Comparison of Efficiencies for a Composite Converter Design Using Series Injection

by

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In this Thesis, the composite converter is modified with the attempts of improving the converter efficiency using series injection. The composite converter was introduced as a DC transformer consisting of a buck, boost, and dual active bridge (DAB) converter that is bidirectional in nature [1]. Few studies since the introduction of the composite converter have attempted to improve the converter design, while the application of the composite converter itself is more common [3,7]. However, studies have been done to improve the performance of the DAB Converter. Series injection is a technique that improves the efficiency of the DAB converter with the use of a series transformer that improves the zero-voltage switching (ZVS) of the DAB. The proposed series injected DAB converter replaces the traditional DAB converter in the composite converter design with the intent of improving the overall composite converter efficiency. The modified circuit is validated via a comparison of converter efficiencies upon a variety of voltage and switching mode combinations modeled via computer simulation.

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1.0 Introduction

Certain dc-dc converter applications require converters to work with higher efficiency with very little compromise to size and cost of the converter itself. These applications also demand such parameters with variance in power and voltage conversion ratios [1] including in electric vehicles and photovoltaic (PV) applications. A Composite converter, which consists of a boost and buck converters as well as a DC transformer (DCX) have been proposed in [1] to provide a solution that is efficient within a range of voltages. A 98.7% 10-kW composite converter was proposed in [2] with the same block diagram as that of [1]. Designs were proposed and tested for a composite converter that have compared it with other converter methods such as a buck converter, but few studies have attempted to improve the design of the proposed composite converter.

Although few studies have attempted to improve the composite converter design, several have been done to improve the design of a dual active bridge (DAB) converters, which is used as the DCX in composite converters.

The purpose of this thesis will be to replace the DCX in [2] with the DAB converter provided in [5]. The DAB converter in [5] has an increased Zero Voltage Switching (ZVS) range in comparison to traditional DAB converters.

The proposed method in this thesis is replace the DAB converter used in the proposed composite converter with the DAB converter in [5] to increase the ZVS range of the Composite converter as a whole. Both methods (traditional DAB converter and proposed DAB converter in place of DCX) will be compared and tested via computer simulation.

1.1 Literature Review

The composite converter was originally introduced in [2] as a converter that performs the functions of all of its parts (buck, boost, and DAB) at higher efficiencies. Since the introduction a 30 kW composite converter was also introduced [1] as well as application, especially electric vehicle (EV) [3][7][8]. Several circuit designs have been designed that improve traditional dc-dc converter efficiency, many of which with different applications in mind. A Quasi-resonant Regenerating Active Snubber (QRAS) was designed, especially for applications in electric vehicles [9]. While efficiency and improved zero voltage switching (ZVS) are positive factors, the focus on electric vehicles resulted in a focus on specifications geared towards such (100 kW, 25kHz). Another focus on electric vehicles uses close-coupled inductors as an attempt to improve efficiency [10]. This is yet another scenario where specifications closely resemble that of an electric vehicle, but there is a higher emphasis on improved efficiency at 98.4%, as well as a duration of use. Unlike the traditional composite converter, this type of converter is not bidirectional.

A traditional composite converter is comprised of three types of DC converters. Modifications of these converters is not a new phenomenon. For a boost converter, the use of a Switch Capacitor Converter (SCC) [11] was proposed to allow for a smaller input reactor, resulting in improved efficiency, but was not based on optimal parameters and was focused on boost ratio. Other attempts have been made to reduce inductor size [12], especially for the use of electric vehicles, but a small-scale model was verified with little verification of higher voltages.

Several types of bi-directional DC-DC converters exits and have been compared [13], but the introduction to series injection mentioned in [5] is one of few methods that improved zero voltage switching as a method of improving efficiency. It is also a method that mentions the size of the addition of the series injection transformer in comparison, which is considered a positive attribute for the traditional composite converter.

1.2 Composite Converter Breakdown

Figure 1 shows a block diagram of a composite converter referenced in [1] and [2]. As shown, a composite converter consists of a buck converter, a boost converter, and a dc transformer (denoted DCX) connected together. This section will go through describing all three components in detail prior to creating a composite converter. Note that the background in the sub-sections to come of all three components will take several assumptions into place. Including the following:

1. Assuming ideal conditions, including no voltage or current ripple
2. The application of Volt-Second Balance and Capacitor Charge Balance is understood
3. The ideal switches shown in the figures of the sub-sections are constantly switching from position 1 to position 2. Duty cycle is denoted D and will be referred to as the percent time spent in position 1.

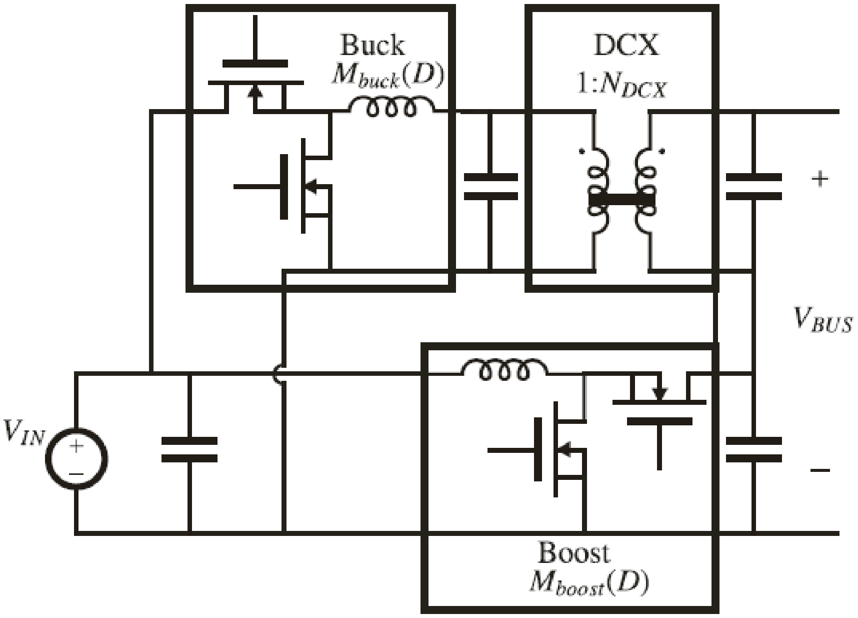


Figure 1: Composite Converter Diagram

1.2.1 Buck Converter

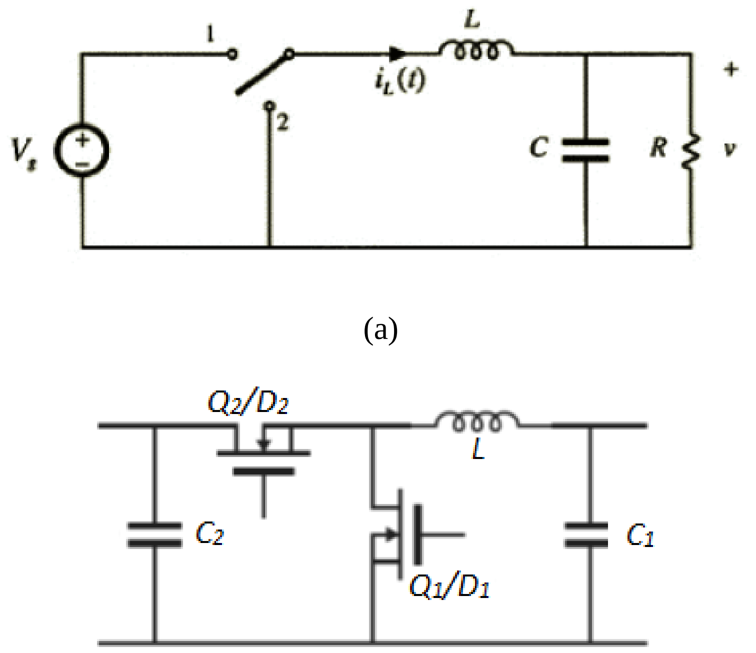
A generic buck converter is shown in Figure 2 (a), (taken from [4]). In position 1, we are given a load (resistor R) in parallel with a capacitor C, and in series with an inductor L and a voltage source. For position 2, we have L, C, and R in parallel. Applying Kirchoffs voltage and current laws (KCL and KVL) followed by application of the Volt-Second Balance and Capacitor Charge Balance gives us the following equations:

$$V_g = \frac{V_R}{D} \tag{1-1}$$

$$M(D) = D \tag{1-2}$$

$$I = V/R \tag{1-3}$$

For composite converter applications, the buck converter portion is designed as shown in Figure 2 (b). This design in [1] is such that Q_1/D_1 and Q_2/D_2 are both a pair of MOSFETs in parallel to each other. Q_1/D_1 and Q_2/D_2 will switch asynchronous to each other at all times. Capacitor C_2 in place of the voltage source will be explained in section 1.2.2 .



