Battery charging system for electric vehicle

Nayan J. Kotmire[1], Anandrao B. Kakade[2]
[1]Department of Technology, Shivaji University, Kolhapur, India
[2]RajaramBapu Institute of Technology, Rajaram Nagar, Islampur Shivaji University, Kolhapur, India

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ABSTRACT

Selecting the appropriate charger for electric vehicles (EVs) is crucial for enhancing performance, with non-isolated DC-DC converters playing a significant role in charging EV batteries. The efficient conversion of input power into output as per the requirement is main perspective in the design of DC-DC converters. This paper delves into the landscape of non-isolated DC-DC converters utilized in EV charging, emphasizing their pivotal role. Additionally, it introduces a novel approach by incorporating machine learning-based pulse width modulation (PWM) control for the buck DC-DC converter. By integrating machine learning algorithms into the control scheme, the efficiency and performance of the charging system can be greatly enhanced, resulting in improved overall EV operation. This innovative application of machine learning not only optimizes charging efficiency but also enables adaptability to varying input/output conditions, ultimately leading to more efficient and effective charging processes for EVs.

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Corresponding Author:

Nayan J. Kotmire
Department of Technology, Shivaji University
Kolhapur 416004, India
Email: njk_tech@unishivaji.ac.in

1. INTRODUCTION

In recent years, electric vehicles (EVs) are gaining popularity across the world, due to their non-dependency on traditional fuel sources. The mobility of the market is mainly affected due to increasing pressure to reduce air pollution and greenhouse gas emissions. The European commission [1] decided to sell cars with less emissions in the near future. The fossil fuels on our planet are limited. The petrol and diesel vehicles cause toxic emissions due to which there are long-term effects on public health. In India, 75% of total vehicles are available for transport [2]. In transport, 14% of CO_2 is emitted by vehicles [3].

A different energy distribution is as shown in Figure 1. EVs are the best substitute over internal combustion engine vehicles all over the world. Since EVs have fewer moving parts, lower fuel cost and higher efficiency [4]. Many western countries, like Norway, have developed new norms for the use of EVs. In recent years, the TESLA electric car is gaining popularity across the world. These types of EVs need sufficient charging to travel long distances. To make this technology more popular in day to day life, suitable charging system have to be developed [5]. There should be, in particular, systems for charging batteries for this kind of EV [6]. A DC-DC converter is used in EVs for changing one voltage level to another voltage level [7].

It is an electronic or electromechanical device. In electronic conversion, the DC-DC converter operates in switching mode. In this type of conversion mode, the energy is stored in an electric field or a magnetic field. The isolation in input and output of the transformer is achieved in this type of DC-DC converter. Many topologies are available in electronic mode [8].

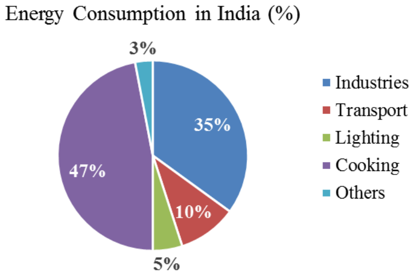

Figure 1. Energy distribution [3]

The DC-DC converter with a transformer is known as the isolated DC-DC converter. They control output voltage and charging current of the battery [9]. Battery chargers used for charging EVs have low cost and volume, which will give reliable and efficient operation. The components used in the design of the EV define their operations along with switching control [10], [11]. The charger is available in two forms, such as an onboard charger and an offboard charger. On board charger gives maximum efficiency when the battery is lightweight [12]. Non-isolated converters have low voltage stress on power diodes and switches. Use of an inductor and capacitor gives low conduction loss in non-isolated converters [13], [14]. The buck converter is best for EV because of low current stress, better control over the battery parameters [15]. This paper introduces a pioneering application of machine learning-based pulse width modulation (PWM) control for the buck DC-DC converter in EV charging. This innovative approach enhances charging efficiency and performance, promising significant advancements in EV operation.

2. PROPOSED METHOD

2.1. Classification of DC-DC converter

DC-DC converters come in two main types: isolated and non-isolated, as depicted in Figure 2. In reviewing DC-DC converters, particular attention is directed towards non-isolated variants. This focus is attributed to their notable advantages, including a high static voltage gain, as well as diminished switching and conduction losses. Non-isolated converters offer distinct benefits that make them a preferred choice in many applications, contributing to improved efficiency and performance in various electronic systems where power conversion is essential.

