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Derivation of Isolated Outputs from a Boost and Buck-Boost Topology

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***Abstract*-- Multiport converters are used to power more than one load using a single conversion stage. Many applications require galvanic isolation between the input and output of the converter. This paper presents a technique using which a boost and buck-boost topology can be transformed to a multiport converter with isolated outputs. The implementation starts with identification of terminals at which transformer can be interfaced for these topologies. Selection and characterization of circuit for implementation are defined. Some design expressions on selection of components for maximum power transfer are also defined. The proposed method is experimentally validated using lab prototypes.**

Index Terms* — *Multi-port converters, LLC Filter, Pulse width modulated Swtch model, Pulse frequency modulation

I. Introduction

Most modern consumer electronics loads don't use 230 V AC directly. They invariably use an interfacing converter between the supply and the loads to bring down the voltage to an usable specification. Among these consumer electronics loads (CELs) some require galvanic isolation between the supply and the loads, e.g., battery charging circuits, wireless power transfer, etc. Therefore, in an attempt to reduce the conversion stages, novel power converters are invented to power multiple CELs at the same time [1]. These converters are commonly known as Multi-Port Converters (MPC). MPCs have several advantages including compact size, increased efficiency, reduced number of switches and drivers [2]-[4].

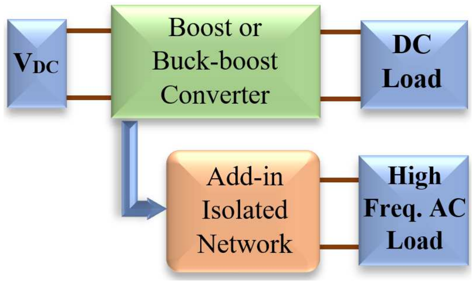


Fig 1. Boost or buck-boost topology converted to MPC using an add-in network.

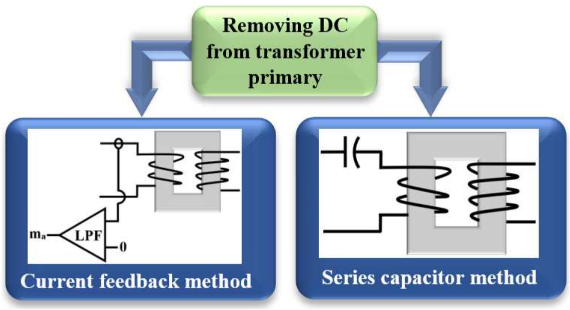


Fig 2 (a). Methods to make transformer input as DC-free.

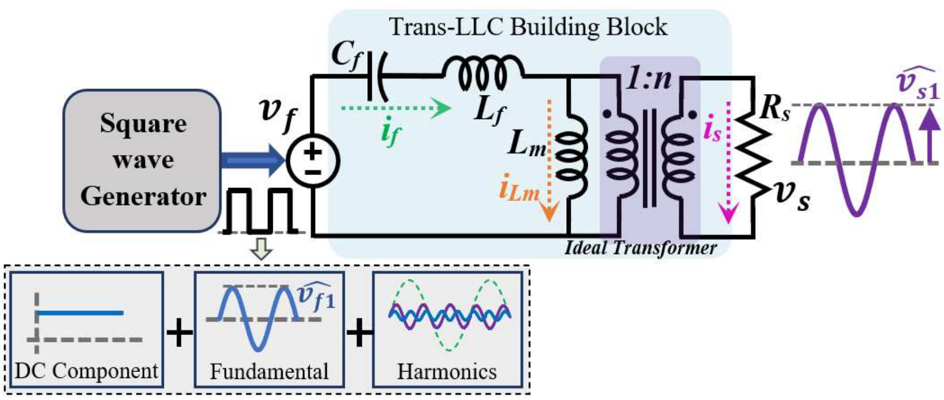


Fig 2 (b). LLC network connected to a square wave input.

This paper proposes a systematic approach to convert a boost and buck-boost topology into a MPC with isolated output. Realization of these new topologies lead to several operational issues. Some of the primary issues are identification of suitable interfacing port, control over power flow and regulation of all the outputs at the same time. All these aspects are discussed in the following sections. Section II reviews the LLC network concept which will be pivotal for power transfer in the proposed circuit. Section III discusses the switch port classification, topology derivations and steady state waveforms. Section IV shows some experimental validations, followed by some conclusions.

