

Design of switched capacitor converter-based wireless power transfer using mutual inductance for micropower applications

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Abstract

Short-range wireless DC-to-DC power transmission using a switched capacitor converter (SCC) for various voltage ranges is presented in this letter. In wireless power transfer (WPT) applications, the main factors to consider are the target's distance from the source coil and the voltage received at the load. In this work, the receiving voltage can be varied according to the application by selecting the voltage ratios (VRs) using the multiphase controller. The different VRs are selected using the Fibonacci series having the arbitrary value of (0, 1). A proposed circuit is designed and simulated using SIMULINK to validate the proposed WPT converter and to verify its transfer efficiency. The constituent blocks of the transmitter and receiver modules are designed, simulated, and examined for WPT. In many studies, step-up voltages are presented and discussed, but not the step-down WPT. This letter discusses the wireless power supply system with different step-down/step-up VRs, which can be used to supply auxiliary systems such as battery charging, audio systems, mobile phone calls, and general voltage regulators. The proposed converter with WPT provides high efficiency, voltage regulation, and target distances. The power of the proposed converter varies from 80 μ W to 100 μ W for the input voltages 12 V–24 V.

Keywords

DC-DC, SCC, WPT, Wireless

1. Introduction

Wireless power transfer (WPT) has gained significant traction across various applications, from low-power bio-engineering devices to high-power battery charging systems. In modern systems, the importance of efficient WPT cannot be overstated, given the increasing power demands and the necessity to transfer power to locations difficult or impractical to reach through conventional means [1]. WPT allows for transmission of electric power from one point to another through free space, eliminating the need for physical wires or mediums [2].

Innovative WPT technologies are currently being explored as highly intriguing and attractive solutions

[1–5]. These new systems offer alternatives to traditional battery usage, and aim to eliminate the need for conventional cable connections between power sources and devices [3,4].

This technology can be used when continuous or immediate energy transmission is required. There are various ways to transfer power: electromagnetic coupling for long ranges, resonant coupling for mid-ranges, and inductive coupling for small ranges [3]. Furthermore, various techniques have been created for WPT, and they are categorized according to various factors including distance, transfer efficiency, and circuit design [4]. WPT, which uses electromagnetic induction, is used, among other things, for autonomous sensors, radio frequency identification systems,

bio-implants, and battery recharging in both home and electric vehicle (EV) systems [5,6]. All WPT applications must supply the load with sufficient power while maintaining a high-power transfer efficiency (PTE).

Coil parameters such as mutual inductance and coupling factor define these crucial elements [7]. Consideration has been given to the frequency impacts of coil position, including the spacing between coils [9]. High-efficiency power electronics converter circuits are necessary for any power transmission [10]. The DC–DC converters are essential components of this setup. Switched capacitor converters (SCCs) are ideal for WPT in various DC–DC combinations because of their high efficiency, low losses, and load-side stability, particularly in low-power applications [10]. Figure 1A shows the proposed system's generalized block diagram. The input is a DC source, which is given to the SCC network for voltage generation, and later, it is fed to the wireless network for power transfer.

In modern power management systems, the role of switched capacitor DC–DC converters is pivotal, offering a compelling alternative to traditional linear regulators. These converters boast advantages such as high efficiency, reduced size, and minimized heat

dissipation, making them indispensable components in various applications, ranging from portable electronics to renewable energy systems.

Switched capacitor DC–DC converters are crucial in various applications, ranging from portable electronics to renewable energy systems. Unlike conventional power converters, SCCs do not require any energy storage in a magnetic field. SCCs have many topologies, allowing both step-up and step-down functions. They are mainly used in voltage regulators, charge pump applications, [1] and PV-based low-power applications.

This letter embarks on a pioneering exploration of advanced switched capacitor DC–DC conversion methodologies to enhance efficiency and adaptability in contemporary power management systems using WPT.