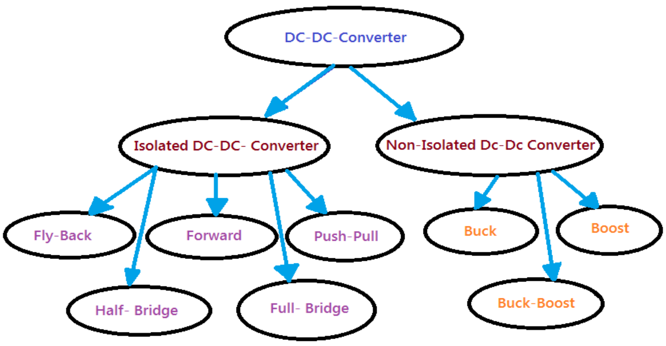

Figure 2. Classification of DC-DC converter

2.2. Non-isolated DC-DC converter

Gupta and Phulambrikar [16] designed a buck DC-DC Converter, the circuit configuration is as shown in Figure 3. They developed a buck converter with switch, diode, inductor, capacitor and a load. They used a single pole double throw switch. By variation of the switch, they reported the voltage was not pure DC. They added an inductor in series with the load to reduce output voltage ripple content. They added capacitors across the load circuit. They reported that by adding capacitor ripple voltage and by adding inductor ripple current was decreased. A control circuit was developed for the switch using an opto-coupler.

They developed a converter decision matrix for buck, buck-boost, CUK, SEPIC converter. They designed a buck converter with open loop control. The input voltage is 12 V and the output voltage is 7 V.

Qiao *et al.* [17] designed a novel buck-boost topology for EVs in hybrid with fuel cells as shown in Figure 4. They discussed the different non-isolated topologies of the DC-DC converter. The boost DC to DC converter consists of two switches, two diodes, inductor and capacitor. They designed a buck boost DC-DC converter in cascaded mode. They compared four topologies. They concluded that buck boost topologies were simple in configuration and required fewer components. They developed a control circuit for controlling the output from the buck boost converter. They designed the circuit by considering operating frequency, inductor value, and capacitor value. The fuel cell output voltage was 280 V-520 V. To increase the motor power rating, they used the buck-boost converters that make use of two switches. The author reported that buck boost converter topology required smaller inductor sizes, less number of switches and inductor losses with higher efficiency.

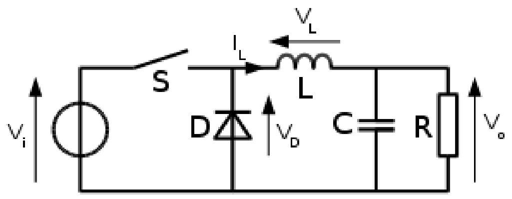

Figure 3. Buck DC-DC converter

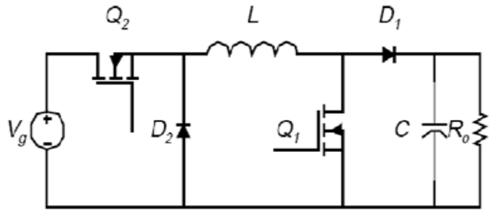

Figure 4. Buck boost DC-DC converter

Hasaneen and Mohammed [18] developed a boost converter as shown in Figure 5 in switch mode. They designed the boost converter in both the modes, continuous and discontinuous. They selected a diode, inductor and capacitor for the design of the boost converter by selecting three inductors for the 12 kW, 200 kW, 500 kW. They have made a simulated model of the Boost converter for the photovoltaic (PV) array. The simulated inductor current, diode current and insulated gate bipolar transistor (IGBT) current were observed. It was concluded that a boost converter with different inductor values for a load from 12 kW to 500 kW. The Table 1 shows various non-isolated DC-DC converters. From the table it is found that buck converter [16] requires less no of components and low output voltage ripple as compared to boost [17], buck-boost converter [18].