(a)

(b)

Figure 2: Buck Converter (a) Ideal and (b) Composite Converter Designed

1.2.2 Boost Converter

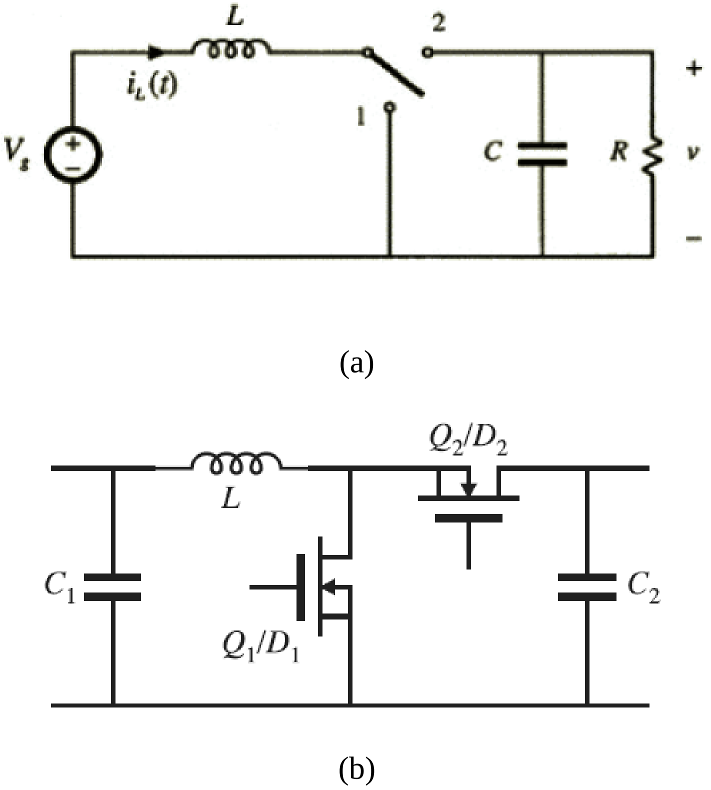
A generic boost converter is shown in Figure 3 (a) (taken from [4]). Position 1 represents a voltage source connected to an inductor L, where position two represents a load (resistor R) in parallel with a capacitor C, and in series with an inductor L and a voltage source. Applying Kirchoffs voltage and current laws (KCL and KVL) followed by application of the Volt-Second Balance and Capacitor Charge Balance gives us the following equations:

$$V_g = V_R(1 - D) \tag{1-4}$$

$$M(D) = \frac{1}{1-D} = \frac{1}{D'} \tag{1-5}$$

$$I = \frac{V_g}{R(D')^2} \tag{1-6}$$

Like the buck converter in section 1.2.1 , the boost converter is designed for the composite converter application, shown in Figure 3 (b). It is to be noted that the buck boost converter in Figure 3 (b) is the same component as the buck converter in Figure 2 (b) in the reverse direction. In both cases, the voltage sources are replaced with capacitors, making the circuit as well as the composite converter bi-directional.



(a)

(b)

Figure 3: Boost Converter (a) Ideal and (b) Composite Converter Designed

1.2.3 DC Transformer (DCX)

Figure 4 shows the DCX model used in a composite converter per reference [2]. The DCX used in the composite converter is a dual active bridge (DAB) converter. The DAB converter was originally introduced as a topology for high-power-density high-power applications, [6] has both a buck and boost capability, and is bidirectional. The DAB converter acts in 2 different stages:

1. $M_{p1,}$ M_{p4}, M_{s1} and M_{s4} are all operating
2. $M_{p2,}$ M_{p3}, M_{s2} and M_{s3} are all operating

If there is assumed to be a resistive load R, Kirchoffs voltage and current laws (KCL and KVL) can be applied followed by application of the Volt-Second Balance and Capacitor Charge Balance to give the following equations:

$$V_g = \frac{V_{out}}{n} \tag{1-7}$$

$$M(D) = n \tag{1-8}$$

$$I = \frac{nV_g}{R(2D-1)} \tag{1-9}$$

When attached in parallel with the buck and book converters mentioned in section 1.2.1 and 1.2.2 , the composite converter acts as both a buck and boost converter dependent on duty cycle, and is highly efficient in comparison to the buck and boost converter alone.

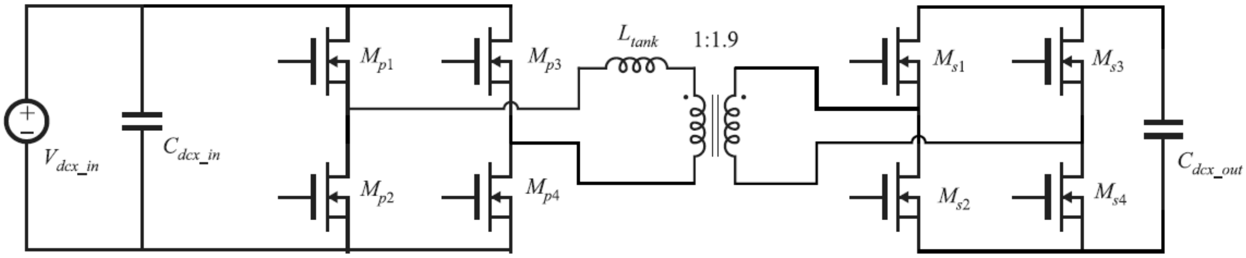


Figure 4: DC Transformer (DCX)

1.3 Series Injected Dual Active Bridge Converter

Figure 5 is the modified DAB converter that was first introduced in [5]. This configuration takes a standard dual active half-bridge (DAHB) converter, attaches a set of IGBTs in a similar configuration as the ones on the low side of a DAHB converter parallel to the low side configuration. This configuration called the Auxiliary series converter includes a transformer winding that is places in series with the low side of the main transformer of the DAHB. This is called the series transformer. This series transformer helps to control the reactive power flow through the converter, resulting in an enhanced ZVS of the DAHB converter itself.