In the literature [1–8], AC–DC and DC–DC converters transfer power from the primary to the secondary coil by boosting the voltage. All the designed WPT devices in previous works in this field are single-voltage conversions. In this letter, multiple voltage ratios (VRs) can be transferred using a single topology. Similarly, in [12–14], WPT is used for charging EVs and is used in biomedical devices. The proposed block diagram can be seen in Figure 1B. Air

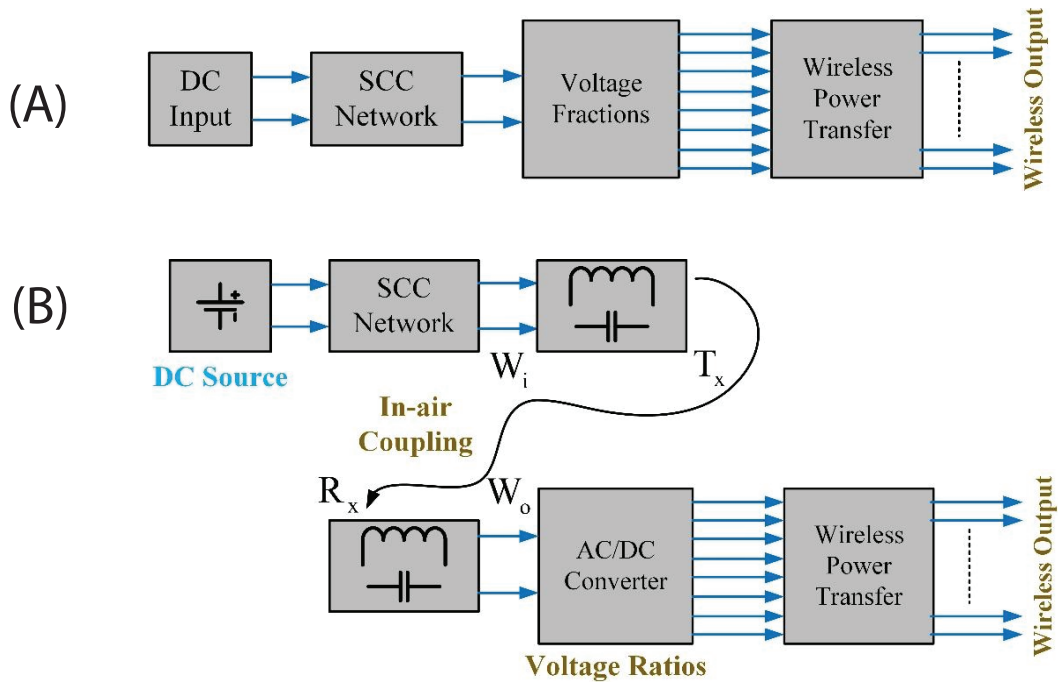


Figure 1: WPT using DC–DC Converter Configuration. (A) Generalized block diagram of WPT using SCC network. (B) Proposed block diagram for WPT using SCC. SCC, switched capacitor converter; WPT, wireless power transfer.

winding is used to transfer power from the primary to the secondary. The following sections provide a detailed explanation of the proposed converter. Furthermore, the designed topology is used to make buck voltage possible. All 21 VRs are generated using the Fibonacci series as a maximum VR [10]. The proposed methodologies show efficiency in overcoming the limitations of conventional DC–DC converters through theoretical analysis, simulation studies, and mathematical validation.

II. Basics of WPT

Power transformers used in energy transmission and distribution networks operate on the fundamental premise of mutual coupling processes, which have been the subject of extensive research. The WPT is designed using an SCC and mutual inductance using the same approach.

a. Basics of mutual inductance and mutual coupling for WPT

Transformers are stationary electrical devices that move power over small distances between a primary and secondary circuit. The main circuit generates a magnetic flux by allowing current to flow via a single winding. This flux is concatenated by a second winding, which is a component of the secondary circuit. It then responds to create an opposite magnetic flux [6–8]. A ferromagnetic core lowers the quantity of scattered flux by containing the magnetic flux inside a predetermined volume. The primary and secondary circuits are perfect for flux generation.