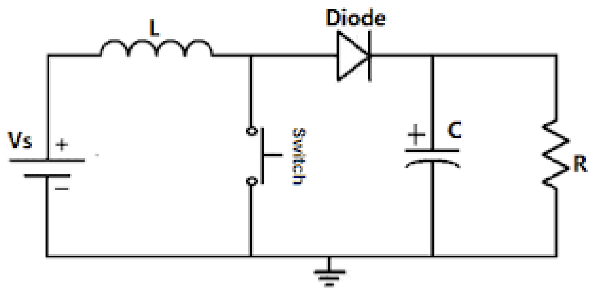

Figure 5. Boost DC-DC converter

Table 1. Non-isolated DC -DC converter

Author	Number of inductors	Number of active switches	Output voltage ripple
Gupta and Phulambrikar [16]	1	1	Less
Qiao *et al.* [17]	1	2	High
Hemasuk and Po-Ngam [15]	1	2	Less

2.3. Application of buck DC-DC converter in EV system

The proposed system will be suitable for efficient and fast charging of batteries. In this system additional facility of monitoring and protection of circuit will be given. Over the period of time simulation model can be developed for the same. Figure 6 shows a basic system block diagram. The system will be consists of 4 entities which are listed follows: i) AC input, ii) full wave rectifier, iii) DC to DC converter, and iv) battery.

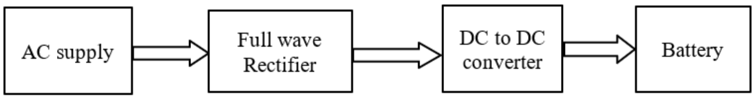

Figure 6. Block diagram of buck DC-DC converter in EV system

The single phase AC input voltage is completely equipped to vary values of voltage that suppose the stretch of charging at a frequency of fifty Hertz [19]. The input filter consists of inductors and resistors that are connected. Four diodes are utilized in a full wave rectifier [20]. The power switch in a DC-DC buck converter might be a MOSFET or a bipolar junction transistor (BJT) [21]. Additionally, it has an LC filter. A MOSFET or BJT is used as a power switch in the circuit. The circuit's pulses are regulated by both switches [22]. The DC-DC converter's input voltage is lower than its output voltage [23]. The diode is forward biased when the MOSFET is off by running current through an inductor. The DC-DC buck converter consists of a MOSFET or BJT as a power switch. The MOSFET or BJT acts as a power switch. The battery supplies the required voltage levels to run the system [24] and more. The battery's capacity of EV is the main measure considered for estimating the range of the vehicle. For storing more energy for longer ranges requirements, higher battery capacities are used which may require more time for the charging. The performance of the battery depends on thermal and load conditions [25].

3. MACHINE LEARNING BASED APPROACH

In the feedback loop-based approach in buck-boost converter, machine learning can be used to get better results. The power electronic converter with the use of machine learning was proposed in [26]. With enhanced data-based training and data driven technique, support vector machine (SVM) was used in [27]. The principle of expectation maximization was used along with principal component analysis. The fault classification task was performed in this work. In supervised machine learning based buck converter approach [28] used dynamic switching control. In the application of PV based step up or step down requirements, buck boost converter was equipped with a machine learning method as proposed by [29]. Also, applications in PV systems were discussed [30], [31]. However, there is very rare work done with the use of a machine learning approach which shows requirement and scope for more advancement with better results [32], [33].

The output voltage from a DC-DC buck-boost converter involves adjusting the duty cycle of the switch which is performed with the use of PWM [34]. In traditional PWM control, the duty cycle is determined based on fixed algorithms or feedback loops [35]. However, with the integration of machine learning, particularly artificial neural networks (ANNs), PWM control can be optimized dynamically based on input/output conditions. An ANN-based PWM control system utilizes a neural network to learn the relationship between input parameters (such as load current, input voltage and output voltage) and the corresponding optimal duty cycle for efficient operation [36]. The ANN is trained using a dataset that includes various operating conditions and their corresponding optimal duty cycles. Once trained, based on operating requirements and conditions, the ANN can predict the optimal duty cycle in real-time. Mathematically, the output of the ANN, representing the predicted duty cycle, can be denoted as (1).

$$D_{predicted} = f(X) \tag{1}$$

Where:
$D_{predicted}$ is the predicted duty cycle.
X represents the input parameters (input voltage, output voltage, and load current).
f is the function learned by the neural network during training.

The switching of the power semiconductor devices in the buck converter is controlled using PWM, with the duty cycle predicted to achieve optimal regulation of the output voltage. By utilizing machine learning-based PWM control, the buck converter can adapt to varying input and output conditions more effectively, with improved efficiency, reduced output voltage ripple enhancing the performance in charging EV batteries. Figure 7 shows the closed loop buck converter.