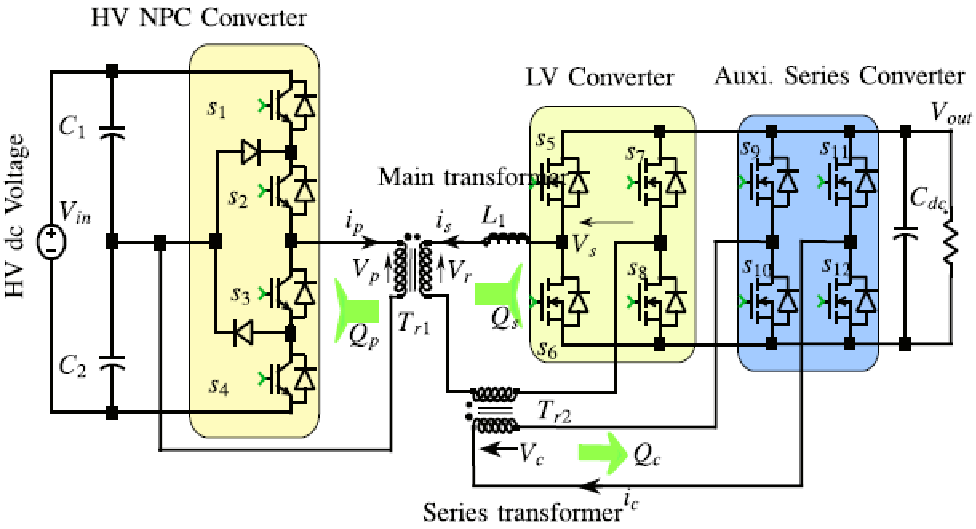


Figure 5: Dual Active Half-Bridge (DAHB) Converter with Series Injection

2.0 Circuitry

2.1 Proposed Circuit Design and Method

The composite converter was originally designed to act as a buck or a boost converter with improvements in efficiency with respect to weight, size, and electrical losses [1]. Current research done on composite converters tests the composite converter design described in 1.2 for different applications, including those related to electric vehicles [7]. Most adaptations to the composite converter itself revolved around the same theoretical circuit but with an updated component, such as a SiC-MOSFET in place of Si-IGBTs [8]. As such, previous results have successfully increased the efficiency of the composite converter.

The method proposed in section 1.3. increases the ZVS range of a DAHB converter. As mentioned in [5], the series injection method is also possible on a conventional DAB converter such as what is included in the composite converter. It is also noted that the series injection switches and transformer are added to the low voltage (LV) side of the DAB to avoid extra devices to isolate the high voltage (HV) side. Simulations done in previous research has proven that similar results are obtained from both methods. The proposed circuit is shown below in Figure 6

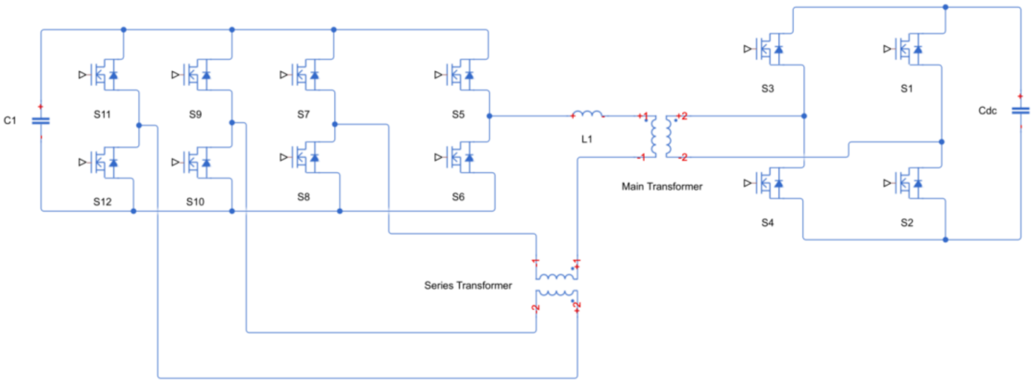


Figure 6: DAB with series injection circuit

The goal is to apply the principals of increasing the ZVS range of a composite converter by adding replacing the conventional DAB converter with a modified series injected DAB. The desired outcome is an updated composite converter that has an increased ZVS range as a result. It has also been noted that the composite converter is also known for efficiency based on its size. It is possible with series injection to be affective without much addition to the size of a modified DAB converter [5] and thus the same principal applies for a modified composite converter.

2.2 Circuit Parameters

In the composite converter designed in [1] and [2], optimized parameters were found for the components listed in Table 1: Optimized Design Specifications. These values will remain unchanged as the results for these are readily available for comparison. A previously designed composite converter also lists restrictions for a design that can process up to 10-kW of output power. The same restrictions apply for the 30-kW composite converter previously mentioned and are listed as the following:

1. $300V \geq V_{in} \geq 150V$
2. $V_{out} < 800V$
3. $3.8 \geq M \geq 1$
4. $N_{DCX} \geq 1.9$

These parameters will remain in place with the addition of the DAB with series injection. It is to be noted that although the 30-kW composite converter uses an N of 2, a turns ratio of 1.9 will be used and consistent in both the traditional and series injected composite converter builds. Theoretical results were tested for the composite converter compared to a conventional boost converter, and the efficiency was experimentally validated for the composite converter for all operating modes (DAB + Boost, DAB + Buck, DAB + Buck + Boost). Comparison of the conventional composite converter and the composite converter with added series injection will compare efficiencies at the same values listed. Though it has been previously mentioned that the composite converter and the DAB with series injection are bi-directional, they were not tested in previous references; it will not be tested in the reverse direction in this thesis. It is expected that the simulated values may differ from previous research due to the changes in components used (i.e. MOSFET vs. IGBT), but the goal is to compare efficiencies as a result of an addition to the composite converter.

Table 1: Optimized Design Specifications Method

COMPONENT	VALUE
TANK INDUCTANCE	2.7 μH
TRANSFORMER RATIO	1.9:1
BOOST INDUCTANCE	17 μH
BUCK INDUCTANCE	32 μH

2.3 Simulation

A model for both a conventional composite converter and a composite converter modified with a series injected DAB converter are created in Simulink via MATLAB R2017a per parameters listed in section 2.2. Prior to a full build, the buck and boost portions of the converter are built first, and voltage tested to ensure proper build of common components to both builds prior to connection of the DAB converters. It is to be noted that due to modeling constraints with an initial transient from zero volts to the initial DC voltage input, a one ohm resistor is placed in series with each capacitor parallel to the voltage source (buck and boost input capacitor) to initialize the simulation without error. This is a slight deviation to what is given in circuit parameters. Voltage outputs are measured at 50% duty cycles for both the buck and the boost converters with scopes and voltage measurement blocks in parallel with the buck and boost output capacitors respectively. An arbitrary test value of 600V is used as an input. Based on formula **(1-1)** and **(1-4)**, it is expected that the buck output and boost output will be approximately 300V and 1200V respectively. Upon assurance that the buck and boost models are correct, the traditional composite converter and series injected composite converter are created. Both models are created with a 100 ohm resistor simulating a load. The models created are tested for efficiencies with the use of voltage and current scopes. It is expected that there will be zero crossing points for power readings due to MOSFET switching. To measure power input, a current scope set in series with the positive terminal of the voltage input source. It is expected that the battery voltage remains constant during each simulation run and will be arbitrarily picked as constant. Current measurement is used along with this constant voltage can be used in the following power formula:

$$P_{in} = V_{in} * I_{in} \tag{2-1}$$

Voltage output is the sum of the DCX and boost converter voltages. In order to simulate power output, a current scope is set in series with the output resistor, in between the contacts of the DCX output capacitor and the output resistor. The voltage is measured with a voltage scope in parallel with the combination of the DCX and boost output capacitors. It is expected that the voltage output is to be expressed as

And the current voltage output is expressed as

$$I_{out} = I_R \tag{2-2}$$

resulting in an efficiency to be the following:

$$\%\, Efficiency = \frac{P_{out}}{P_{in}} * 100 = \frac{(I_R) * (V_{DCX\, C_{OUT}} + V_{BOOST\, C_{OUT}})}{V_{in} * I_{in}} * 100 \tag{2-3}$$

which is modeled as the following formula via a combination of voltage and current scopes, adders, and multipliers:

$$\%\, Efficiency = \frac{I_R * V_R}{V_{in} * I_{in}} * 100 \tag{2-4}$$

It is expected that power inputs and outputs will be represented graphically as sinusoidal or sawtooth functions. As a result, the presence of zero crossing points leads to an incorrect graph. A loss model was also avoided due to potential phase shifts.