If the primary and secondary windings were placed far apart and the ferromagnetic core was removed, the electrical system's efficiency would be greatly reduced. Even if the primary winding's current intensity increased, the secondary circuit could still receive enough power. However, it could only truly absorb a portion of the available power. This type of technology is an increasingly popular magnetic induction-based wireless power transmission method. The same concept is used in this proposed system.

b. SCC for WPT

A DC–DC converter is designed to transform an input voltage source that is erratic or poorly specified into a predetermined and constant output voltage for a load. Linear regulators and switching converters are the two most popular DC–DC converters. The output current of a linear regulator is obtained straight from

the power supply. As a result, the output VR to the supply voltage roughly defines efficiency. SCCs are widely used in applications requiring low power consumption and no input/output separation. Capacitive converters are becoming increasingly popular for use in wireless power transmission and power management for mobile devices because of their advantages, which include minimum radiated EMI, practically silent operation, and the ability to fabricate them as integrated circuits. The block diagram of the suggested topology functioning operation is shown in Figure 2.

III. Proposed SCC for WPT

WPT systems transfer electric energy from a source to a load without any wired connection and can transport power to impossible or impractical locations. It is found in numerous applications, such as high-power battery charging systems and microwatt bio-engineering devices.

The proposed SCC is used to generate different output VRs. The VR are fed to WPT as input W_p , as shown in Figure 2.

The proposed topology of the WPT converter using a switched capacitor configuration is shown in Figure 2. The proposed WPT SCC consists of a DC source, 12 switches (S1–S12), and four capacitors (C1–C3), including a load capacitor (C0). All the capacitor values are considered to be symmetric. In this topology, C1, C2, and C3 charge and discharge to generate different voltage levels, and capacitor C0 is used as a filter capacitor. The proposed topology can produce 21 different VRs (1/2, 1/3, 2/3, 1/4, 3/4, 2/5, 3/5, ..., 1/n) [10]. The sequence of VRs is generated using the mathematical series with $VR_{na} = x_{na-1} + x_{na-2}$, where na is the integer, x is the sequence variable, and VR is the voltage ratio. The mathematical modeling and the VRs are discussed in [10]. Multiphase switching is used to control all the switches S1–S12 to generate different VRs. The multiphase switching is divided into four phases, as shown in Figure 2.

a. Generation of VRs

The generalized signed Fibonacci series is in the range of A_m . The number of series is denoted by “A”, and it is synthesized using Eq. (1) as follows:

$$V_n = \sum_{m=0}^n A_m * F_{n-m} + 1 \quad (1)$$

Where A_m can be 0 or 1, “N” is an integer, and n is the maximum number of capacitors, which sets

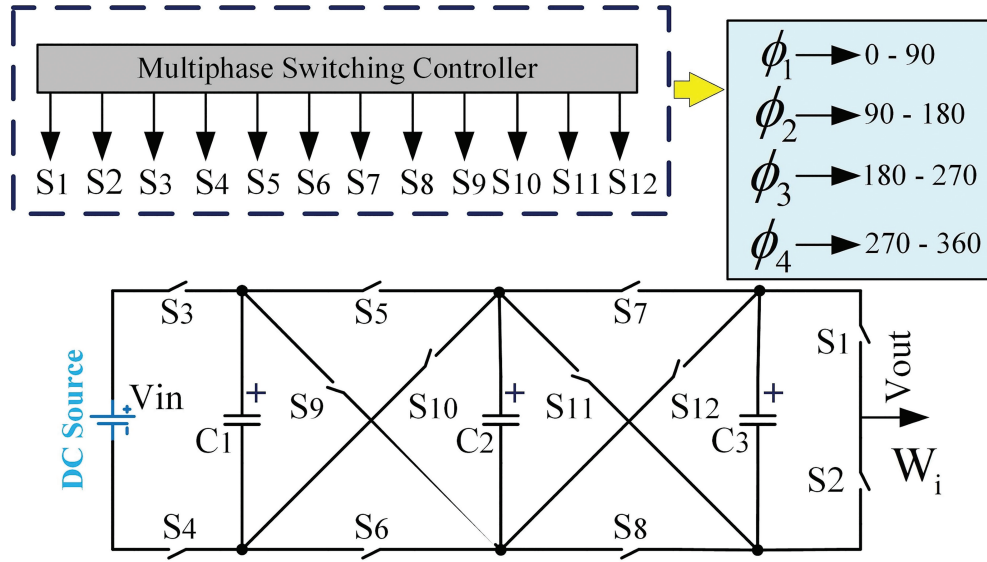


Figure 2: Proposed SCC circuit diagram. SCC, switched capacitor converter.

