output voltage of buck converter is given by Eq. 1.

$$d = \frac{V_{out}}{V_{in}} \quad (1)$$

where d , V_{out} and V_{in} are duty cycle, output voltage and input voltage of buck converter respectively. Point-of-Load buck converter exhibits almost perfect regulation at output terminals. Buck converter may operate in Continuous and Discontinuous Conduction Mode (CCM and DCM) depends upon inductor current. In CCM, inductor current of buck converter will be non-zero value at any time. In this paper we focus only on CCM for controller design. Next part of system is CPL and explained in Subject. 2.3.

2.3 Constant Power Load

CPL will have characteristics such that input power to 2nd stage buck converter (PC2) is constant, i.e., as voltage decreases current drawn increases and vice versa. As output voltage of PC1 (1st Buck converter) is the input voltage to PC2 (2nd Buck converter), it is necessary to maintain output voltage of PC1 at a desired level. As visualized in Fig. 3, for a small perturbation in BUS2 voltage, current drawn by CPL will be higher than specified load current due to constant power load nature; which makes the capacitor

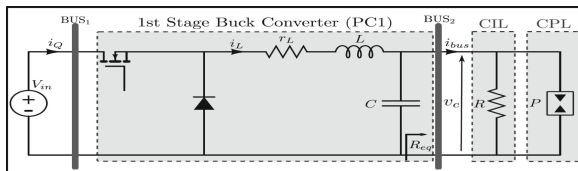


Fig. 2. DC-DC Buck Converter [1]

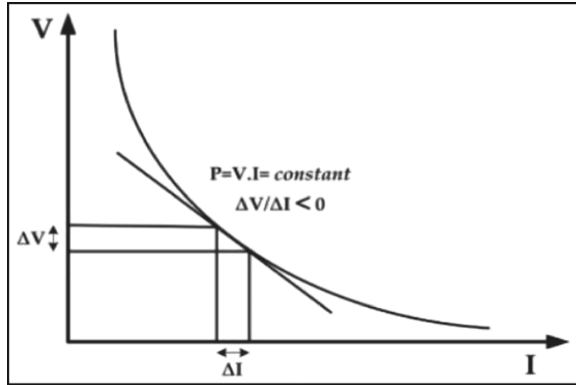


Fig. 3. V-I plot of CPL [10]

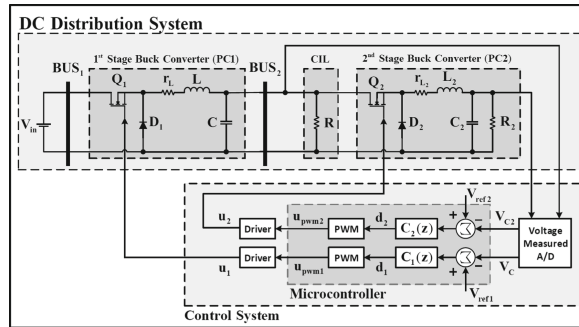


Fig. 4. DC Distribution system [1]

to discharge. Value of CPL impedance (instant) is positive ($v/i > 0$), yet incremental impedance will be negative ($\Delta v/\Delta i < 0$) [10].

The overall system under study is given in Fig. 4 and mathematical modelling is given in [1]. With perturbations in supply voltage, negative incremental impedance has a detrimental effect on the operation of multi-stage converter system which leads to uncertainty in system performance [1].

The energy of source converter will swing between inductor and capacitor and results in an unstable limit cycle behaviour [5]. Therefore, the mentioned dynamic characteristics must be taken into account (expert knowledge of the system) for designing a fuzzy controller which will give robust performance to supply voltage and parameter variations.

3 Design of Fuzzy Logic Controller

To explain the design procedure of FLC, single buck converter is considered first. Choice of inputs and outputs for design of FLC is dependent on type of system and the required

output. The most prevalent choice for inputs of controller are error in voltage ($e(n)$) and change in error ($\Delta e(n)$) and are formulated in Eq. (2) and (3).

$$e(n) = V_o(n) - V_{ref} \quad (2)$$

$$\Delta e(n) = e(n) - e(n-1) \quad (3)$$

where, $V_o(n)$, V_{ref} , $e(n-1)$ are actual output voltage at n^{th} instant, reference voltage (required voltage) and error in voltage at $(n-1)^{\text{th}}$ instant respectively.