2.4 Efficiency Measurement

As mentioned in section 2.1, the composite converter was designed with the intent for the same function as both the buck and boost converter with improvements in efficiency. Previous research compares the efficiency of a composite converter in comparison to a conventional boost converter. The series injection DAB converter was also proposed under the principal that the converter operating in ZVS is done for better efficiency. To best measure the potential positive impact that series injection would have on a total composite converter, efficiency is measured for both a traditional and modified composite converter. Using the simulations for a composite converter and modified composite converter mentioned in section 2.3, scopes are used to graph voltage and current inputs. For each circuit, the current output of the load resistor, current input, and total maximum voltage output are recorded in excel. To eliminate concerns of zero crossings with voltage and current inputs, signal statistics is used to retrieve steady-state RMS values. formula **(2-4)** is modified to be the following as a result:

$$\% \, Efficiency = \frac{I_{out\_rms} * V_{out\_rms}}{V_{in} * I_{in\_rms}} * 100 \tag{2-5}$$

Data is collected for both circuits with the voltage input varying from constant values of 140 V to 1200V and recorded in Excel. The varying voltage is simulated for a scenario with 50% buck and 50% boost duty cycles, and a scenario with boost at full passthrough (0% duty cycle) and buck at 50% duty cycle. These two cases provide a sample of all operating modules (boost only, DCX + Boost, DCX + Buck, and DCX + Buck + Boost). The efficiencies of both cases are plotted and graphed in Excel. The results of the created efficiency graphs are to be analyzed as a comparison of efficiency values with all other variables remaining constant. Power input to Power output is also recorded to ensure consistent power outputs and to analyze for potential anomalies.

3.0 Results

3.1 The Building Blocks

Figure 7 shows the Simulink model for the buck and the boost circuits. The result of the simulation is shown as graphs in Figure 8 and Figure 9. Although previous data is available, the simulation is only shown starting at about .015 seconds to account for initial transients that do not contribute to expected Buck and Boost output values. Though a visual representation of the graphs provided provide assurance that the circuit outputs are approximately what is expected, Signal Statistics are also provided to confirm the RMS values. Values that were recorded are acceptable and provide assurance that the different factor on the buck and boost (DCX and Series injected DCX) can be incorporated into the circuit without a future need to verify the Buck and Boost model for troubleshooting purposes.

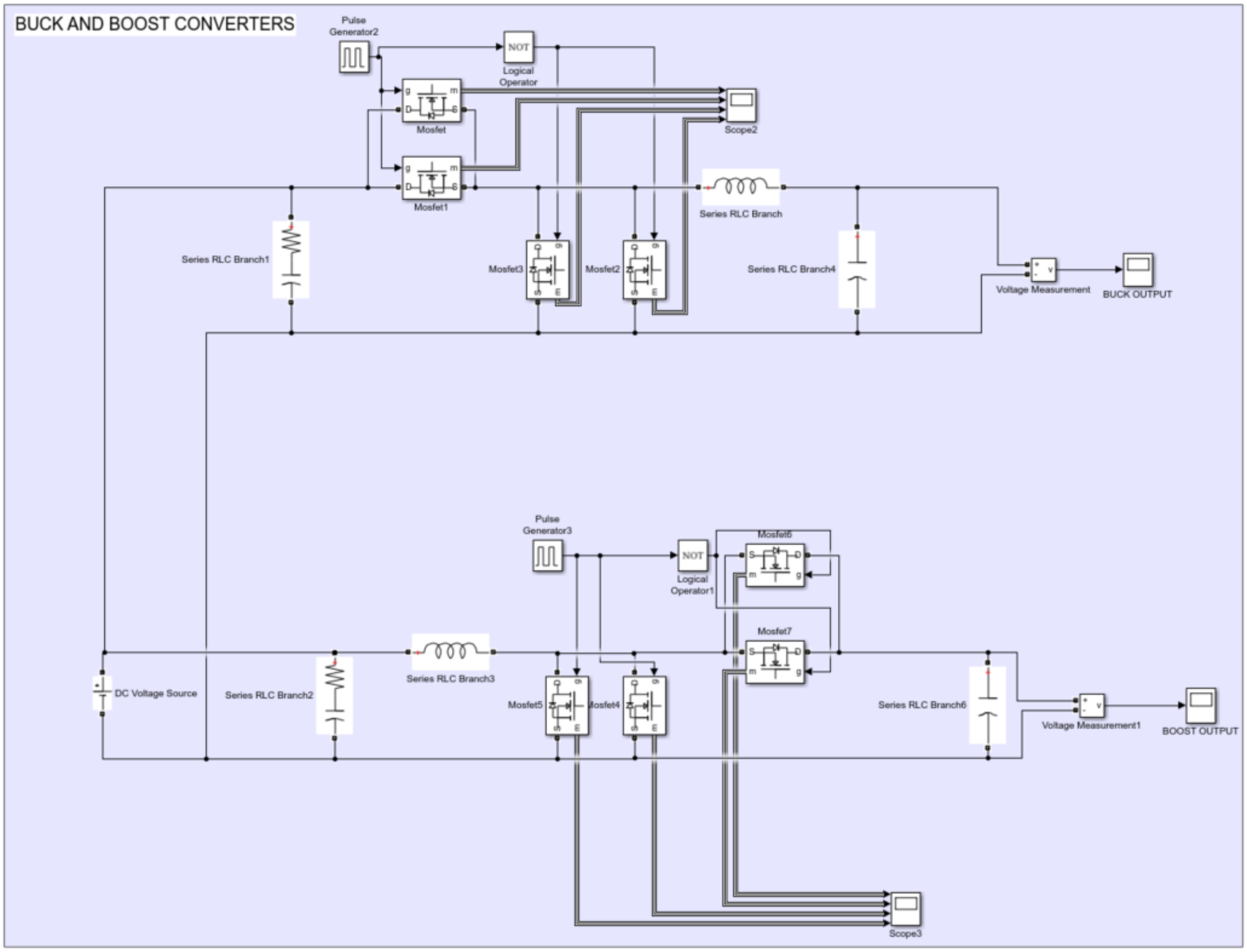
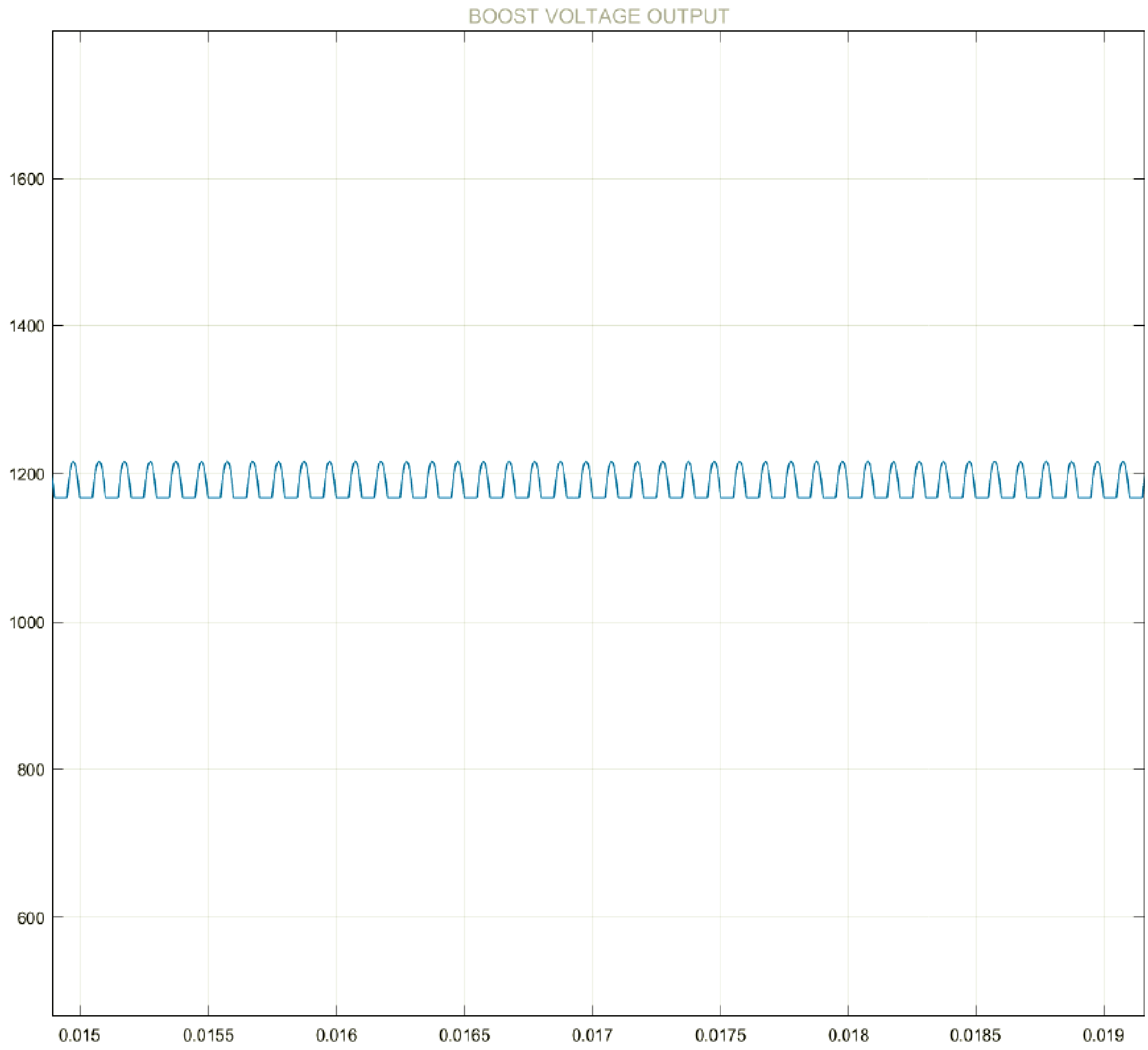
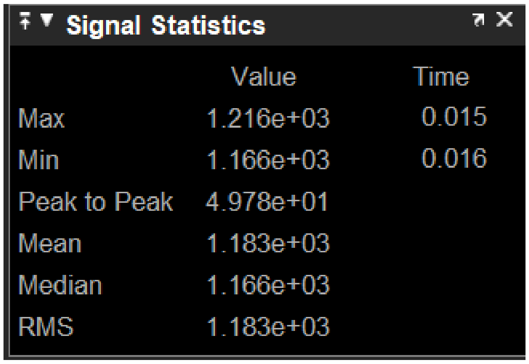


