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Estimating Dynamics of Switching Converters Using System Identification Technique

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***Abstract*—The switching converters are widely used in power electronics. These converters convert low input DC voltage to higher DC output voltage by switching the source voltage. These converters are nonlinear in nature. This paper deals with the estimation of dynamics of converters. Applying system identification technique, one can estimate the transfer function of switching converters which can be used for the controller design. Although many identification techniques such as cross correlation and circular correlation-based and state space averaging have been used to estimate converter dynamics but they require heavy mathematical computations. In the proposed research, frequency response-based data from duty cycle to output voltage estimation have been employed to estimate converter dynamics. In this method, frequency response data (FRD) are collected by injecting the sine stream signal having frequency from few hertz to many kilo hertz at duty cycle input which excite the system at different frequencies and varying output response is obtained. The transfer functions of converters such as buck-boost, boost and buck are estimated using such a system identification technique. Well- estimation of the converter transfer functions is validated through MATLAB/Simulink based simulation results.**

***Index Terms*—Bode plot, frequency response data, identified transfer function, switching converters, system identification, MATLAB/Simulink.**

I. INTRODUCTION

In modern era, all the services depend upon continuous functioning of different electronics devices and systems which require energy for their reliable operation. The energy is treated by switching converters for reliable operation which is prime importance for their quality. These are used to convert one DC voltage level to other one by switching the source voltage. Due to their switching behavior, they are nonlinear in nature. Determining their dynamics through well-established techniques is a difficult task. Because the lengthy derivation and complicated calculation is compulsory to obtain desired results. Firstly, one has to linearize, then average the circuit over a complete cycle to get approximated dynamics. To overcome past complications, we will use frequency response technique to achieve the intended objectives. By using this technique, we will be able to find the transfer function of any system as it does not require haddock mathematical derivation.

The dynamics of switching converters can be characterized by transfer function. In this paper, the transfer function of the switching converter is estimated using the system identification techniques. In one of the techniques, the transfer function is determined from frequency response data with the help of Sine Sweep Method (SSM) [1]. In this method, frequency response is obtained by injecting the sinusoidal signal having frequency from few hertz to many kilo hertz into the input of the converter. The estimated transfer function will be helpful to find the controlling parameters of the switching converter to regulate the output. Three converters, namely buck, boost and buck-boost are considered and have been identified. MATLAB/Simulink will be used for simulation purposes.

Besides, it is possible to create arbitrary excitation waveform with a broad band spectrum to collect all spectral information in one measurement. There are ten signals used in [2] to estimate transfer function of switching converters by frequency response data. It used Maximum length binary sequence (MLBS) to estimate the transfer function. The MLBS is used to evaluate transfer function of any linear system and now also being used in field of acoustic [3], impedance spectroscopy of single living cells [4], sensors for gas, odor and or aroma analysis [5], sonar system for zooplankton survey [6]. The method is equally employed for power converters [7]-[11]. But this method is not feasible to measure all transfer functions of power converters. So, we will use sine sweep method to estimate transfer function of purposed switching converters. Linear systems can also be identified by extensively studied method called cross correlation in system identification tools [12]. But this method, working on the basis of cross-correlating the system input and output, causes errors in results when we deal with finite signal length. Another familiar method Autoregressive with Exogenous Terms (ARX) is used in system identification to estimate the frequency response of model. This method creates disturbances which are also part of the system dynamics.

In the proposed method named Sine Sweep Method (SSM), a change in amplitude and phase of sinusoidal output with respect to input signal, on the application of a sinusoidal signal of known frequency to a linear system input, is observed. The frequency response data estimation is best technique to find the dynamics of a switching converters.

The paper is constructed in the following way. Operation of switching converters is described in Section II. Dynamics of the converters using system identification technique are estimated in Section III. In Section IV, additional simulation results are presented to further validate the estimated transfer functions. Section V contains conclusion.