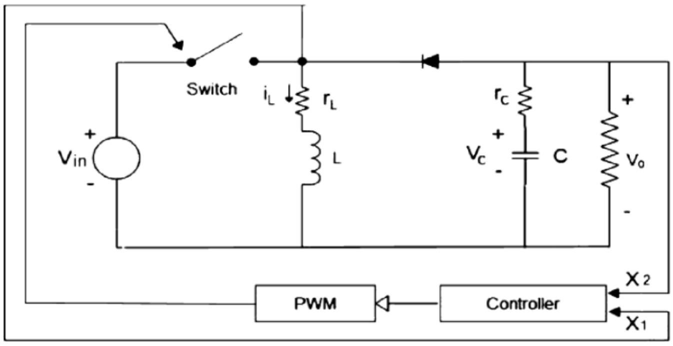

Figure 7. Closed loop buck converter

4. RESULTS AND DISCUSSION

In Table 2, the non-isolated DC to DC Converters are compared in terms of conversion ratios, design specifications and advantages and disadvantages [16]–[18]. The buck converter steps down the voltage with low capacitance value with low output voltage ripple. This is achieved with the use of opto-coupler for interfacing the control circuit in the buck converter. Buck-boost converter can be configured in flexible specifications as compared to boost DC to DC converter making it possible to be used for high power applications through cascading of the stages. Design of boost DC to DC converter operates in various operating conditions. From the table it can be found that buck converter will be good for batteries of EV, its topology offers fast charging hardware power processing control and flexible control power of battery.

Table 2. Comparison of non-isolated DC to DC converters

Non-isolated DC to DC conveters	Conversion ratios	I/P Vtg. (V)	O/P Vtg. (V)	Duty cycle	Inductor value (µH)	Capacitor value (µF)	Output power (KW)	Switching frequency (Khz)
Buck DC to DC converter [16]	D	12	7	0.63	151.5	4.7	5	82.241
Buck-boost DC to DC converter [17]	D/(1-D)	520	310-410	0.5	80	113	15 kW, 45	15
Boost DC to DC converter [18]	1/(1-D)	300	550	0.5	0.67 mh, 78, 22	3500	12,200	50

The three types of the converter are compared with respect to their advantages and disadvantages as shown in Table 3. Buck converter had fewer number of components. Boost converter requires cheaper filter components while buck boost converter had simple configuration [37]. The less output ripple is seen in buck and boost converters and also polarities are also positive. The reverse polarities are seen in the buck boost converter [38]. Buck converter had continuous output current and best efficiency per cost. The advantages of buck converter is not significant due to its drop problem. Buck converter is better in general but its drop problem and control are more challenging. Buck converter topology is used to provide controlled output power supply to the batteries of EV [31]. Topology selection for the charging of EV would depend on charging voltage, time and resource available [32]. As there is no inversion in the output voltage and also voltage reduction is possible the important requirement is satisfied by buck converter. The specifications requirement are thus satisfied [33] with the choice of buck converter.

In the buck converters, disturbances handling scenario in terms of sliding control based fast switching mechanism is achieved in [39]. On the other hand, stabilizer-controlled boost controller is designed for handling the disturbances in case of constant load characteristics in micro grid [40]. The effective control mechanism achieved with the help of PWM management, the analysis with respect to small and large signals is provided in [41]. The important tuning strategy is defined in [41]. In machine learning based approaches, reinforcement learning is also used in the method in [42]. The impact of adaptive control changes is analyzed in this method. With the use of artificial intelligence algorithms [43], fuzzy rules-based control is presented in [44]. In the internet of things (IoT) based real time control, the use of machine learning based strategy is discussed in [45]. While using the machine learning algorithms, the computational complexity considerations are important to achieve the synchronization in feedback to control signal estimation during design of converters [46]. The predictive outcome along with achievements and challenges are discussed in [47]. The overall up gradation facilities with the use of reinforcement learning are discussed in [48].