II. Fundamental of Transformer Coupling and LLC filter

The concept of interfacing a transformer to a DC/DC topology requires a square wave switching output, which has zero DC bias. This is due to the fact that a transformer will saturate, if there is a DC voltage in its inputs. Traditionally, either the Pulse width or the pulse frequency of this square wave are controlled to modulate the isolated DC output. There are two ways to remove DC bias from a switching signal, as shown in Fig. 2. (a) Current feedback method: In this method the primary current is sensed through a Low pass filter and feedback-controlled to force its DC to zero. (b) Series capacitor method: In this method, a series capacitor in series with the primary forces the input voltage to have zero DC bias.

As shown in Fig. 2 (b), the series capacitor works with the magnetizing and leakage inductance of the transformer to form an LLC filter [5]-[6]. This has two advantages, namely, zero DC bias and effecting resonant operation of the switches. The important equations of LLC-resonance network are discussed below (refer to fig 2(b)).

A. Tuned Frequency (f) is the frequency of the square wave at which power transfer to secondary is maximum.

$$f = \frac{1}{2\pi}\sqrt{\frac{-A \pm \sqrt{A^2 + B}}{2{L_m}^2 L_f C_f}}$$

$$\text{where, } A = L_m\left(\frac{R_s}{n^2}\right)^2 C_f + L_f\left(\frac{R_s}{n^2}\right)^2 C_f - {L_m}^2$$

$$\text{and, } B = 4\left(\frac{R_s}{n^2}\right)^2 {L_m}^2 L_f C_f \qquad (1)$$

B. Voltage gain is the ratio of primary and secondary voltages as a function of square wave frequency.

$$\frac{\hat{v}_{s1}}{\hat{v}_{f1}} = \frac{j\omega L_m || R_e}{j\omega L_m + \frac{1}{j\omega C_f} + (j\omega L_m || R_e)}$$

$$\text{where, } \hat{v}_{f1} = \frac{2 * \hat{v}_f}{\pi}\sin(D\pi) \; and \; R_e = \frac{R_s}{n^2} \qquad (2)$$

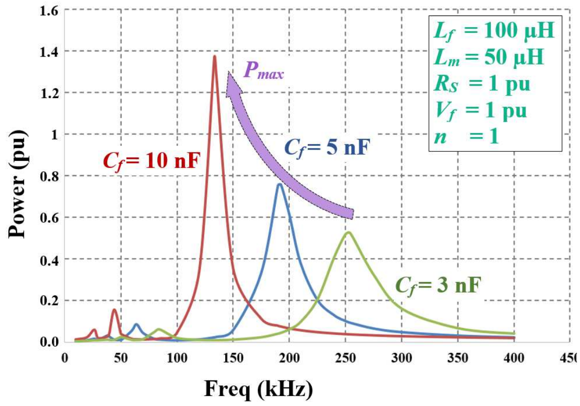


Fig 3. MPT for different C_f values.

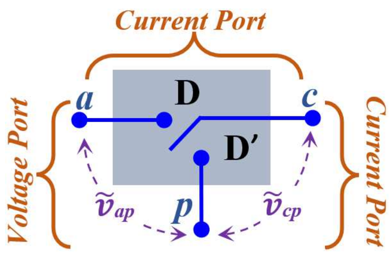


Fig 4. PWM Switch model

Where, vf1 is the fundamental part of vf , D is the duty ratio and ω is the angular frequency

C. Filter Current is the fundamental input LLC current

$$\hat{\imath}_f = \sqrt{{\hat{\imath}_{Lm}}^2 + (n\hat{\imath}_s)^2} = \sqrt{\left(\frac{\hat{v}_{S1}}{n\omega L_m}\right)^2 + \left(\frac{n\hat{v}_{S1}}{R_s}\right)^2} \qquad (3)$$