II. Switching Converters Fundamentals

Switching converters are electronic systems which alter one DC level to another DC level by switching action. Switching converters are DC to DC voltage converters which provide high efficiency as compared to linear power supplies. The main trend of using switching converters is their smaller size, flexibility, not having transformer and provides efficiency of 75% to 98%. Therefore, they are used extensively in solar battery charging system, UPS system, medical electronics, communication, computer peripherals and personal computers [13]. Modern electronic instruments need light weight, high quality and efficient power supplies. The operation of buck converter, boost converter and busk boost converter is discussed here. The input and output of switching converters are shown in Fig. 1. Here duty cycle is input to switching converters and voltage is the output.

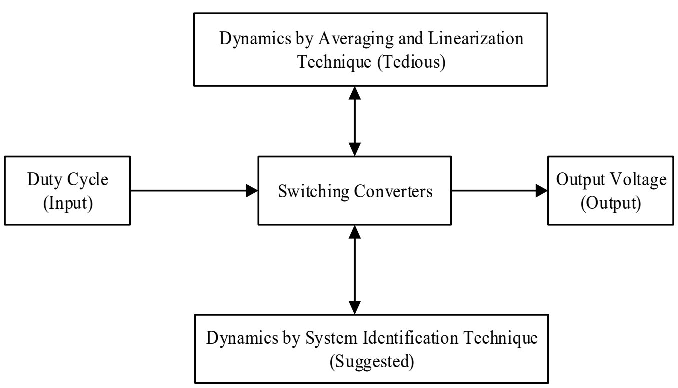

Fig. 1. Input-output representation of switching converter.

A. Buck Converter

The buck converter circuit consists of a switching transistor along with flywheel circuit containing capacitor, inductor and diode. When transistor is on, the current starts to flow through the energy storing element called inductor and stores energy in the form of magnetic field. The inductor opposes the abrupt change in current. In this way the output of switching transistor output is prevented from increasing suddenly to its peek value because inductor stores energy taken from the increasing output. The stored energy in the form of magnetic field is delivered to the circuit when transistor is switched off. The basic buck converter circuit is shown in Fig. 2.

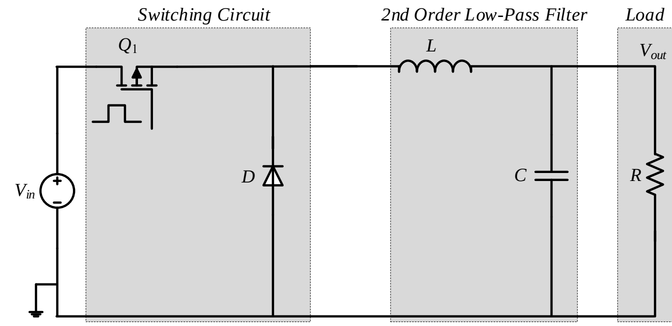

Fig. 2. Basic buck converter circuit.

The duty ratio k relating input voltage V_{in} and output voltage V_{out} of the of buck converter is given in (1)

$$\frac{V_{out}}{V_{in}} = k \tag{1}$$

B. Boost Converter

Boost converter is the DC to DC converter which converts low DC voltage level to another DC voltage level higher than input. The boost converter consists of a MOSFET switch, energy storing elements inductor and capacitor, diode, power supply and load as shown in Fig 3.

The input voltage V_{in} and the output voltage V_{out}, in case of boost converter, are related as [14]

$$V_{out} = \frac{V_{in}}{(1-k)} \tag{2}$$

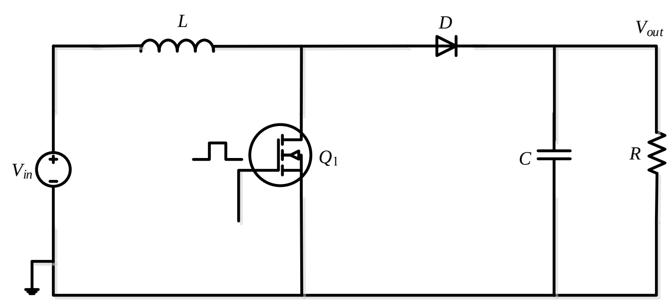

Fig. 3. Basic boost converter circuit.