The components of FLC namely: (1) a fuzzification block which converts crisp inputs into fuzzy inputs; (2) rule base block which relates fuzzy inputs and fuzzy output; (3) defuzzification block that modifies fuzzy output into crisp output will be described now.

3.1 Membership Functions

Membership functions of inputs of controller, Error, Change in error and change in duty cycle (Output of Controller) are plotted in Fig. 5(a), 5(b) & 5(c) respectively.

Membership values for inputs and output are formulated based on overshoot, ripples and time to reach steady state. Frequent changing the membership values is not desired [3], gains can be modified easily to achieve desired performance. Overall structure of FLC is explicated in Fig. 6.

Duty cycle of converter which will be input to switch of buck converter is calculated by Eq. (4).

$$d_n = d_{n-1} + \eta \times \Delta d \quad (4)$$

where d_n , d_{n-1} , η and Δd are duty cycles at n^{th} and $(n-1)^{\text{th}}$ instant, scaling gain and duty cycle change at each instant respectively.

Feedback network provides the error and gains $\wedge e$, $\wedge ce$ and η can be fine-tuned to get the required output voltage.

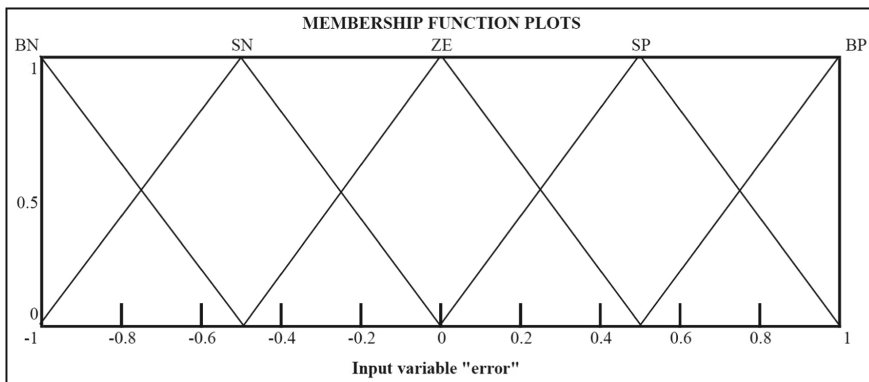


Fig. 5(a). Membership function of “Error” input

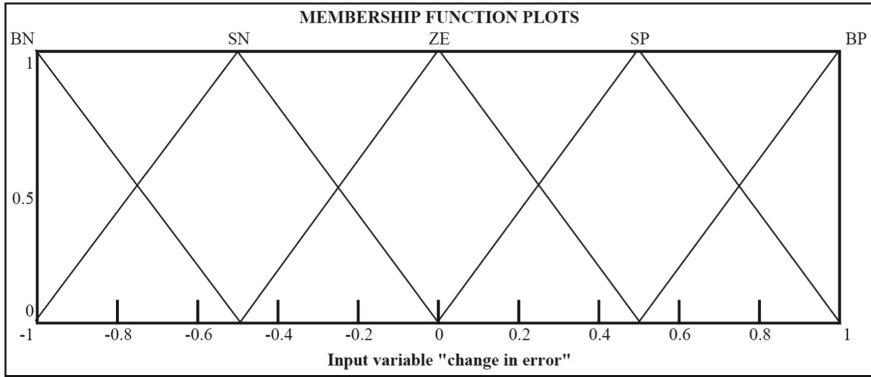


Fig. 5(b). Membership function of “Change in Error” input

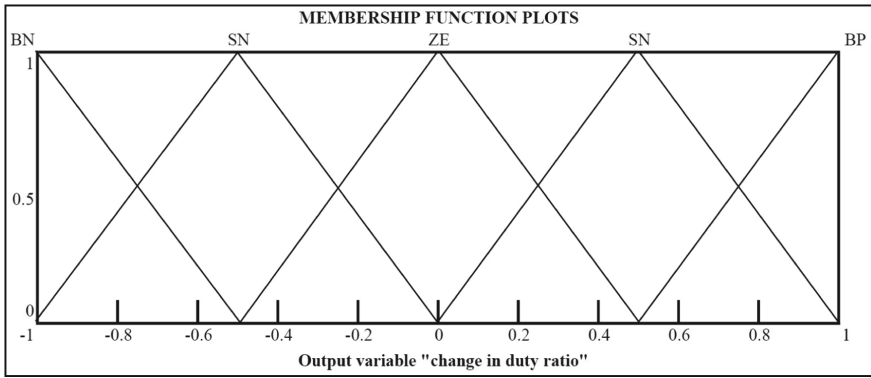


Fig. 5(c). Membership function of “Change in Duty Cycle” output

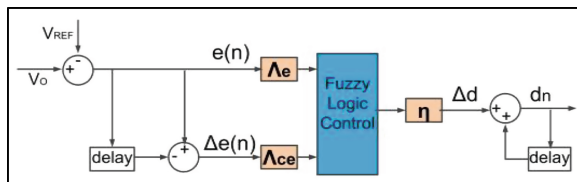


Fig. 6. Overall Fuzzy Logic Controller [3]

3.2 Fuzzy Rule Base

To design a rule base for FLC, good understanding of system is required.

By analysing Eq. 1, general approach for buck converter is “in order to increase output voltage magnitude, duty cycle must be increased”. Justification for formation of rule base can be given with help of Fig. 7a and 7b.

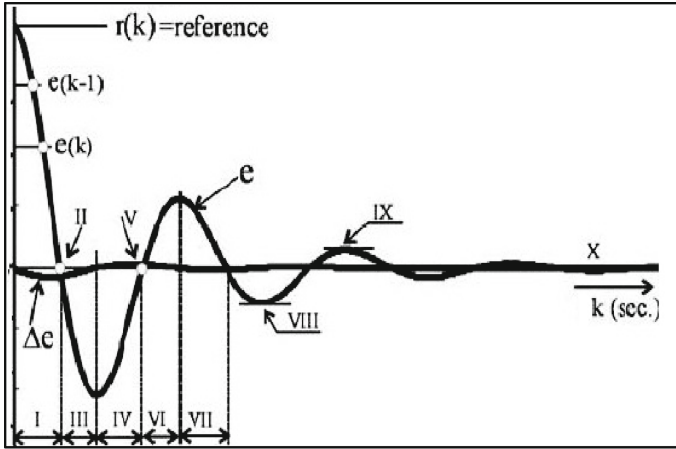


Fig. 7(a). Justification for Fuzzy Rule base

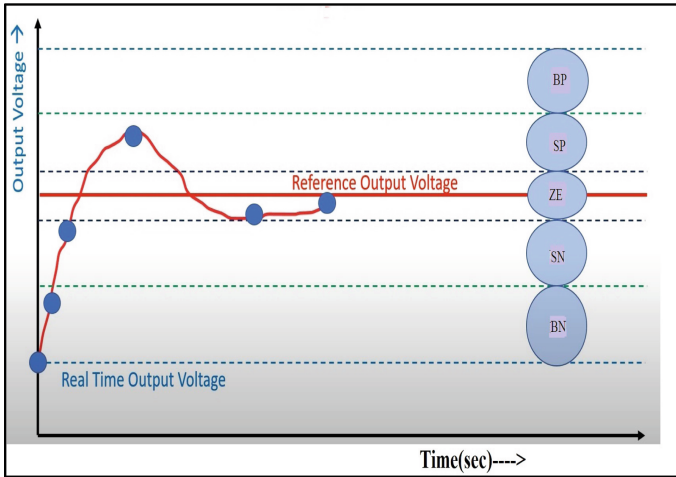


Fig. 7(b). Justification for Fuzzy Rule base [3]

BP, SP, ZE, SN and BN in Fig. 7(b) denote BIG POSITIVE, SMALL POSITIVE, ZERO, SMALL NEGATIVE and BIG NEGATIVE of error input respectively.

