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Pandian's dc-dc Boost converters for Solar Panels using Twisted Multi wire Transmission Line Transformers: High gain up to 7.4, and no need for additional MPPT control circuits

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ABSTRACT: A dc to dc Boost converter with a single inductor limits the voltage gain due to stray resistances in the inductor to about 1.5. This paper proposes dc to dc Boost converters by using twisted multiwire transmission line transformers specifically for solar panels. An output voltage of 225V in to 3260 ohms (dc voltage gain of about 7.4) was obtained by using a converter with a 5 wire transformer. The circuits work over a wide range of frequencies. Interestingly, the circuits exhibit a DCM mode of operation with good performance when the PWM ratio D is less than about 0.16. In this mode, the solar panel current charges the input capacitor for 84% of the PWM period and the energy in the capacitor is “converted” in the short 16% of the PWM period where the input current of the converter is many times the solar panel current. This results in a good performance of the solar panel without any need for additional MPPT control. The functioning of the converter is explained with waveforms and equations where it is shown that if the frequency of the converter is increased by a factor F, for optimum performance, the D value has to be increased by SQRT(F). The major feature of the proposed converters with solar panels is that no additional MPPT control is required. The efficiency of the converter was better than 81% when the 200W solar panel was tested in door at 12 Watts. The high dc gain possible with the proposed converters will reduce the wiring costs in solar panels and the copper loss in the solar panel wirings.

I. INTRODUCTION

THE DC to DC Boost converter is widely used [1-5] since the circuit is simple and operates with just an inductor and a Mosfet. While using the Boost converter along with the solar panels, one of the additional requirements is to provide the MPPT control. Another challenge is to build a converter with high dc gain, since the series resistance present in the inductor and other losses theoretically limit the possible practical gain to about 1.5. This paper presents multiwire transmission line transformers based dc to dc boost converters specifically for solar panels, with very good features.

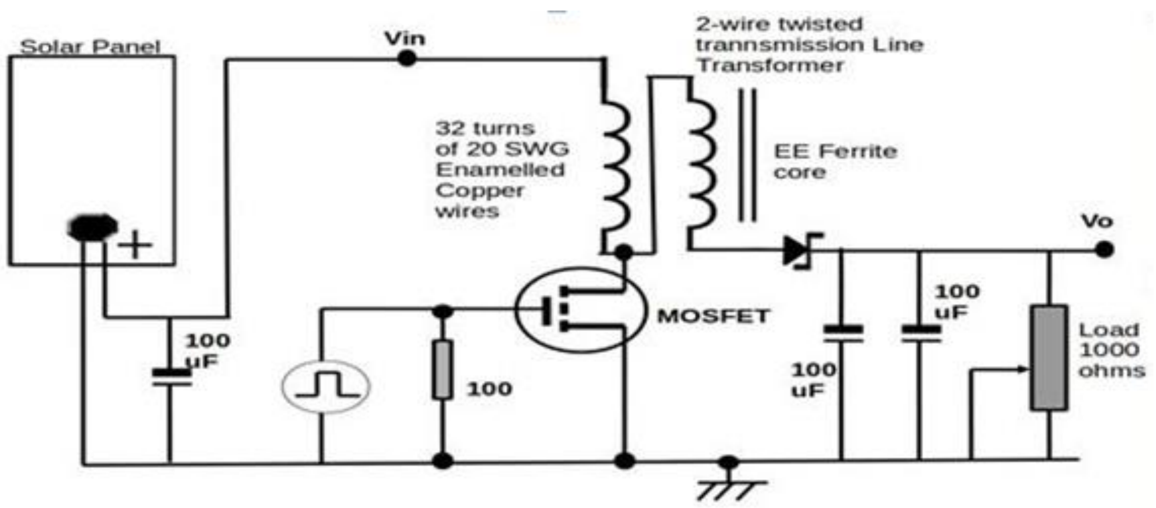

Figure 1: Dc to Dc boost converter using a twisted 2-wire Transmission line Transformer.

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II. DC TO DC BOOST CONVERTER WITH 2-WIRE TRANSMISSION LINE TRANSFORMER

Initially we will consider the operation of the proposed boost converter with a 2 wire transmission line transformer. Figure 1 shows the circuit diagram used. The transformer used was known as Ruthroff Transformer [6]-[8] and was extensively used in RF circuits. A multi wire transmission line transformer provides the theoretical minimum leakage inductance even without a magnetic core [8].