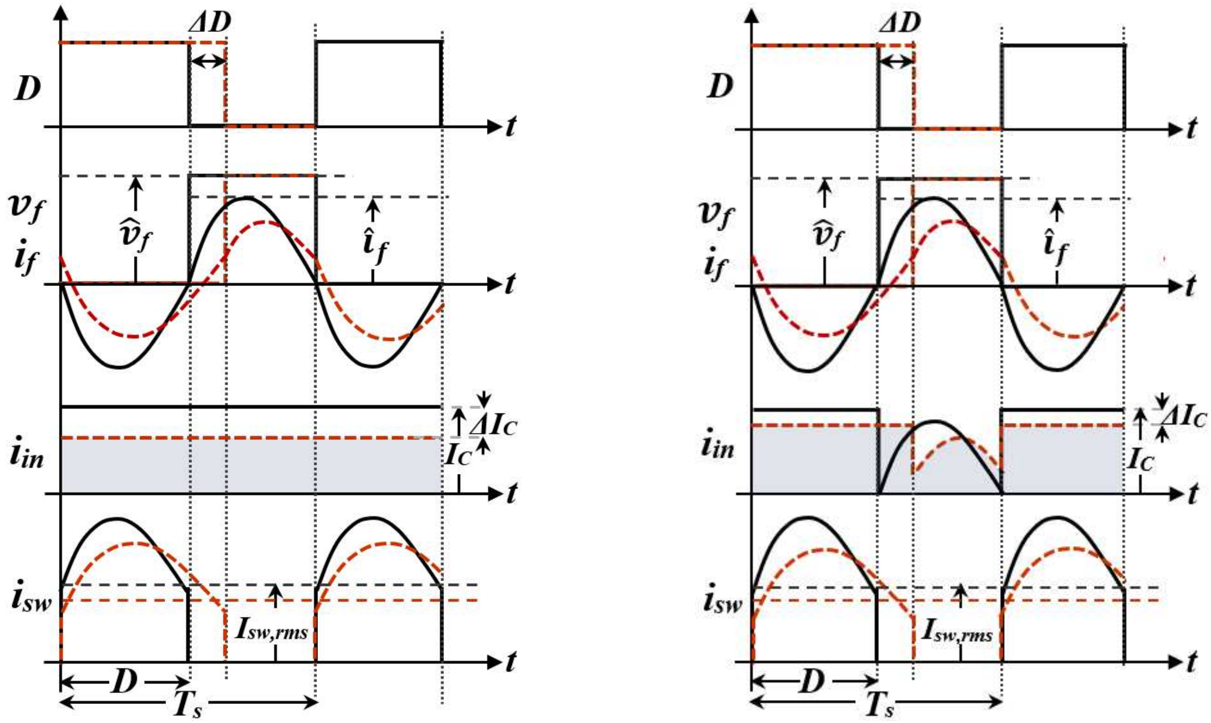
At tuned frequency condition,

$$\frac{\hat{v}_{s1}}{\hat{v}_{f1}} = \sqrt{n^2 + \left(\frac{R_s}{n\omega L_m}\right)^2} \angle \tan^{-1}\frac{R_s}{n^2\omega L_m}$$

$$\text{and, } \hat{\imath}_f = \frac{\hat{v}_{f1}}{\Re(Z_{in})} \qquad (4)$$

Where Z_{in} is the LLC input impedance and $\Re(Z_{in})$ is the real part of Z_{in}.

The power transfer to the isolated LLC interfacing network can be changed by varying the filter component values. Fig 3(c) shows the increase in max power transfer (MPT) when the C_f value is increased. Using (2), it can be inferred that the output voltage will be maximum when duty ratio is 0.5. Fig 3 shows the variation in power transfer as a function of frequency with a duty cycle of the square wave equal to 0.5. Thus, it can be deduced that both duty and frequency have an impact on maximum power transfer to the isolated load.



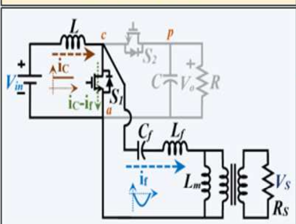
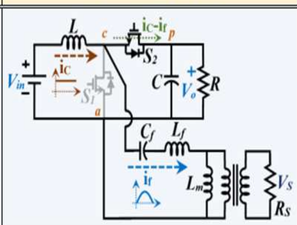
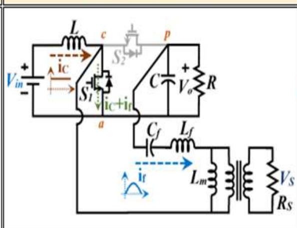
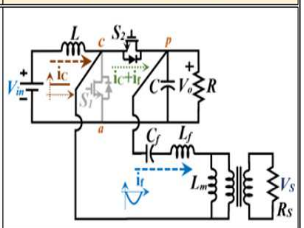
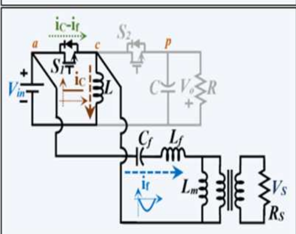
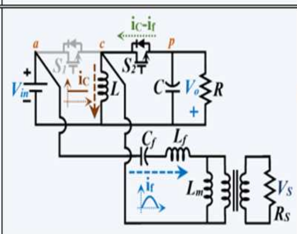
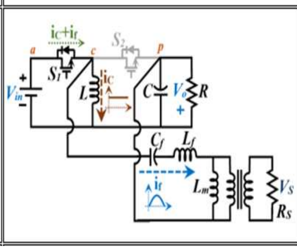
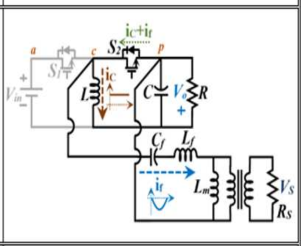
(a) (b)