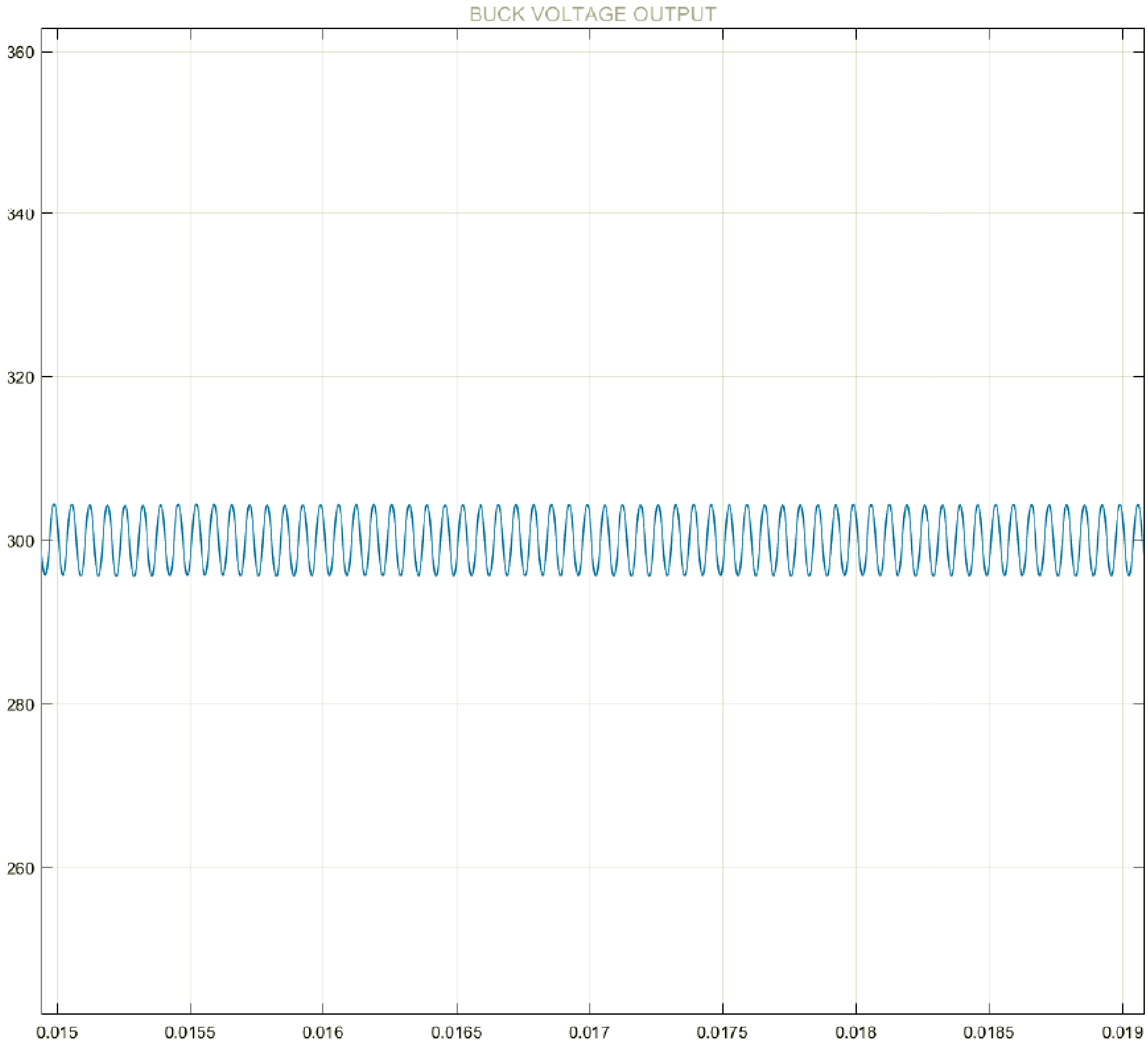
Figure 7: Buck and Boost Simulink Models

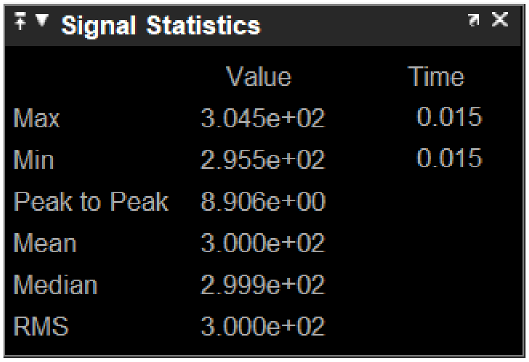




	Value	Time
Max	1.216e+03	0.015
Min	1.166e+03	0.016
Peak to Peak	4.978e+01	
Mean	1.183e+03	
Median	1.166e+03	
RMS	1.183e+03	

Figure 8: Boost Voltage Output Result





Signal Statistics

	Value	Time
Max	3.045e+02	0.015
Min	2.955e+02	0.015
Peak to Peak	8.906e+00	
Mean	3.000e+02	
Median	2.999e+02	
RMS	3.000e+02	

Figure 9: Buck Voltage Output Result

3.2 Composite Converter Simulation

Figure 10 shows the models of both a traditional and a modified composite converter. Though multiple points have been plotted to create a graphical representation of the circuit's efficiency, Figure 11 shows an example of the Power Input, Voltage output, and current output waveforms for a 280V input, with the buck converter running at 50% duty cycle and the boost converter running at full passthrough. (note: although passthrough is 0% duty cycle, modeling constraints only allow for a duty cycle of 0.01%). The voltage output values are what are expected based on formula **(2-2)(2-5)** and thus the model is assumed to be correct.