Table 1: Voltage fraction 7/8

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
ϕ_1	0	1	1	0	1	0	1	0	0	0	0	0
ϕ_2	1	0	1	0	1	0	0	1	0	0	0	0
ϕ_3	1	0	1	0	0	1	0	0	0	0	1	0
ϕ_4	1	0	0	1	0	0	0	0	1	0	1	0

the resolution value by incrementing the index m . Any positive number N can be expressed uniquely as a sum of distinct $(h, k)^{th}$ Fibonacci numbers using Daykin's theorem [10]. The (h, k) is assumed as a pair of (0, 1) or (1, 0). Using the same Eq. 1, the VRs are generated by applying the concept discussed in [10]. The same procedure in [10] generates switching sequences for all 21 VRs. For simplicity, in this work, 7/8 VR is considered for analysis, simulation, and efficiency calculation. From Figure 2, the multiphase control technique used ($\phi_1 - \phi_4$) is the difference phase that is used to trigger the switches (S1–S12) as shown. The pulse pattern is shown in Table 1 for 7/8.

IV. Mathematical Modeling for WPT Configuration

a. WPT using inductive coupling

A transmitter and a receiver are necessary components of any wireless power system to function

effectively. In an inductive connection, the transmitter and receiver are two separate coils wound on highly conductive materials. The mutual inductance of connected coils is proportional to their center-to-center distance when they are properly aligned and in parallel planes [7]. The coupling factor (k) represents the coil orientation. The coupling coefficient is particularly small when the distance is relatively large or the coils are misaligned. Magnetic coupling can be improved using a loss-free clamp (LFC) circuit and a few compensatory circuits [8].

In [11] is covered the electric equivalent model of the inductive coil-based WPT system.

The zero-frequency DC must be converted by mutual inductance into an extremely high-frequency signal that can be sent over the inductive link to transport the voltage. As shown in Figure 1B, the WPT unit receives the high-frequency signal through the inductive link and converts it back into a zero-frequency DC signal. There is a direct proportionality between the mutual inductance value and the transmission

distance. The general current law is used to calculate the coupling inductance.

b. Theoretical details

According to Ampere's law, the loop integral of the $\vec{B}$ field equals the net current enclosed by the loop, as given in Eq. (2):

$$\oint (\vec{B} \cdot d\vec{l}) = \mu i \quad (2)$$

Where $\vec{B}$ is the magnetic flux density, i is the net current, and μ is the permeability and $\mu = \mu_o \mu_r$.

According to Biot-Savart Law (3), the magnetic flux is calculated as follows:

$$dB = \frac{\mu \times i \times dl \times \sin \theta}{4\pi r^2} \quad (3)$$

Where, dl is the infinitesimal length of the conductor carrying the electric current i . r is the distance from the length element dl to the field point "P". The magnetic flux, calculated using Eq. (3), is given as follows:

$$\phi = \int \int_A \vec{B} * d\vec{A} \quad (4)$$

Where A is the area enclosed in a given loop. The voltage in the coils for primary and secondary terminals is given in Eqs (5) and (6) as follows:

$$V_{wi}(t) = L_p \frac{di_1(t)}{dt} + M \frac{di_2(t)}{dt} \quad (5)$$

$$V_{wo}(t) = L_s \frac{di_2(t)}{dt} + M \frac{di_1(t)}{dt} \quad (6)$$

Where $V_{wi}(t)$, i_1 , and L_p represent the voltage, current, and inductance of the primary coil (transmitter),

$V_{wo}(t)$, i_2 , and L_s are the voltage, current, and inductance of the secondary coil (receiver), and M represents the mutual inductance. The coupling coefficient k and inductance ratio, calculated using Eqs (5) and (6) are given as follows:

$$k = \frac{M}{\sqrt{L_p L_s}} \quad (7)$$

$$n = \sqrt{\frac{L_s}{L_p}} \quad (8)$$

The coupling factor is calculated from Eqs 7 and 8. So, the distances are defined.