For Figure1, an initial classical theoretical analysis [1]-[4] based on the assumption that the average voltage across the "inductor" has to be zero, predicts that for CCM:

$$V_{in} \text{ x } D \text{ x } T + [(V_{in}\text{-}Vo)/2] \text{ x } (1\text{-}D) \text{ x } T = 0$$

$$Vo/V_{in} = [1+D] / [1-D] \qquad (1)$$

Where T is the period of the PWM square wave signal and D is the Duty cycle ratio. The above result predicts that the gain will be high if D is high (say 0.8). But there was a surprise in the experiment with the solar panel, as it was found that the dc voltage gain was high when the value of D was very low of about 0.16.

Intuitive thinking showed that the solar panel is not a voltage source but a current source. At low frequencies.

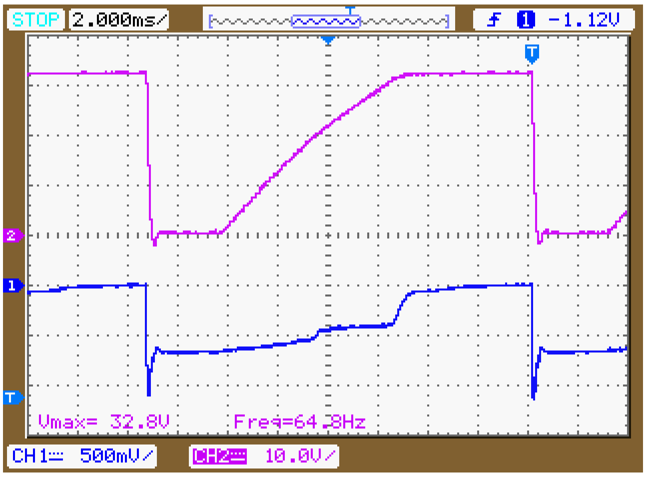

Figure 2: Top Trace: Solar Panel Voltage V_{in} for D= 0.195. Bottom Trace: Solar input current (inverted) when the PWM frequency is very low (64.8 Hz). At normal PWM frequency in kHz, the Solar panel voltage will become an almost constant dc voltage, See Figures 4 and 5.

When the Mosfet is ON, the current source of the panel multiplied by the almost zero ohms of the conducting Mosfet should give a solar panel voltage of 0 volts. Figure 2 shows what happens to the solar panel voltage when the converter is fed with a very low PWM frequency of 64.8 Hz for D = 0.195. As expected, the dc voltage of the solar panel was becoming zero when the Mosfet was ON (so our boost converter will not work in the way it would have worked with a proper dc supply voltage). When the Mosfet is OFF, the solar voltage ramps up from zero to the maximum value by charging the large electrolytic capacitor at the input. If we increase the value of D (that is decrease the time during which Mosfet is Off) in Figure 2, the solar panel voltage will not be able to ramp up to the maximum. For Figure 2, if we increase the frequency of switching in the kHz range, the input capacitor will hold the dc voltage V_{in} at a constant value and the transformer inductive reactance will not allow the panel voltage to become zero when Mosfet is ON. This constant dc voltage V_{in} will build up to the maximum when D is small (say less than 0.2) but will decrease towards zero if D is increased towards 1.

The dc voltage gain of the converter of Figure 1 is about 3.8 (See Table 1) when the value of D is small (0.16). Further probing showed that when D is small it results in discontinuous current mode (DCM) and the drain voltage was having an oscillatory signal. It appeared that the "inductor" was resonating with some capacitor. On the input side there was an input capacitor of 100 micro Farads and on the output side a diode and a 200 micro Farads output capacitor were present. Both these large capacitors were not taking active part in the oscillations as there was almost no sine wave across these capacitors. Literature survey [9] showed that the oscillations were a result of the inductor resonating with stray capacitors of the Mosfet and other stray capacitors. Gussemé et al. have derived expressions for the oscillating drain voltage in terms of L and C [4].

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Table 1: Data For Converter Of 2-Wire Transmission Line Transformer With Ferrite Core.