C. Buck-Boost Converter

Buck-boost converter (see Fig. 4) like other switched mode power supplies converts one DC level to another DC level and is the combination of principles of both buck and boost converters in single circuit due to switching action of MOSFET.

When switch is turned on, the input energy is supplied to inductor and it gets magnetized. The current flows from positive polarity to negative polarity via inductor. The diode is reverse biased and current passes through load and charges the capacitor. The load is supplied by the capacitor that was charged in previous cycle. When MOSFET is turned off, the inductor and input is disconnected. During off state the

inductor is the main source of energy. Now diode is forward biased and circuit current flows through load and capacitor is discharged. In this way the output voltage is at least equal to or greater than source voltage.
The output voltage V_{out} and the input voltage V_{in} are related as

$$\frac{V_{out}}{V_{in}} = -\frac{k}{1-k} \tag{3}$$

where k *is* duty cycle of buck-boost converter.

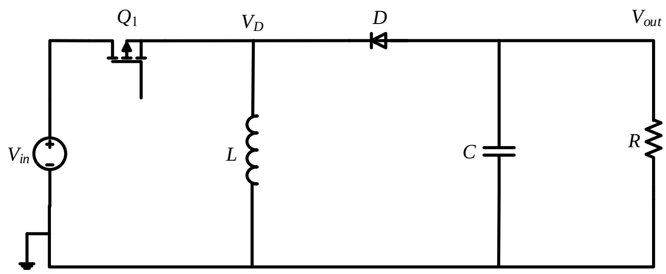

Fig. 4. Basic buck-boost converter circuit.

III. System Identification Technique

System identification refers to making the mathematical models of dynamic system with the help of measured data. System identification is divided into parametric and nonparametric techniques [15], [16]. In parametric identification a system model is assumed and model parameters are estimated. But in nonparametric no assumption is made about the model under test and identification is used to directly compute the frequency response of system. Nonparametric method includes correlation analysis, transient response analysis, frequency response, Fourier, and spectral analysis. In this research, we focus on nonparametric identification. We have used frequency response estimation to find the dynamics of converter.

Frequency response estimation requires input signal at input linearization point which excites the model at desired frequencies, like sinestream or chirp signal. We have used sinestream signal as shown in Fig. 5, which is a series of sinusoids. Output response is achieved at output linearization point (see Fig. 6).

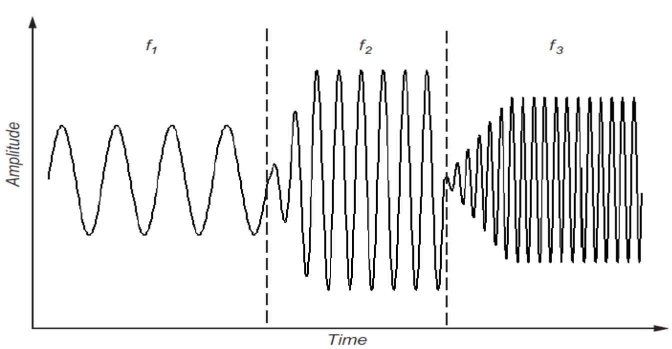

Fig. 5. Sinestream having different frequencies.