V. Simulation Result Analysis

The proposed topology of the switched capacitor DC-DC converter for WPT is simulated in MATLAB/SIMULINK. The VRs of the proposed configuration are designed based on the mathematical sequence with the help of the Fibonacci series by selecting arbitrary values to generate different voltage levels. The values considered for each are as follows: input voltage is 24 V, capacitors C1-C3 are 27 μ F, and load resistance is 10k Ω , respectively. Output is mentioned in Table 2. The distance varies from 5 mm to 20 mm. The VR is selected as 7/8.

Figure 3 shows the proposed SC configuration simulation result for buck topology voltage fraction 7/8 with the input voltage of 24 V and load resistance of 1.5 k Ω .

Figure 3A The simulated output voltage is 20.85 V, and the analytical value is 21 V. From the simulated results, the output voltage is almost equal to the analytical value for an input voltage of 24 V. The output voltage of the proposed buck SCC topology is designed based on the triggering sequence

Table 2: Simulated output of WPT for different distance

Distance (mm)	5	10	15	18	20
VR	7/8	7/8	7/8	7/8	7/8
Input voltage	24	24	24	24	24
Output voltage	21	21	21	21	21
Load resistance (kOhm)	10	10	10	10	10
Receiving voltage	20.97	20.96	20.93	20.903	20.89
Output power	88.29 μ W	87.61 μ W	85.84 μ W	84.1 μ W	83.51 μ W

VR, voltage ratio; WPT, wireless power transfer.