We explain the basis for one of the rules presented in Table 1. As shown in Fig. 7(a) and 7(b) is: “if ‘Error’ and ‘Change in Error’ is BIG NEGATIVE value then then required voltage is far less than the desired voltage and so ‘Duty Cycle’ should be increased by big magnitude i.e., BIG POSITIVE value in change in duty cycle value to bring the output voltage to the required voltage”.

Similarly, the fuzzy rules tabulated in Table 1 can be justified. In this paper we use centroid method of defuzzification.

Table 1. Fuzzy Rule Base

Δe	e				
	BN	SN	ZE	SP	BP
BN	BP	BP	SP	SP	SP
SN	BP	SP	SP	SP	ZE
ZE	SP	SP	ZE	SN	SN
SP	ZE	SN	SN	SN	BN
BP	SN	SN	SN	BN	BN

4 Simulation Results

Steady state and transient state simulation of Fig. 4 by varying supply voltage and parameter values are presented in this section. Specifications of cascaded converters are tabulated in Table 2. Range of input voltage and parameter variation are shown in Table 3.

In this paper, membership function, rule base, defuzzification method and scaling gains are same for the two fuzzy controllers used for two power converters (PC1 and PC2). By proper tuning of gains ($\wedge e = 0.03$, $\wedge ce = 250$ and $\eta = 0.003$) of two fuzzy controllers for two buck converters (PC1 and PC2) desired output voltages for PC1 and PC2 are achieved. 3D picturization of fuzzy controller output is shown in Fig. 8.

From Fig. 9(a) and 9(b), fuzzy controller shows robust behaviour when input voltage and parameters are varied as per Table 3. With minimum limit and maximum limit variations, graph settles slowly at steady state compared to graph with no variations. With nominal values, for source converter (first stage) output settles at 0.15 s and CPL converter (second stage) output settles at 0.25 s, with low steady state ripples.

Response of system under variations in supply voltage and parameter values are shown in Fig. 9(a) and 9(b).

Further performance of FLC is compared with that of robust PID controller given in [1]. The PID controller gains given in [1] are used and simulation results are plotted in Fig. 10(a) and 10(b). From Fig. 10(a) and 10(b) FLC controller gives better performance than PID controller.

Table 2. Converter specifications [1]

Symbol	Parameter	Value
Line regulating Buck Converter (PC1)		
V_{in}	Microgrid (BUS1) Voltage	50 V
V_c	PC1 Output (BUS2) Voltage	24 V
CPL Buck Converter (PC2)		
V_{in1}	PC2 Input (BUS2) Voltage	24 V
V_{c2}	CPL Output Voltage	15 V
L and L_2	Inductor Inductance	2.5 mH
C and C_2	Capacitors	2200 μ F

Table 3. Minimum and Maximum limits of input voltage and parameter values [1]

Symbol	Nominal Values	Minimum limit Values	Maximum limit Values
V_{in}	50 V	40 V	60 V
r_L, r_{L2}	50 m Ω	48.5 m Ω	52.5 m Ω
R	10 Ω	5 Ω	15 Ω
R_2	5 Ω	2.5 Ω	7.5 Ω