Fig. 5. Steady state waveforms for boost (a) and buck-boost(b) conv.

III. Switch Port Classification and Topology Derivation

In this Section, a boost and buck-boost converter is used to implement an isolated output using LLC concept. In any arbitrary DC-DC converter, the active and passive switches can be lumped together to form a single functional block called the PWM switch [7] as shown in fig. 4. The terminal designators a, p and c refer to as active, passive, and common, respectively. If we investigate the current and voltage of the PWM switch model, we can observe that the common point is always directly or indirectly connected to one or more inductors; therefore, the current passing through 'c' will always be constant. Similarly, the port a-p is always associated with a capacitor; therefore, the voltage at the 'a-p' port will be constant so it is apparent that either 'ac' (Active port) or 'pc' (Passive port) can be considered as switch port. It is

TABLE I.
Different Intervals In Boost And Buck-Boost Topology Converted To MPC

	LLC connected to Active Port		LLC connected to Passive Port	
	D- interval	D'- interval	D- interval	D'- interval
Iso-Boost Topology				
Iso-buck-boost Topology				

preferred to connect the +ve terminal of LLC interfacing network to a higher potential point.

Since isolated buck converter topology results in a conventional LLC half-bridge structure, its explanation is redundant as far as the proposed theory is concerned. The various topologies of boost and buck-boost with hybrid output and their operating modes are shown in Table I. These topologies are referred to as iso-boost and iso-buck-boost in this paper. The operation of these topologies can be distinguished with switch conduction states and is similar to the basic DC/DC operation. But, as the power supplied to the isolated load is from the same source, it creates some typical operational behavior in the source and switch currents.

Among all the possible topologies, the case with trans-LLC being connected to an active port is considered here and is shown by the shaded portion of the table. The expression for all the other topologies can be obtained using a similar approach. Fig. 5 shows the steady-state operating waveforms of iso-boost and iso-buck-boost topology. This implicates that with change in duty ratio, the fundamental peak of switch node voltage ($\hat{v}_{f1}$), average input current, rms switch current and power transfer to the trans-LLC network decreases.

The input power (P_{in}) and the new inductor current (i_c) expression due to the trans-LLC connection for the two topologies are given below. Here P_{in} and P_{out} are input power and output combined power (Isolated and non-isolated power both), respectively, and D is the duty ratio, io is the DC load current. All other notations are shown in the circuit diagrams of Table I.

Iso-boost:

$$P_{in} = V_{in} * i_c \quad \left[P_{in} = P_{out} = \frac{V_o^{\,2}}{R} + \frac{\hat{v}_s^{\,2}}{2 * R_s}\right],$$

$$i_c = \frac{i_o}{D'} + \frac{\hat{v}_s^{\,2}}{2V_{in}R_s} \tag{5}$$

Iso-buck- boost:

$$P_{in} = V_{in} * \left(i_c D + \frac{\hat{\imath}_f}{\pi}\sin(D\pi)\right),$$

$$i_c = \frac{i_o}{D'} + \frac{\hat{v}_s^{\,2}}{2DV_{in}R_s} - \frac{\hat{\imath}_f}{D\pi}\sin(D\pi) \tag{6}$$

The above equations shows that, with inclusion of isolated network parameters (terms containing $\hat{v}_s$ and $\hat{\imath}_f$), the input power and input current will be substantial compared to conventional DC/DC topologies. Due to the increment in inductor and switch currents, the components are used with a relatively higher ratings.