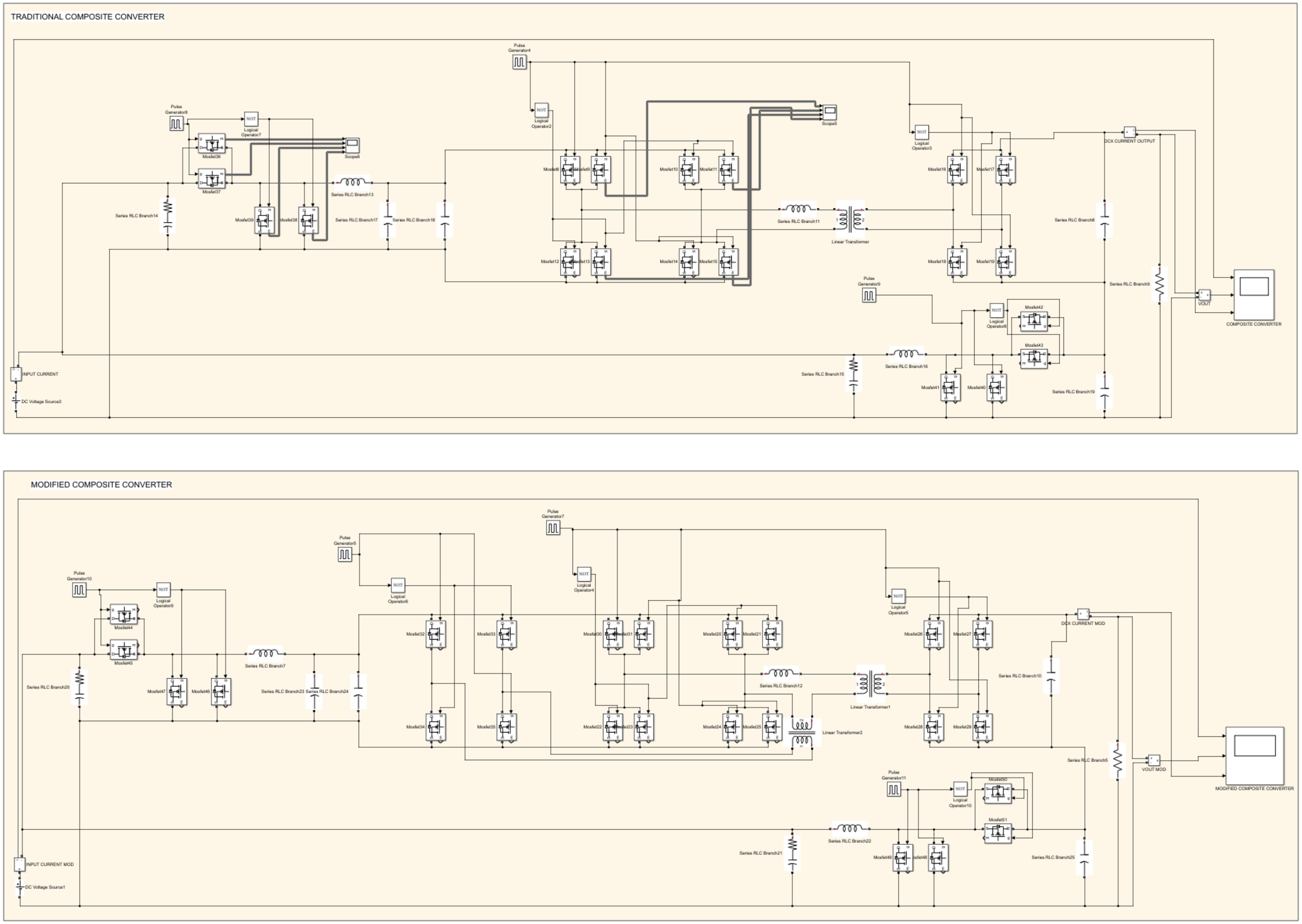


Figure 10: Traditional (Top) and Modified (Bottom) Composite Converter Circuit

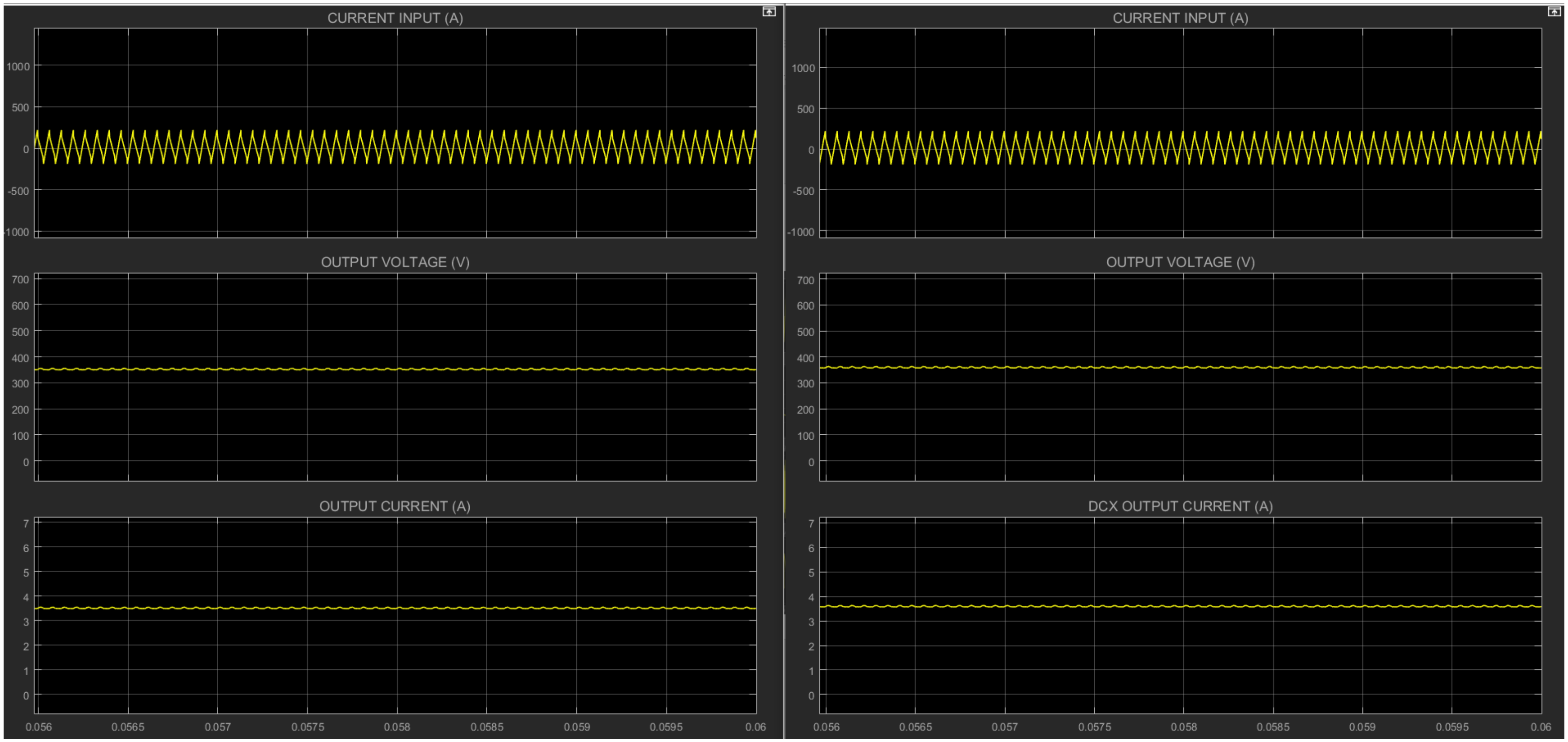


Figure 11: Traditional Composite Converter (Left) and Modified Composite Converter (Right) Sample Graphs.