Freq kHz	V_o Volts	P_0 Watts	D	Vin Volts	dc-dc gain
0.991	41.4V	1.71	0.16	8.28 pk	5
2.14	4.7V	7.17	0.16	16.8 pk	5
3	96.8V	9.37	0.16	20.4 pk	4.7
4.04	101.7V	10.34	0.16	22.4 pk	3.9
5	109.3 V	11.95	0.16	27.2	4
6.13	115.1 V	13.25	0.16	29.6	3.9
7.06	**118.7 V**	**14.09**	**0.16**	**31.2**	**3.8**
8	117 V	13.69	0.16	31.2	3.75
9.85	113.4 V	12.86	0.2	31.2	3.63
10.4	117.9V	13.9	0.2	33.6	3.5
19.1	119.4 V	14.26	0.29	32	3.73
33.43	19.6 V	14.3	0.33	30.4	3.93
46.37	120 V	14.4	0.36	32	3.75
60.25	120 V	14.4	-	32	3.75
70.23	120.4 V	14.5	0.43	30.4	3.96
88.03	**120.1 V**	**14.42**	**0.5**	**32**	**3.8**
100.1	119.1 V	14.18	0.56	32	3.72
200.2	108.9V	11.86	0.54	29.6	3.68
292.2	109.5V	11.99	0.62	33.6	3.26
410.9	100.5 V	10.1	0.6	33.6	2.99
603.3	94.2 V	8.87	0.6	33.6	2.8
703.5	86.5 V	7.48	0.6	33.6	2.57
804.8	81.7 V	6.68	0.6	33.6	2.43
1005	74.0 V	5.45	0.55	33.6	2.22

Actually, in our case of Figure1, we will be having a good amount of inter-wire capacitance of the transformer (more than say 400 pF) and so we may have to tune the analysis of [4] accordingly. The oscillations in DCM does not affect the dc output voltage of the converter much and the exact analysis of the oscillations is not attempted in this paper. Wuhua Li et.al [10] discussed an Interleaved Converter using step-up coils but the operation of this converter is different from the converter proposed in this paper as they used D >0.5 but this paper uses D vales less than 0.5 (Typically D=0.16). Also [10] does not use twisted multiwire transformers leading to considerable leakage inductance in the transformer that affects the operation of their converter.

From Table 1 we see that the dc voltage gain was peaking at one low frequency (7.06 kHz) with a low value of D of 0.16 and at a high frequency (88.03 kHz) but with a higher value of D (0.5).

III. DC TO DC BOOST CONVERTER WORKS WITH AIR_CORE TRANSFORMER

The dc to dc converter of Figure1 was tested by removing the ferrite core. The Air-core Transformer exhibited mode-1 operation for a frequency of about 60 kHz (compared to 7.06 kHz with ferrite core). The dc gain with the air-core transformer shown in Table 2 was slightly poor, only 3.1 instead of 3.8.

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Table 2: Converter With Air-Core 2-Wire Transformer.

Freq kHz	V_o Volts	P_0 Watts	D	Vin Volts	dc-dc gain
42.1	99.6	9.92	0.16	29.6	
55.5	104.2	10.86	0.16	32.6	
58.4	105.3	11.09	0.16	33.6	3.13
65.3	104.7	10.96	0.16	33.6	3.12
70.6	103.3	10.67	0.16	33.6	
75.5	102.1	10.42	0.16	33.6	
85	99.9	9.98	0.16	33.4	
98.2	97	9.41	0.16	33.6	

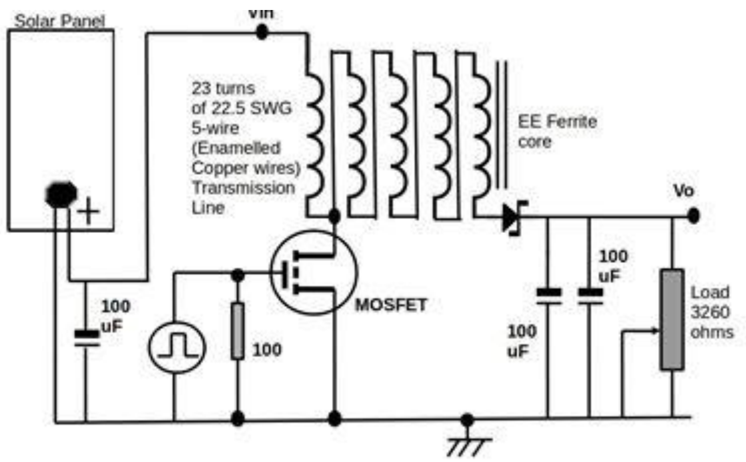

Figure 3: DC to DC Boost converter using a twisted 5-wire Transmission line Transformer