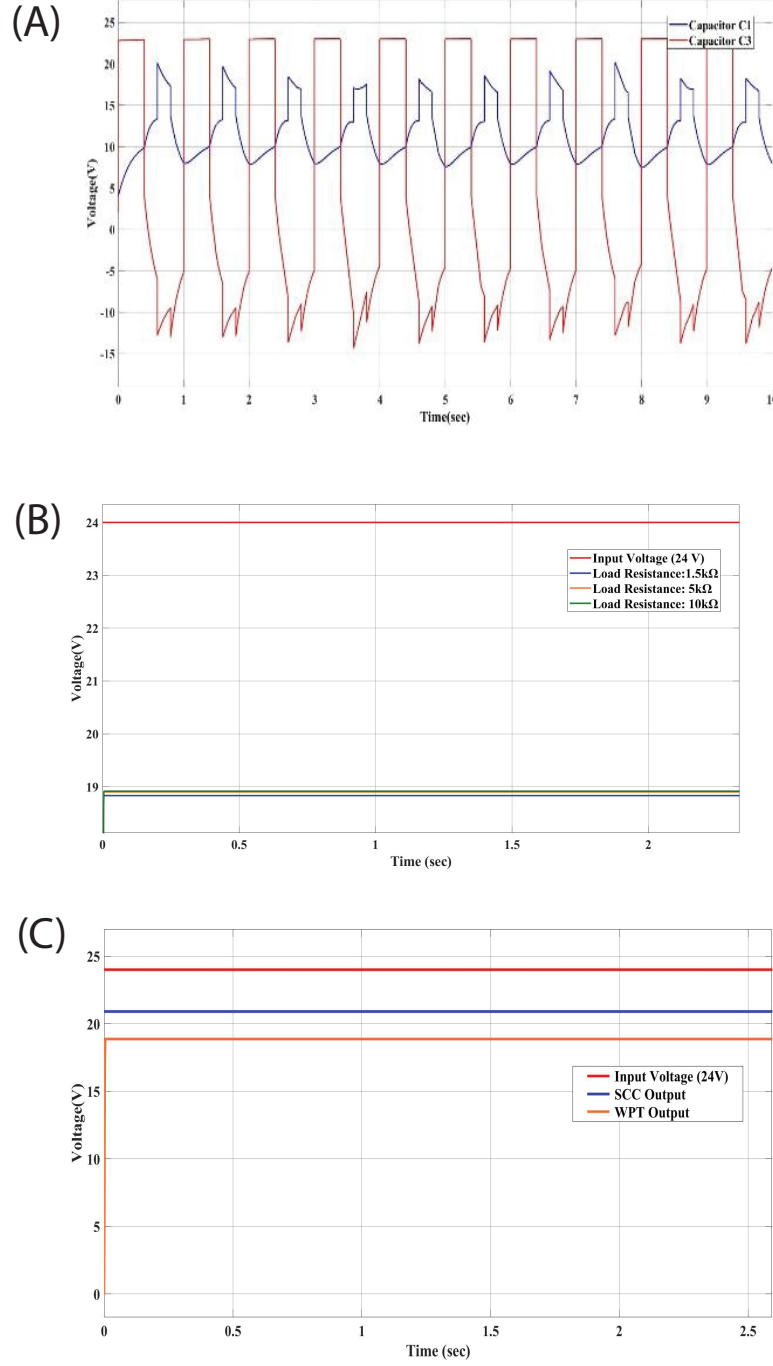


Figure 3: Simulated output of proposed WPT (Buck). (A) The input voltage, the converter's output voltage, and the WPT output. (B) Capacitor voltage C1 and C3. (C) Load change for WPT. WPT, wireless power transfer.

mentioned in Table 1. Figure 3B shows that the voltage level of capacitors C1 and C3 rises to 20 V and 23 V, respectively, for an input of 24 V. Figure 3C shows the voltage variation of WPT topology (buck) for different loads (1.5 kΩ, 5 kΩ, and 10 kΩ Load)

having the steady-state values of 18.714 V, 18.621 V, and 18.334 V respectively.

Figure 4 displays the proposed SC configuration simulation result for boost topology voltage fraction 7/8 with the input voltage of 7 V and load resistance