3.3 Efficiency and Power Graphs and Values

The circuit and graphs described in section 3.2 is modeled for different duty cycle combinations and at an input voltage range of 140V to 1200V, with 20V increments until 300V and then in increments of 300V until 1200V. with currents, and voltages recorded and efficiencies calculated per formula **(2-5)** listed in 2.4. Collected data for 50% buck duty cycle and 50% boost duty cycle for boost is shown in Table 2. This method is repeated for multiple scenarios. The graphs are shown in Figure 12.

Table 2: Sample of data collected for 50% buck and boost duty cycle

FIXED VALUES				COMPOSITE CONVERTER						COMPOSITE CONVERTER MODIFIED					
INPUT VOLTAGE (V)	BUCK DUTY CYCLE (%)	BOOST DUTY CYCLE (%)	OUTPUT RESISTANCE (OHMS)	CURRENT INPUT (AMPS RMS)	POWER INPUT (W RMS)	VOLTAGE OUTPUT (V RMS)	CURRENT OUTPUT (A RMS)	POWER OUTPUT (W RMS)	EEFFICIENCY (%)	CURRENT INPUT (AMPS RMS)	POWER INPUT (W RMS)	VOLTAGE OUTPUT (V RMS)	CURRENT OUTPUT (A RMS)	POWER OUTPUT (W RMS)	EFFICIENCY (%)
140	50	50	100	93.99	13158.6	351.6	3.516	1236.2256	9.39481099	93.87	13141.8	359.2	3.592	11290.2464	9.817881873
160	50	50	100	107.6	17216	401.7	4.017	1613.6289	9.37284444	107.8	17248	410.5	4.105	1685.1025	9.76984288
180	50	50	100	121	21780	451.9	4.519	2042.1361	9.37619880	121.1	21798	461.8	4.618	2132.5924	9.783431507
200	50	50	100	134.5	26900	502.1	5.021	2521.0441	9.37191115	134.2	26840	513.1	5.131	2632.7161	9.808927347
210	50	50	100	141.1	29631	527.4	5.274	2781.5076	9.38715399	140.9	29589	538.9	5.389	2904.1321	9.814904525
220	50	50	100	148	32560	552.4	5.524	3051.4576	9.37179852	148.2	32604	564.4	5.644	3185.4736	9.770192614
240	50	50	100	161.5	38760	602.6	6.026	3631.2676	9.36859545	161.4	38736	615.7	6.157	3790.8649	9.786412898
260	50	50	100	174.7	45422	652.8	6.528	4261.4784	9.38196997	174.8	45448	667	6.67	4448.89	9.788967611
280	50	50	100	188	52640	703.1	7.031	4943.4961	9.39114008	187.9	52612	718.5	7.185	5162.4225	9.812252908
300	50	50	100	201.4	60420	753.4	7.534	5676.1156	9.394431645	201.2	60360	769.8	7.698	5925.9204	9.817628231
600	50	50	100	402.3	241380	1507	15.07	22710.49	9.40860469	402.4	241440	1540	15.4	23716	9.822730285
900	50	50	100	605.1	544590	2260	22.6	51076	9.378798729	605.1	544590	2309	23.09	53314.81	9.789898823
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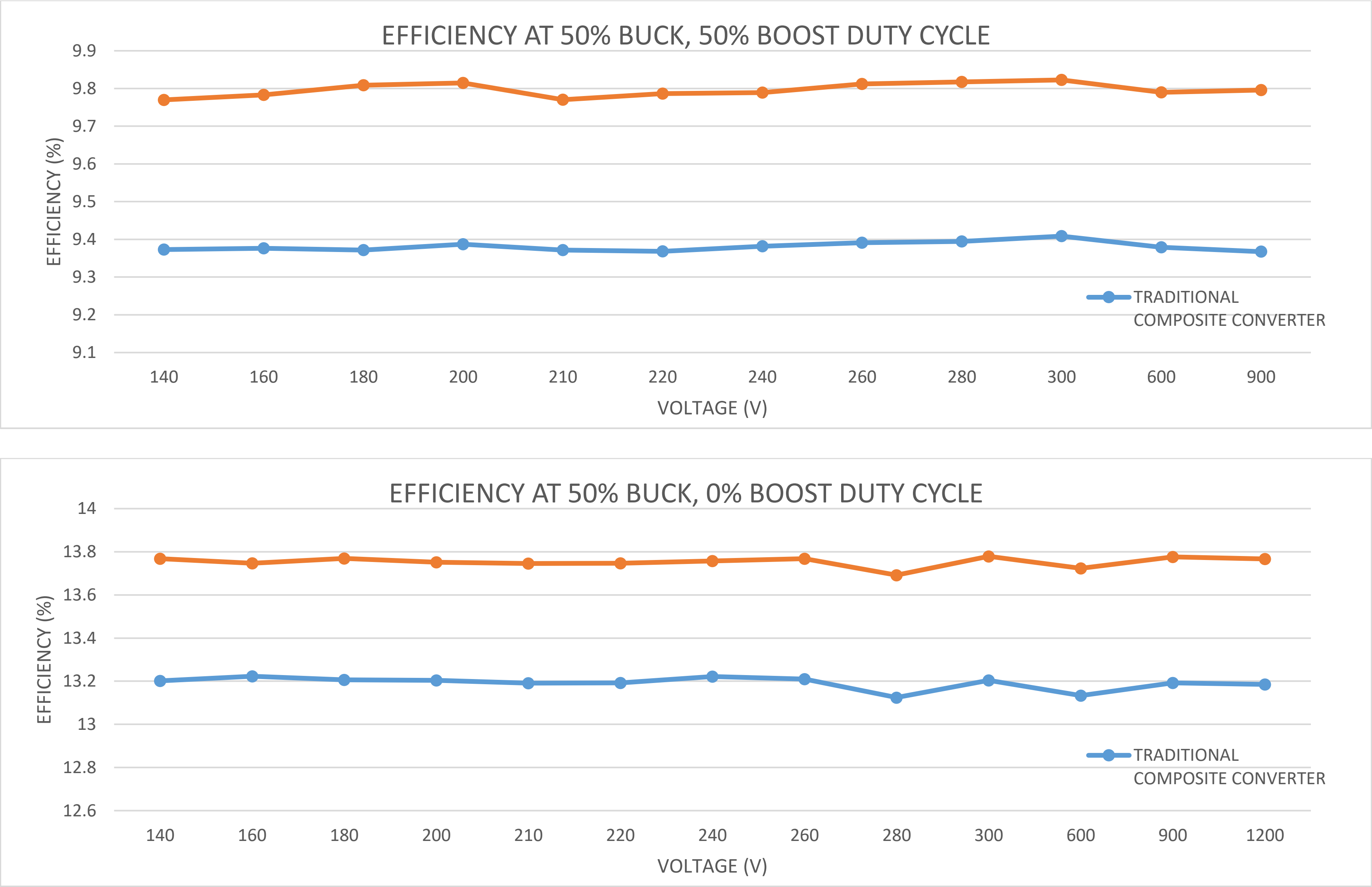
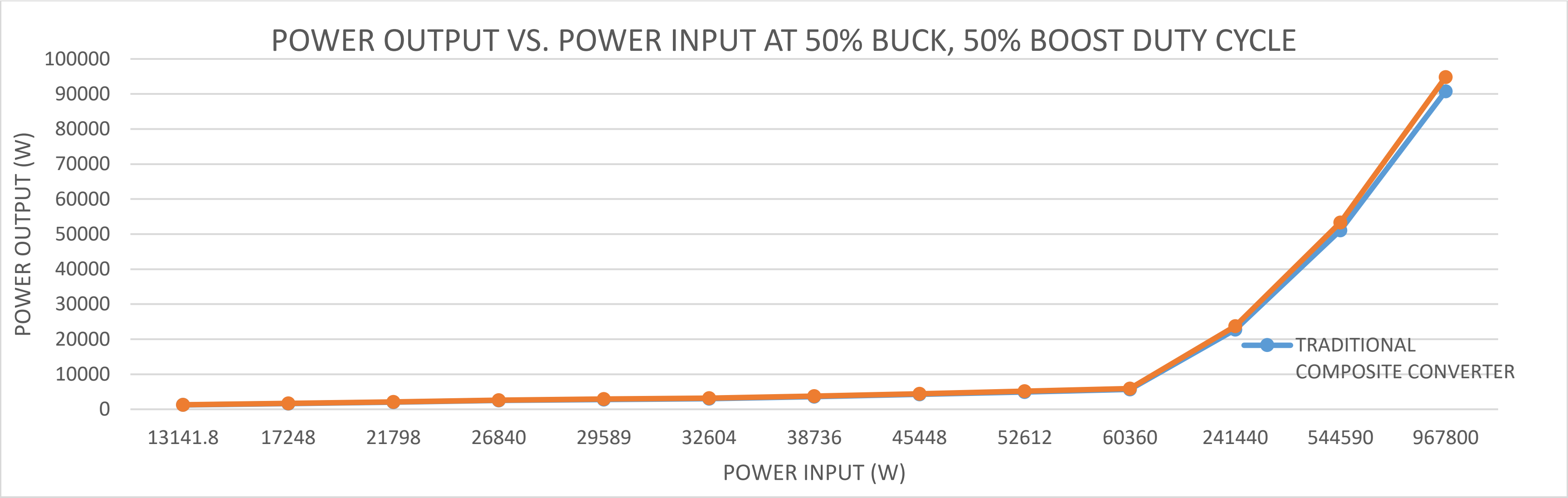