Table 3. Comparative study of advantages and disadvantages

Buck	Buck boost	Boost
– Simple topology, easy to implement and control. – High efficiency due to low power dissipation. – Lower cost compared to some other converter topologies. – Limited output voltage range (output voltage < input voltage). – Not suitable for applications requiring higher output voltage than input.	– Wide input voltage range, suitable for battery-powered devices. – Allows for both step-up and step-down voltage conversion. – Can regulate output voltage even when input voltage fluctuates. – More complex circuitry compared to Buck or Boost converters. – Efficiency decreases as the duty cycle approaches 50%.	– Step-up voltage conversion, suitable for applications requiring higher output voltage than input. – Provides galvanic isolation between input and output. – Can operate with input voltage lower than output voltage. – Higher voltage stress on components compared to Buck converter. – Lower efficiency compared to Buck converter, especially at high input/output voltage ratios.

The conversion ratios can be compared as shown graphically in Figure 8. The output is reduced compared to input voltage in the buck converter. The conversion ratio is M(D)=D. For getting greater output voltage than input voltage boost converter is used. Its conversion ratio is M(D)=1/(1–D). For either increasing or decreasing applications the buck-boost converter is suitable. The output is obtained with inverted polarity. The conversion ratio is M(D)=-D/(1–D).

From the observations, buck converter is best choice for the EV charging system which is upgraded with the use of machine learning based PWM control approach [49]. With the use of machine learning based approach a system is implemented in MATLAB Simulink for the analysis of conversion capacity. Figure 9 shows the output for different duty cycles. In the work presented in this paper, the implementation is done with the use of Simulink based approach. In the machine learning based design of buck DC-DC converter, artificial neural network is used to control the PWM [50], [51]. The important requirement of the implementation is generation of the data for training which is obtained through the use of simple proportional integral derivative (PID) controller in terms of values of errors and target outputs. In the analysis of the DC-DC converter, parameter selection plays important role [52]. The actual output and desired output are compared to find the error. To minimize the error as a fundamental objective, pulse widths are adjusted to control the switching. The input voltages are varied from 10 V, 24 V, 36 V, and 48 V. In the analysis one at a time is considered as fixed output voltage which especially 12 V in experimental results shown in Figure 9. For the duty cycle of D=[0.20, 0.25, 0.33, 0.54] the analysis is performed as shown in Figure 9.

Figures 9(a) to 9(d) display the output voltage Vo regulated by PID controller under different duty cycle values, D. In Figures 9(a) and 9(b), with duty cycle 0.20 and 0.25, significant oscillations occur initially which have ranged from 10 V to 24 V peak to peak during the transient state. Although overshoot is noticeable, it remains within acceptable bounds. Contrasting with Figures 9(c) and 9(d), for duty cycle 0.33 and 0.54 oscillations reach higher amplitudes of 36 V to 60 V peak to peak indicating increased oscillation levels compared to previous cases. Overshoot remains a prominent feature across all graphs in Figure 9, with no significant improvement observed. The subsequent graphs in Figures 9(a) to 9(d), spanning duty cycles from 0.2 to 0.54, consistently exhibit excessive oscillations around the set-point during transient conditions, contributing to notably high overshoot levels. Moreover, all responses in Figure 9 demonstrate prolonged settling times, consequently impeding the efficiency.