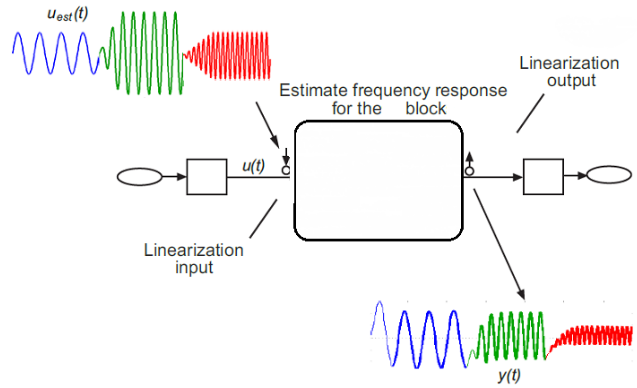

Fig. 6. Sinestream injected at point of linearization.

The complete algorithm is illustrated in flow chart shown in Fig 7.

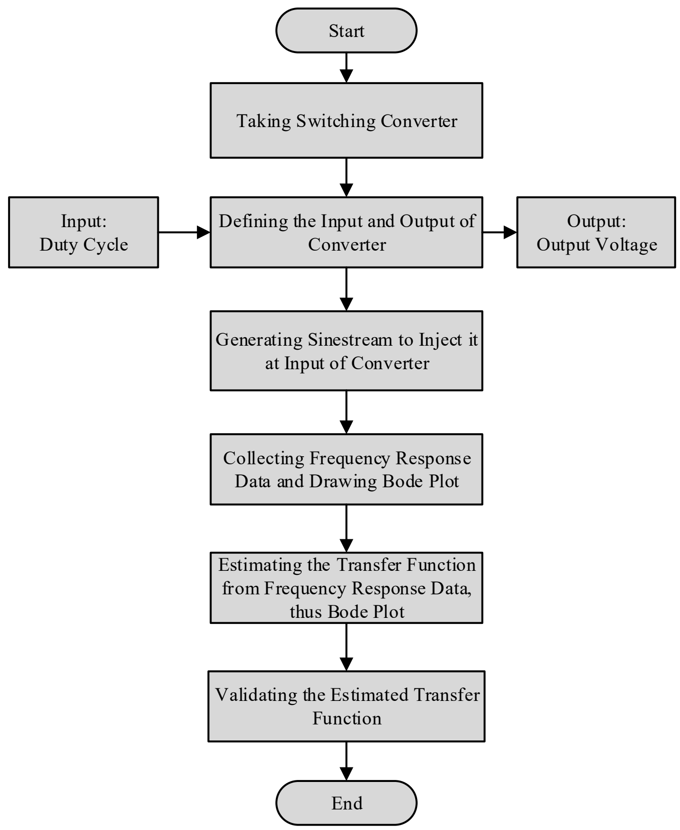

Fig. 7. Flow chart describing identification technique mechanism.

The input and output, duty ratio and switching frequencies for the three converters, namely buck, boost and buck-boost have been summarized in Table I.

TABLE I
Converter Specifications

Converter	Switching Frequency	Input Voltage	Output Voltage	Duty Ratio
Buck	10 kHz	200 V	150 V	75 %
Boost	100 kHz	24 V	48 V	50 %
Buck-Boost as Inverting Buck	10 kHz	12 V	-5 V	29.4 %
Buck-Boost as Inverting Boost	10 kHz	12 V	-28 V	70 %

A. Buck Converter Transfer Function Estimation

Buck converter (stepping down 200 V to 150 V by duty ratio of 0.75) to be estimated is illustrated in Fig. 8. The open loop response is obtained by introducing the sinusoidal signal having frequency variation from few 100 kHz to 20 kHz at the ‘duty cycle input’. Resultantly, a plot of gain and phase variation with respect to frequency sweep is shown in the form of Bode plot in Fig. 9.

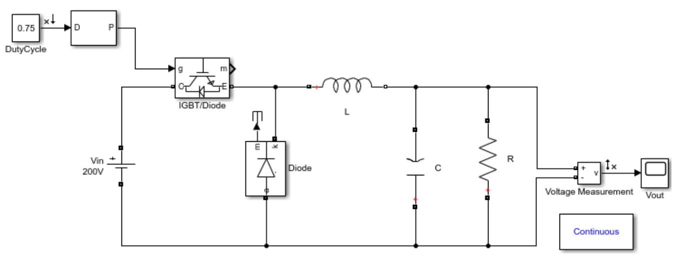

Fig. 8. Buck converter Simulink model.