IV. BOOST CONVERTER WITH 5-WIRE-TRANSFORMER

By using 3-wire, 4-wire, 5-wire, and 6-wire transmission line transformers with many different impedance ratios, many different dc to dc converters are possible so that the solar panel can be impedance-matched for different values of the load resistance. Also it should be possible to increase the dc to dc gain from 3.8 achieved earlier to much higher values of say more than 7.4. Figure 3 shows the circuit diagram of a 5-wire Transmission-line transformer based boost converter. The theoretical voltage gain for this circuit in in CCM can be shown as

$$Vo/V_{in} = [1+4D]/[1-D] \qquad (2)$$

Table 4 shows that a gain of 7.3 was achieved in mode-1 at a low frequency (4.15 kHz) with a low value of D (0.17) and a gain of 7.4 was achieved (6 predicted by eqn.2 for D = 0.5) in mode-2 at a higher frequency (29.86 kHz) with a high value of D=0.5. The Air-core transformer converter gave a dc gain of about 6.9 in mode-2 and 6.3 in mode-1.

Table 3: Converter With 5-Wire Transmission Line Transformer.

Core	Freq	D	Vin Volts	Vo Volts	dc to dc gain
Ferrite (Mode-1)	4.15	0.17	30.4	222V	7.3
Ferrite (Mode-2)	29.86	0.5	30.4	225 V	7.4
Air Core (Mode-1)	69.33	0.18	32V	202	6.3
Air Core (Mode-2)	303	0.5	29.6	203	6.9

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V. ANALYSIS OF 5 WIRE LINE CONVERTERS

Details of the functioning of the converter in mode-1(that is at low frequencies) can be understood with the help of the waveforms shown in Figure 4. First we need to select a low frequency say f and D such that the dc output voltage is maximized at the desired maximum load power for a given maximum irradiance. Once this setting is done, no separate MPPT control is required. If the irradiance changes, the circuit delivers the maximum power possible to the output, due to automatic changes in the charging and discharging currents in the input capacitor.

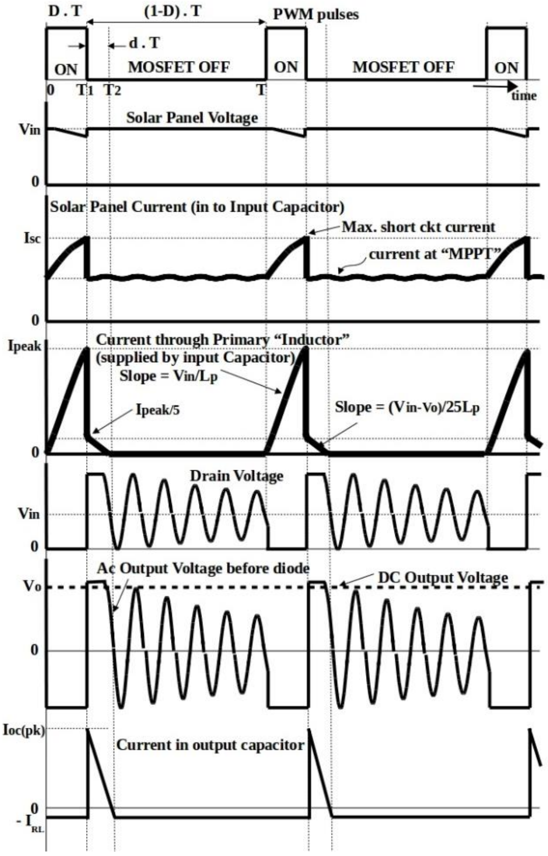

Figure 4: Waveforms for 5-wire-Transformer-based Converter.

The peak value of the inductor current I_{peak} (in to the Mosfet) is many times larger than the input solar panel photo current. When the Mosfet is OFF, the photo current charges the input capacitor to a high dc output voltage that corresponds to the MPPT point (adjusted in the initial setting) and this photo current is less than the short circuit current. The panel voltage at MPPT is appropriately close to the open-circuit voltage of the panel. When the Mosfet is turned ON, the inductor current increases linearly with time t reaching a peak value of

Ipeak = (V_{in} /Lp) D T.