Figure 12: efficiency graphs for (a) buck and boost at 50% passthrough, and (b) buck at 50% passthrough with Boost at no passthrough



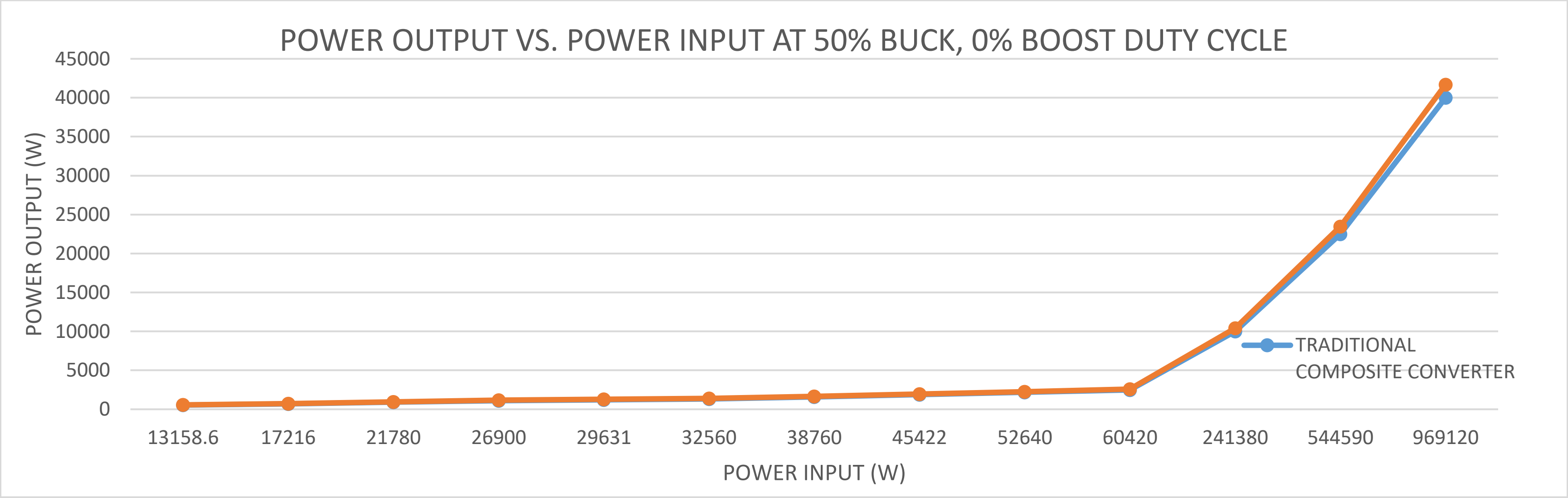


Figure 13:Power Graphs for (a) buck and boost at 50% passthrough, and (b) buck at 50% passthrough with Boost at no passthrough

4.0 Conclusion

4.1 Results

This thesis proves a comparison of a traditional composite converter design, consisting of a buck, boost, and DAB converter, with that of a modified composite converter, created as a result of replacing the conventional DAB converter with that which has been modified via series injection. The introduction of the series injected DAB improved the overall DAB efficiency for high voltages as a result of improved zero voltage switching and thus it was believed that the same method would be true for the composite converter build with this modification. Graphical representation of the efficiencies upon multiple trials, voltages levels, and Buck and Boost converter duty cycles shows consistent improvement in efficiency with the series injection modification of the composite converter.

4.2 Potential Application Benefit

On average, the modified composite converter was more efficient than its traditional counterpart by approximately 0.4% in comparison. Consider the 30-kW designed and used for EV application [1],7]. For 30-kW, a 0.4% increase of 120 W. A utility loses an average of $2000 per Kilowatt. With just over one million electric vehicles in the U.S. [14]. if every electric vehicle used a modified composite converter, this results in a nation-wide gain of 120 MW and would result in a cost saving of approximately $240,000,000.

4.3 Losses, Errors, and Unforeseen Results

Previous research found the traditional composite converter to be at a maximum of 98.7% efficient. The results simulated did not yield the same results. This is believed to be the result of some modeling loss, including the addition of one ohm resistors in series with the capacitors in parallel to the DC voltage source. Switching losses are also possible due to modeling constraints, which include not allowing for a duty cycle of 0% or 100%. 0% was represented at 0.01% where 100% was represented as 99.99%. This slight deviation could be a potential cause of a switching loss. Previous composite converter builds used semiconductors whose parameters were not readily available due to the use of different modeling programs. This is another deviation to previous methods that could also result in potential errors, including replicating semiconductor loss. To correct for this, consistency in circuit parts available in the Simulink library remained between the traditional and modified composite converters such that the result was a comparison to each other rather than to previous results.

4.4 Future Work

Because the purpose of this thesis was to prove the improved efficiency of a composite converter via the use of series injection, all parameters were maintained, which are optimal values of the traditional composite converter found in previous research. It is not to be assumed that these are optimal for the modified composite converter and thus it is possible to find optimal parameters for the modified converter and run another comparison. Optimal parameters also include the transformer ratio. The values provided were for different operating modes, as well as previously tested duty cycle values. It is possible to test a larger range of scenarios, including different duty cycle combinations, and voltage inputs. The series injected dual active bridge converter was built into the composite converter circuit in the opposite direction in which it was tested in previous research. It is possible to mimic this research by swapping the output voltage scope with the voltage dc input locations in this study and simulate larger voltage inputs. Different loads were also not considered and are areas for future research. Previous research had also proven simulated results experimentally, which was not done in this study and can be a potential for future research. Simulink was used to build and simulate both composite converter circuits. Future research could validate results using another program similar to what was used in previous research.

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