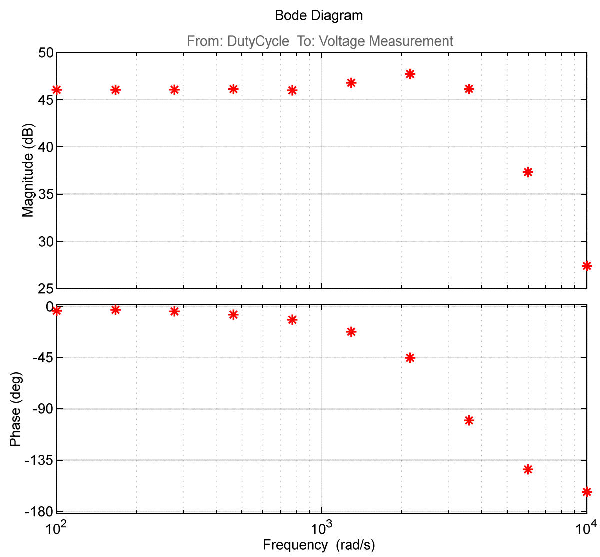

Fig. 9. Frequency response Bode plot of buck converter Simulink model.

The filtered steady state time response along with its FFT of the circuit is shown in Fig. 10.

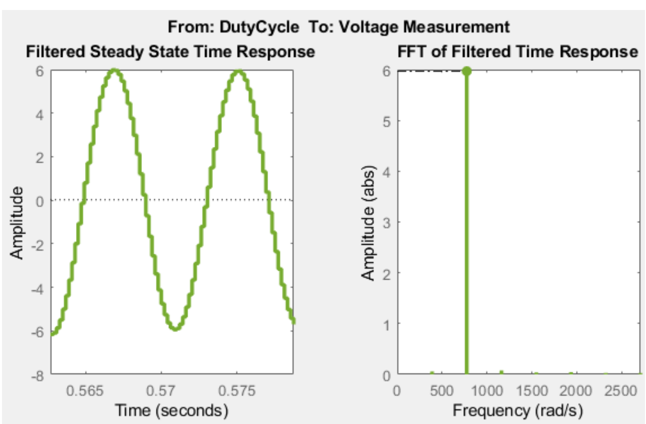

Fig. 10. Output response of buck converter against sinestream.

Once the Bode plot is achieved from the frequency response data, transfer function of the converter can be easily extracted from the Bode plot. The estimated transfer function of the buck converter, thus, is

$$G_{Buck}(s) = \frac{2.198\times10^{9}}{s^{2} + 2975\ s + 1.105\times10^{7}} \tag{4}$$

The Bode plot of the estimated transfer function of the buck converter matches exactly to the one obtained through frequency response data (see Fig. 11). This confirms the well-mapping of FRD into the transfer function.