Where Lp is the primary inductance. The large current in the inductor decreases the panel input voltage (across the input capacitor) slightly and the photo current will move towards the maximum constant current (short circuit current Isc) away from the MPPT point as seen in Figure 4 and Figure 5. After generating the primary current of Ipeak, when the Mosfet turns OFF, due to the stored magnetic energy and the transformer action, a current of value Ipeak/5 flows in the coils and the output capacitor (and the input capacitor). Figures 4, 6 and 7 show the waveforms of the currents through the input capacitor and the output capacitor. The transformer current Ipeak/5 falls with a slope of (V_{in}-V_o)/(25 Lp) and should become zero in a time of d. T as shown in Figure 4.

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$$[(Vo-Vin)/(25Lp)]\ d.\ T = Ipeak/5 = (Vin/Lp)\ D.T\ /\ 5$$
$$d = 5D\ Vin\ /\ (Vo-Vin) \qquad (3)$$

If Vo/Vin = 6, we see that d = D, meaning that the magnetic energy discharges in a time equal to d.T that is equal to the PWM ON time (D.T). We see that in Table 2, the gain Vo/Vin has a maximum value of 7.4 and may decrease below 6 if the solar irradiance reduces from the maximum value and it has been seen that d/D varies from less than one to greater than 1 depending on the operating conditions.
The energy used in charging the output capacitor can be shown with reference to the input capacitor current waveform of Figure 6, as $(1/2)L_p\ (I_{peak})^2 + V_{in}\ [\{(Ipeak/5)/2\}\ (d\ T)]$ that is equal to Vo2 T/RL. Substituting for I_{peak} from (1),

$$(V_o/Vin)^2 = (T\ RL)\ [(D^2/2Lp) + (dD/10Lp)]$$

We can show that by approximating d = D,

$$(V_o/Vin)^2 = 1.2\pi\ R_L\ D^2/X_{Lp}$$

where $X_{Lp} = 2\ \pi\ \ (1/T)\ Lp$.

The above equation predicts that if XLp or the PWM frequency is increased by a factor of F, then D must be increased by a factor of SQRT(F) to get the best performance. The experimental readings for a 5-wire converter (where for each frequency, D was tuned so as to get the maximum output voltage V_o) in Table 4 verify this fact. The last column (calculated D) was obtained as Dref x SQRT(F) where D_{ref} = 0.173 and F = Frequency in kHz / 5.43.

Table 4: The experimental readings for a 5-wire converter.

Frequency	DCM?	Ton	D	Calculated D
5.43 kHz	Yes	32.0 ms	0.173	Dref = 0.173
10.86 kHz	Yes	23.5 ms	0.255	0.25
16.27 kHz	Yes	19.0 ms	0.309	0.30
20.72 kHz	Yes	15.8 ms	0.327	0.34
26.15 kHz	Yes	14.0 ms	0.366	0.38
31.58 kHz	Border	15.8 ms	0.499	0.42

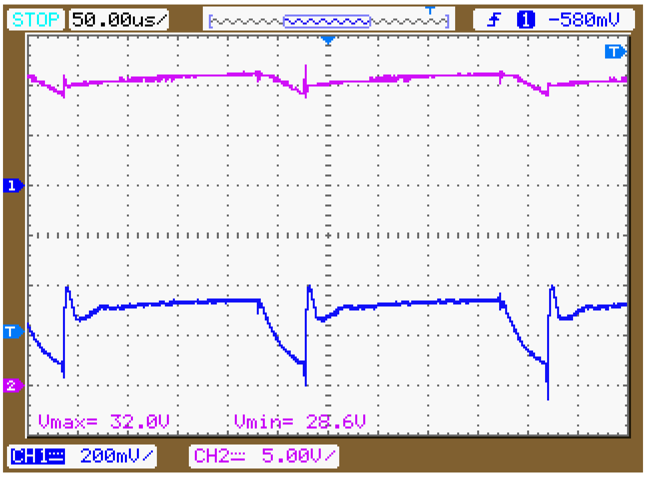

Figure 5: Top Trace: Solar panel voltage V_{in}. Bottom Trace: Solar panel current waveform (shown inverted).

VI. EFFICIENCY OF THE 5-WIRE BOOST CONVERTER

The efficiency of the 5-wire transformer was measured as 81.2% at 26.17 kHz for an output power of 12.5 Watts. The efficiency may be improved by using proper layout and short and thick wires. Special attention in layout is required for the Connection of input capacitor and the primary where the current is high. (Efficiencies of above 90% are expected at

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200 Watts). Operating the converter at a high frequency with a high value of D will reduce the peak current in the primary coil but that will not reduce the copper loss. However that will reduce the rating of Mosfet and v-i loss in the Mosfet. Efficiency is expected to be slightly better, if a higher operating frequency is selected. On the other hand, at low frequencies core losses may be lower and the stray capacitances of transformer will not affect the performance.