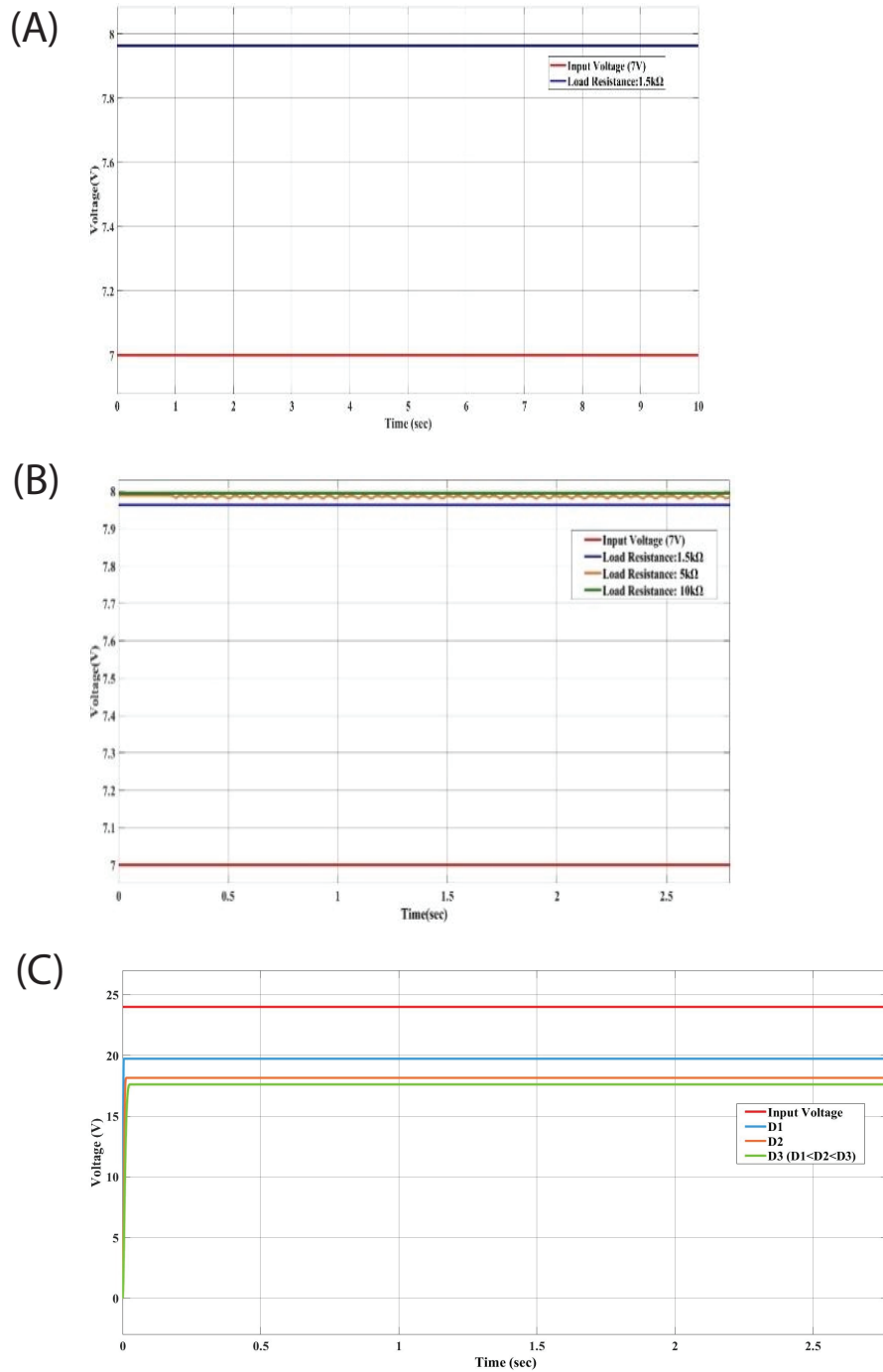


Figure 4: Simulated results of the proposed system. (A) Boost output voltage. (B) Output voltage with different load resistance. (C) Distance measured of Boost WPT. WPT, wireless power transfer.

of 1.5 kΩ (Figure 4A). The simulated output voltage is 7.91 V, and the analytical value is 8 V. From the simulated results, the output voltage is almost equal to the analytical value for an input voltage of 7 V. Figure 4B

shows the voltage variation of WPT topology (boost) for different loads (1.5 kΩ, 5 kΩ, and 10 kΩ Load) has steady-state values of 7.91 V, 7.94 V, and 7.99 V, respectively. Figure 4C shows the variation of WPT

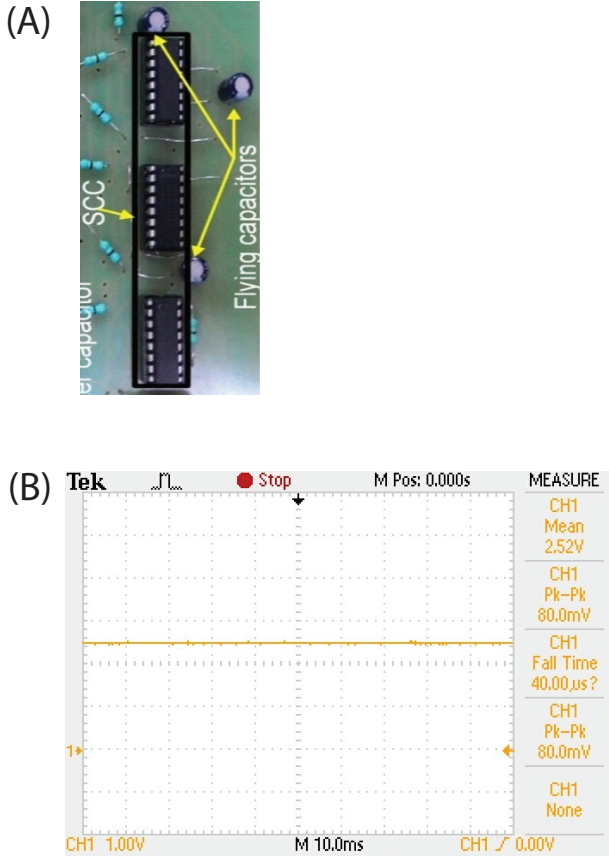


Figure 5: Experimental prototype for SCC. (A) Switched capacitor converter. (B) Output voltage of proposed converter of ratio 7/8. SCC, switched capacitor converter.

voltage output with a change in distance between the coils. (Buck).