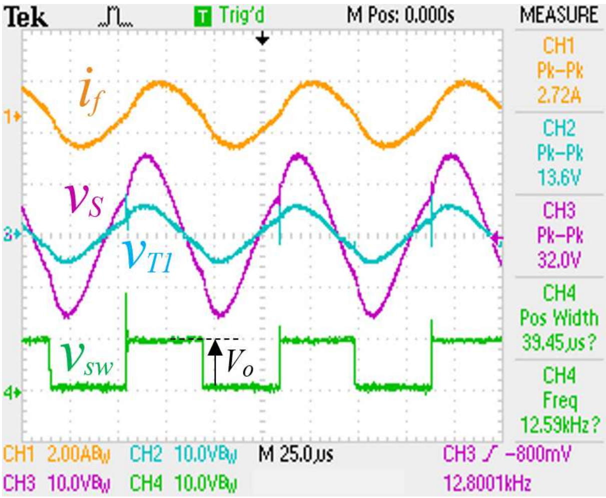
IV. Experimental Verification

With the specifications mentioned in table II, the prototypes are built to verify the proposed circuit. In a conventional boost converter, pulse width modulation (PWM) is done to regulate output. In case of trans-LLC there are two outputs, namely a non-isolated output and an LLC based isolated output. The regulation of the isolated output is done through change in carrier frequency (Calculated using (1)). Now this carrier is compared with the reference duty (Calculated from DC/DC voltage gain) to generate the gate signal of control switch (S_1). The signal to the switch (S_2) is just the complement of what is given to S_1.

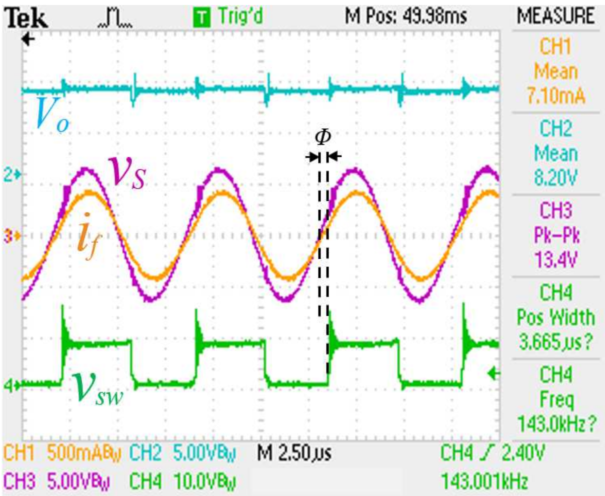
Fig. 6(a) is the result of boost MPC connected to high power load. The rest of the results are shown for low power isolated load model. From (4), we can observe that at tuned condition, with increase in R_s the voltage gain and the phase angle(Φ) will increase. The same can be verified from fig 6(b) and fig 6(c), where a change in R_s from 45 Ω to 500 Ω, leads to increase in voltage magnitude and Φ and decrease in switching frequency. Fig 6(d) shows the tuned operation of buck-boost converter with 500 Ω load. Fig 7 shows the change in voltage magnitude with different R_s for low power LLC model with C_f of 10 nF. Fig 6(e) shows the voltage regulated operation for a buck-boost converter with R_{iso} of 2 kΩ, where with a change in frequency, regulated voltage can be supplied, this is popularly known as pulse frequency modulation (PFM). This can also be verified from fig. 7, which shows that with a deviation in switching frequency from the tuned frequency, the voltage magnitude decreases. As the low voltage output is of higher frequency (fig. 6 (e)), the operating point is in the right side of the tuned frequency condition which inherently provides an advantage of soft switching.