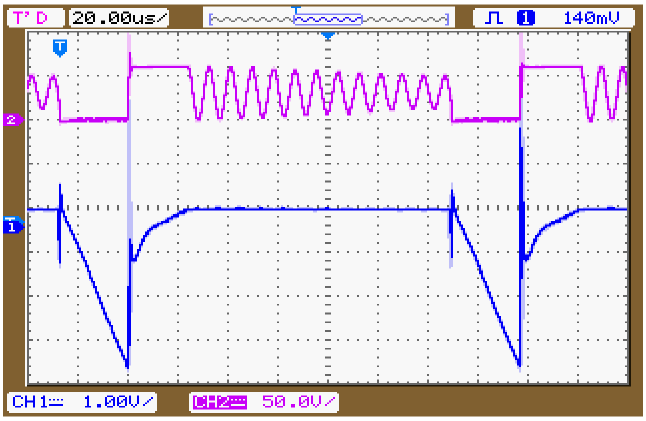

Figure 6: Top Trace: Drain voltage Bottom Trace: Current through input capacitor (inverted).

VII. NO NEED FOR MPPT CONTROLLERS

It has been verified that there is no need for any further tuning of the boost converter when the irradiance reduces (up to Sun- set). The photo current always stayed in the MPPT region when the Mosfet is OFF (with current less than the maximum short-circuit current) and the photo current increased towards the maximum current equal to the short-circuit current during the period when the Mosfet was ON. The circuit remained at an operating point where the output power was always the maximum possible for any given irradiance. This was experimentally verified by checking the solar panel input current waveforms, when the irradiance was decreasing from maximum to zero. What this means is that when using these boost converters on solar panels, no additional MPPT circuits are required, removing the need of micro-controller and associated circuits for MPPT.

VIII. APPLICATIONS OF THE MULTIWIRE TRANSFORMERS BASED BOOST CONVERTERS

The converters proposed will find major applications in solar panels. A 250W panel can have a small circuit attached to it to boost the dc voltage from say 32V to 220V with the panel current reduced by a factor of about 7 (say from 8 A to 1.1 A). This can result in reduction in the cost of wirings and reduction in copper loss in the wirings. One more major relief that comes with the proposed converters is no need for additional MPPT control gear.

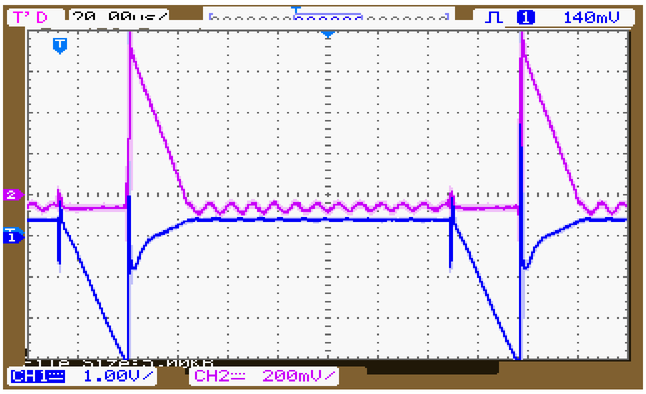

Figure7: Top Trace: Current through output capacitor. Bottom Trace: Current through input capacitor (inverted).

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The proposed boost converters can provide impedance matching of a given dc load to any solar panel system. The impedance ratios possible are 4:1, 9:1, 16:1, 25:1, 36:1, 2.25:1, (16/9):1, (25/4):1, (25/9):1, (25/16):1, etc. It is also possible to provide isolated dc output or buck operation if required. In this paper the 4:1 and 25:1 cases were studied.

IX. CONCLUSION

This paper presented multiwire transmission line transformers based dc to dc Boost converters for use in solar panels. The converters have a major feature that no additional MPPT controller is required. Dc Gains of up to 7.4 and efficiency above 81% were achieved. The paper gave a theoretical analysis on the functioning of the converters, predicting that if the frequency of PWM is increased by a factor of F, the D value is to be increased by SQRT(F). The proposed converters will find major applications in solar energy harvesting and will reduce the wiring costs and copper losses of solar panels.

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