It is clearly seen that the voltage drops if the distance varies from small to high. This topic is left for future study. However, from Figure 4C, it is clear that the voltage is transferred from primary to secondary within acceptable voltage drops. The same procedure is followed for other VRs; the WPT output is given in Table 3. Finally, the comparison with existing WPT technologies is shown in Table 4. The comparison result gives good clarity about the proposed WPT for multiple VRs. From Figure 4C, it is seen that the voltage drop is within acceptable limits when the distance varies. So, the efficiency is almost in the range of 80%–85%. The advantages of the proposed WPT are given in Table 4. The input and output voltages are variable, and the efficiency is maximum. Figure 5 shows the experimental prototype of the proposed converter for a 1/2 VR. The

Table 3: Different VRs SCC output and WPT output

Voltage fraction	Input voltage	SCC output voltage	Receiving end voltage
1/2	24 V	11.63 V	10.81 V
1/3	24 V	9.72 V	8.98 V
1/4	24 V	5.58 V	4.82 V
1/5	24 V	4.5 V	3.79 V
1/6	24 V	3.56 V	2.73 V
1/7	24 V	2.89 V	1.89 V
1/8	24 V	2.77 V	1.97 V
2/3	24 V	15.66 V	14.79 V
2/5	24 V	8.99 V	8.29 V
2/7	24 V	5.82 V	5.13 V
3/4	24 V	17.65 V	16.88 V
3/5	24 V	13.82 V	13.17 V
3/7	24 V	9.66 V	8.87 V
3/8	24 V	8.77 V	7.97 V
4/5	24 V	18.54 V	17.89 V
4/7	24 V	12.88 V	11.93 V
5/6	24 V	19.88 V	18.93 V
5/7	24 V	16.32 V	15.48 V
5/8	24 V	14.78 V	13.99 V
6/7	24 V	19.41 V	18.46 V
7/8	24 V	20.90 V	19.73 V

SCC, switched capacitor converter; VRs, voltage ratios; WPT, wireless power transfer.

input voltage is 3 V, and the output voltage is approx. 2.5 V for the 1 k ohm, as shown in Figure 5B. The prototype model is designed using analog switches having $R_{on} = 0.4 \Omega$. The required voltage for the proposed converter is 2.68 V for a 7/8 fraction having an input voltage of 3 V. The input voltage is restricted to 3 V due to the switch parameters, which can deliver a maximum voltage of 10 V.

VI. Conclusion

This research designed and implemented a new topology of an SCC with WPT to get different voltage levels from fixed voltage. The proposed topology has buck/boost configurations. To obtain 21 levels of voltage, three capacitors, 12 switches, and a DC voltage

Table 4: Comparison with existing WPT topology

Papers	Buck/Boost	Topology used	Input voltage	Output voltage	Maximum distance	Efficiency (%)
[2]	Boost	Frequency tracking WPT system based on PLL	30 V	106.8 (effective)	5 cm	70–80
[3]	Boost	Wireless battery recharging	14 V	10 V–38 V	15 cm	<20
[7]	Buck	WPT (Resonant frequency technique)	24 V	23.5 V	15 cm	90–95
Proposed	Buck/boost	WPT using PWM SCC	12 V–24 V	1 V–21 V	20 mm	80–85

SCC, switched capacitor converter; WPT, wireless power transfer.

source have been used, which provide 80%–85% efficiency at the receiving end based on the distance measured. Compared with other WPT systems, the proposed topologies show good advancement with each other and are unique in getting different voltage levels, low values of error, and better efficiency. The proposed configurations can be used for WPT for low-power applications such as voltage regulators, mobile chargers, and battery charging units. The proposed topology can be further extended with high voltage and EV pavement charging.

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Conflict of Interest

The authors declare that they have no conflicts of interest.

Electronic Supplementary Information

No electronic supplementary information is added.

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