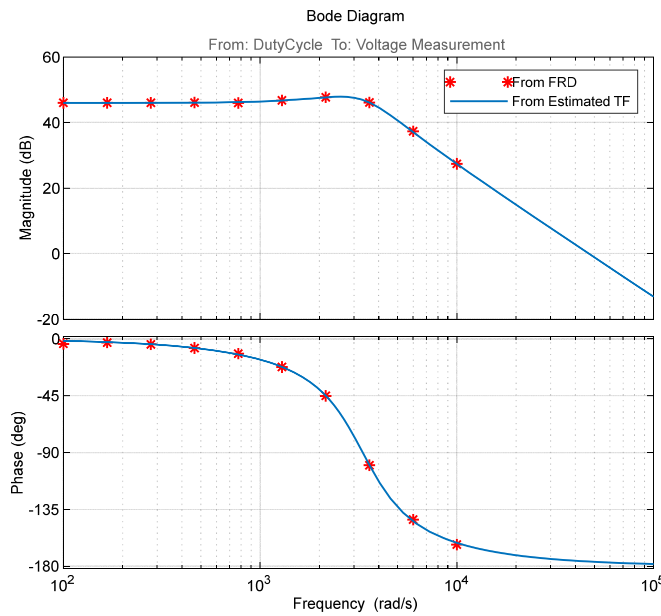

Fig. 11. Bode plot of FRD (blue line) and estimated transfer function (asterick red line).

B. Boost Converter Transfer Function Estimation

The boost converter steps up 24 V to 48 V. The sine stream input signal is a series of sinusoids with frequency range 100 kHz to 20 kHz. The proposed model configuration is shown in Fig. 12. The frequency response data is collected and then used to get the Bode plot. The Frequency Response Bode Plot (FRBP) is illustrated in Fig. 13.

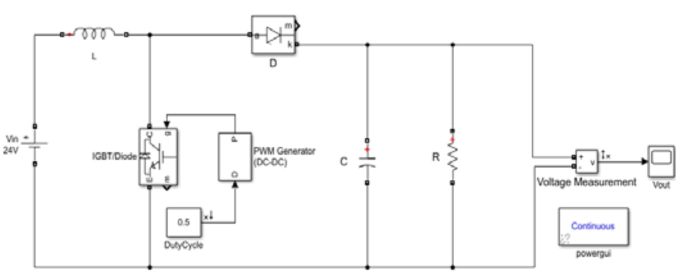

Fig. 12. Boost converter Simulink model.

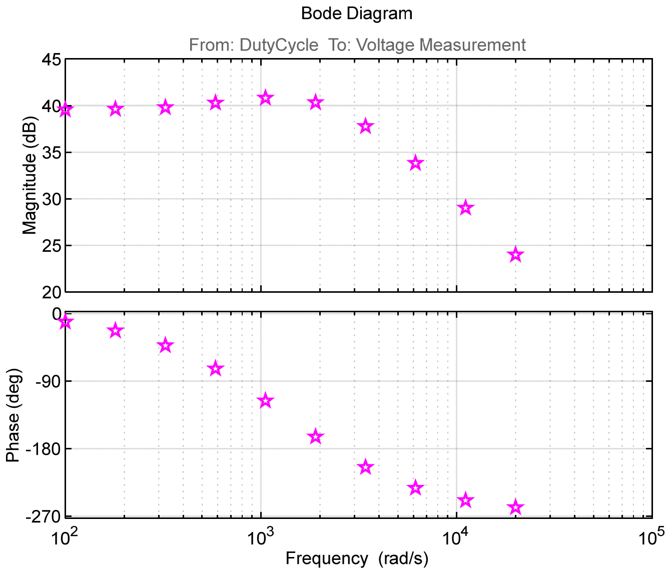

Fig. 13. Frequency response Bode plot of boost converter Simulink model.

The transfer function of boost converter stepping up voltage from 24 V to 48 V is estimated using frequency response data and is expressed as

$$G_{Boost}(s) = \frac{-3.151\times10^{5}\,s + 2.637\times10^{8}}{s^{2} + 3282\;s + 2.789\times10^{6}} \tag{5}$$

The Bode plot of the estimated transfer function of the boost converter matches exactly to the one obtained through frequency response data (see Fig. 14). This confirms the well-mapping of the frequency response data into the transfer function.