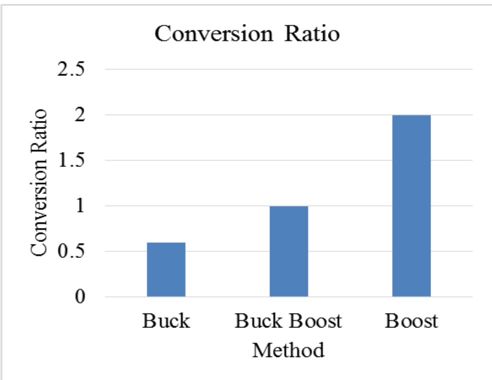

Figure 8. Comparison of conversion ratios

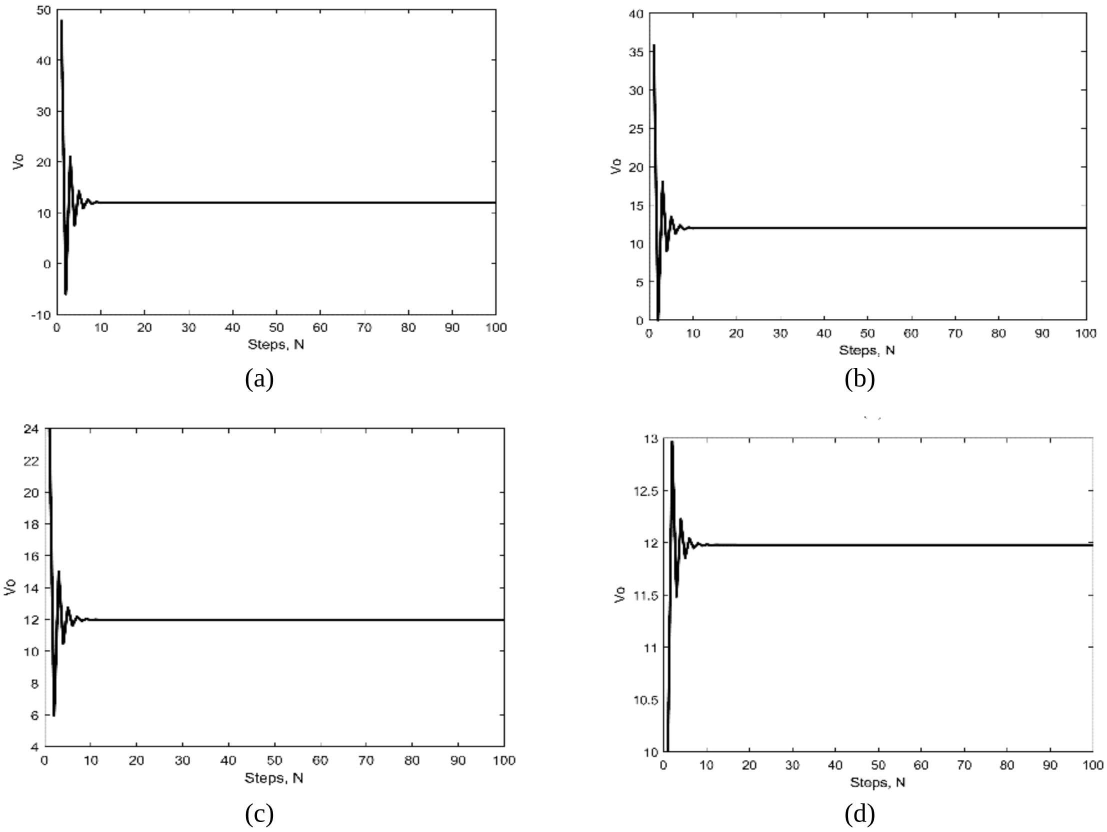

Figure 9. *Vo* output of buck converter for duty cycles (a) *D*=0.20, (b) *D*=0.25, (c) *D*=0.33, and (d) *D*=0.54

5. CONCLUSION

EVs are used to reduce environmental pollution, with the battery being the most critical component. Various chargers are available for recharging these batteries, but selecting the optimal charger design for better efficiency can be challenging. The performance of a charger is determined by its control technique and the components used. From the comparative study presented in this paper, it is concluded that a buck converter requires fewer components and exhibits reduced output voltage ripple. An EV charger utilizing a buck converter enables efficient fast charging. This proposal suggests potential improvements in chargers for EVs using a buck converter. The proposed approach aims to deliver a consistent and efficient charging voltage to the battery. It is observed that with the use of a machine learning-based approach, the buck DC-DC converter demonstrates more stable performance compared to other methods. Additionally, dynamic control of the output is achieved through PWM management with a machine learning-based approach. Further refinement of the PWM control coefficients in the design of a buck DC-DC converter can enhance system efficiency and reduce costs, supporting better battery life management amid the growing demand for EV charging.

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BIOGRAPHIES OF AUTHORS

Nayan J. Kotmire received a B.E degree in electrical engineering from the Shivaji University Kolhapur, India, in 2003 and an M.E. degree in Control System Shivaji University Kolhapur, India in the year 2009. She is currently working as assistant professor in the Department of Technology, Shivaji University Kolhapur, India. She can be contacted at email: njk_tech@unishivaji.ac.in.

Prof. Dr. Anandrao B. Kakade received the B.E. degree in Electronics Engineering from Shivaji University, Kolhapur, India, in 2001 and the M.Tech. and Ph.D. degrees in RF and Microwave Engineering from the Indian Institute of Technology, Kharagpur, India, in 2005 and 2010, respectively. He is currently an Assistant Professor in the Department of Electronics and Telecommunication Engineering, Rajarambapu Institute of Technology, Sakharale, Islampur, India. His research interests are novel antennas, metamaterials, and guided-wave components. He can be contacted at email: anandrao.kakade@ritindia.edu.