TABLE II.
SPECIFICATIONS

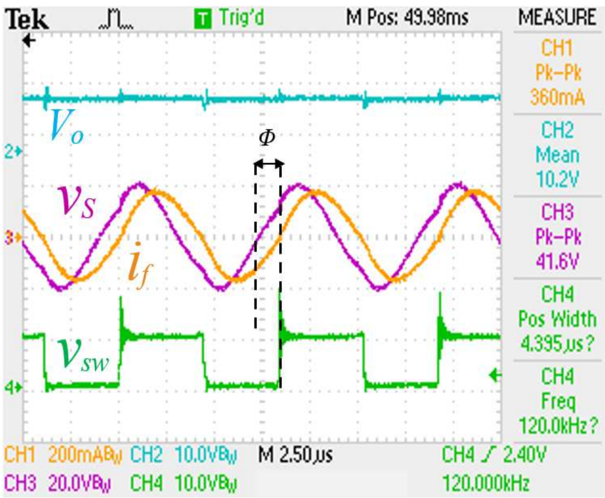
Parameters	Value
Input Voltage (Boost and Buck-boost)	5 V
Output non-iso voltage (Boost)	10V
Output non-iso voltage (Buck-boost)	5 V
Isolated high power load Specifications	36V pk-pk, 45 ohm
Isolated low power load Specifications	(a) 20V pk-pk (max) and 45 Ω, (b) 36V pk-pk (max) and 500 Ω, (c) 75V pk-pk (max) and 2 kΩ
L_f	116 μH
L_m	80 μH
n	3
C_f	1 μF (High Power) 10 nF (Low Power)



(a)

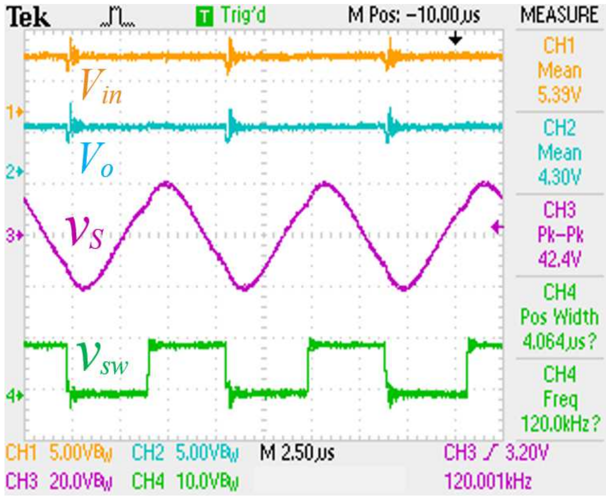


(b)

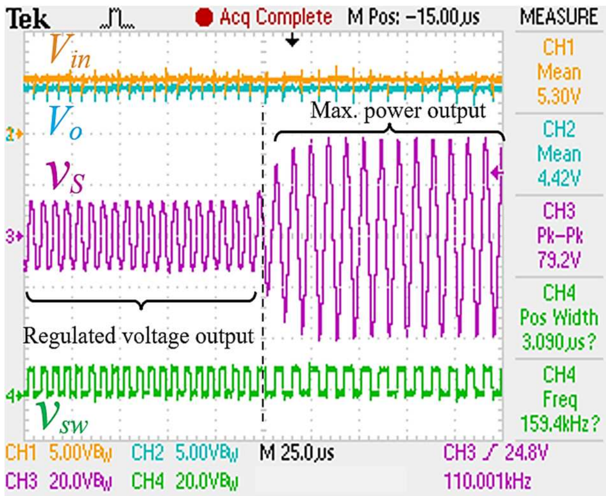


(c)

Fig 7. Output of iso-boost converter with high power load (a) and with low power load (b-c).



(d)



(e)

Fig. 6. (d) Buck-boost converter with low power load and (e) voltage regulated operation with R_s of 2 kΩ.

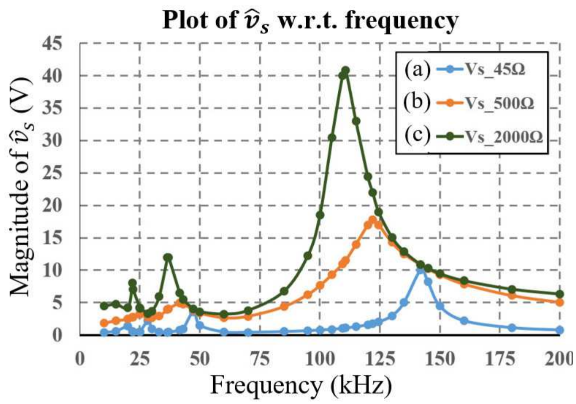


Fig 7. Plot of $\hat{v}_s$ w.r.t. frequency for $\hat{v}_{f1}$=10 V

V. Conclusion

In this paper, the boost and buck-boost topologies were transformed to provide isolated output. Irrespective of the converter topology, a generalized switch port classification and topology deriving procedure were shown, which can be used to convert any topology to MPC. The proposed theory is validated for boost and buck-boost converter using lab prototype.

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