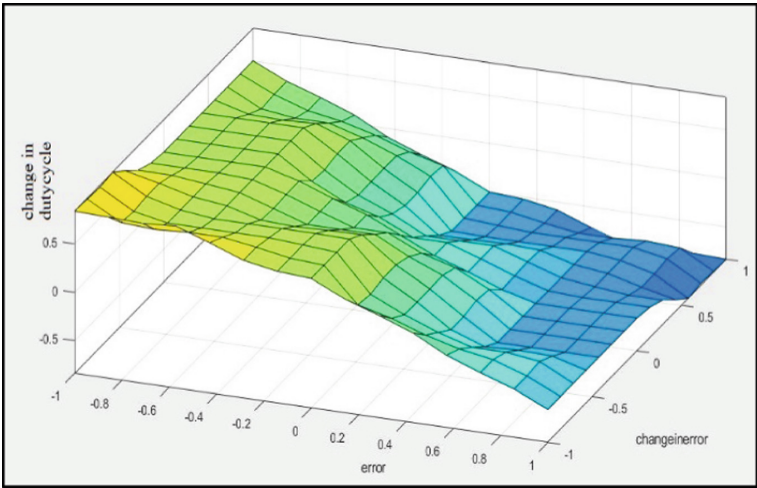


Fig. 8. Fuzzy Controller output

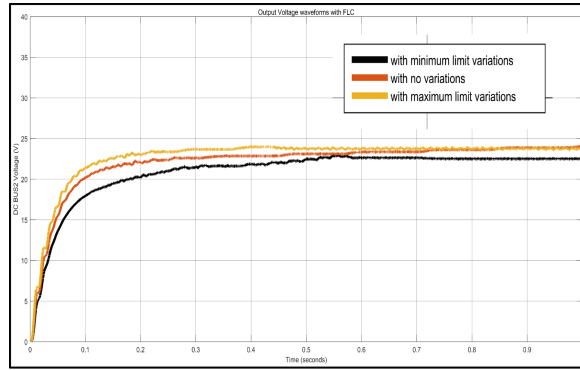


Fig. 9(a). DC BUS2 voltage waveform with nominal values and extreme variations of system parameters and input voltage with FLC

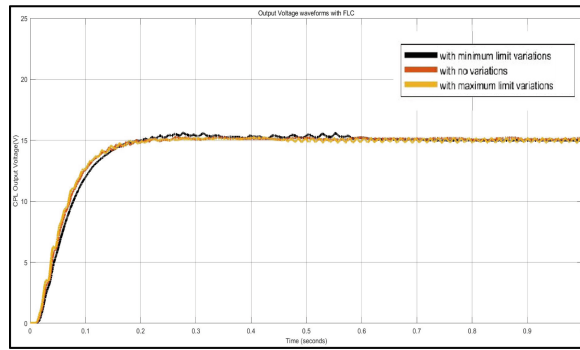


Fig. 9(b). CPL output voltage waveform with nominal values and extreme variations of system parameters and input voltage with FLC

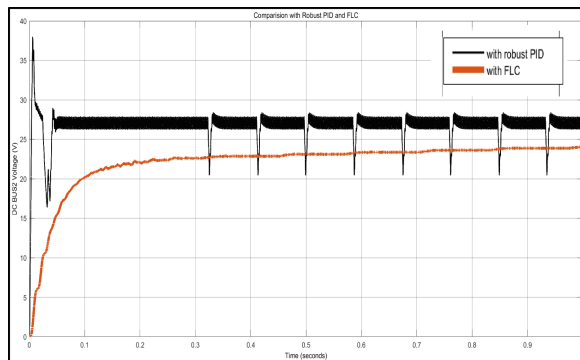


Fig. 10(a). DC BUS2 voltage waveform with nominal values of system parameters and input voltage with FLC and robust PID controller

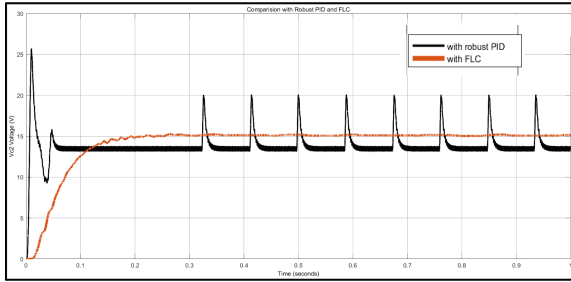


Fig. 10(b). CPL voltage waveform with nominal values of system parameters and input voltage with FLC and robust PID controller respectively.

5 Conclusion

In this paper, we have presented the design of FLC for cascaded power converters (two stages) to reinforce the performance of microgrid. Design of FLC doesn't require mathematical model of system and can be done based on expert's knowledge. By fine adjustments of scaling, FLC shows robust behaviour to supply voltage and system parameter variations and it doesn't depend upon system transfer function. Finally, comparison between robust PID controller and FLC shows that FLC has superior performance over robust PID controller owing to its inherent nonlinear structure.

Authors' Contributions. All authors have formulated and contributed to this work. Ummaleti SaiSangeeth (saisangeeth_m200379ee@nitc.ac.in) designed the controller and compiled fuzzy rule base and wrote the paper under the supervision of Dr. N. K. Arun (arunkm@nitc.ac.in). All authors have contributed to typescript revisions. All authors have approved the final copy of typescript and agrees to held accountable for the work presented.

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