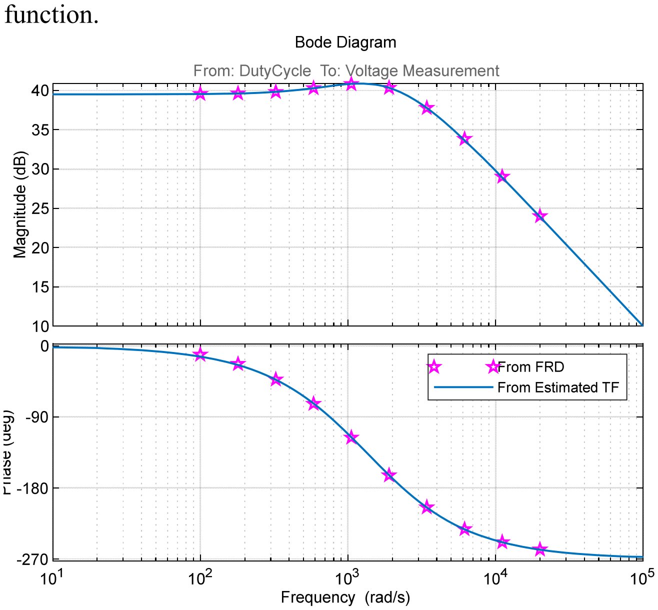

Fig. 14. Bode plot of the FRD (blue line) and estimated transfer function (asterick red line).

C. Buck-Boost Converter Transfer Function Estimation

The buck-boost converter is constructed by amalgamating the principle of both buck and boost converter. The proposed technique is very simple and can be used to linearize all types of plant.

1) Buck-Boost as An Inverting Buck

The Simulink model is illustrated in Fig. 15. The frequency response Bode plot of buck-boost converter is shown in Fig. 16 against the sinestream applied at the duty cycle input.

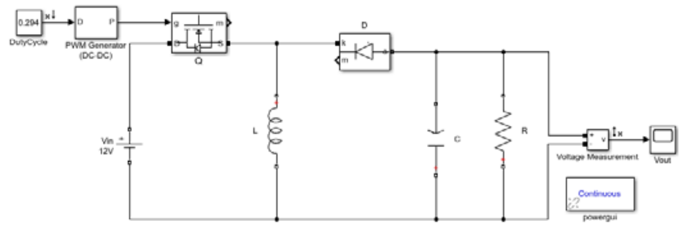

Fig. 15. Buck-boost Simulink model.

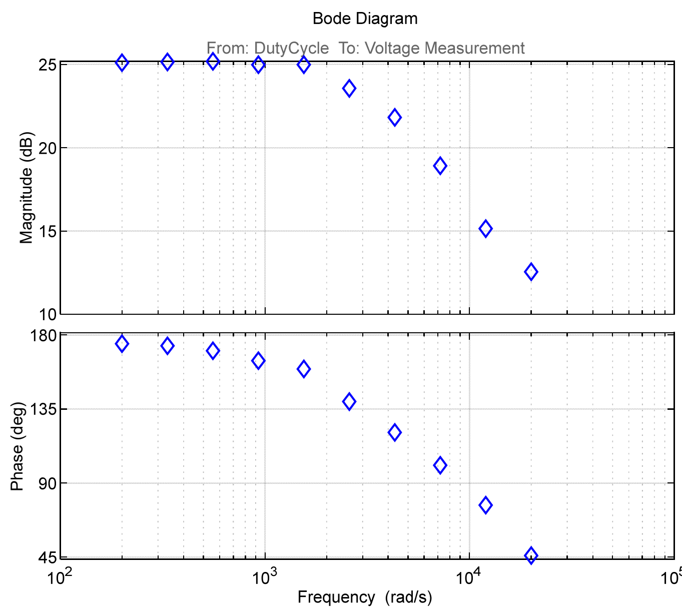

Fig. 16. Frequency response Bode plot of buck-boost Simulink model.

When buck-boost converter acts as buck converter then its duty cycle should be less than 50%. The considered buck-boost converter converts 12 V to -5V using duty cycle of 29.4%. The output displayed by the converter against the sinestream is shown in Fig. 17.

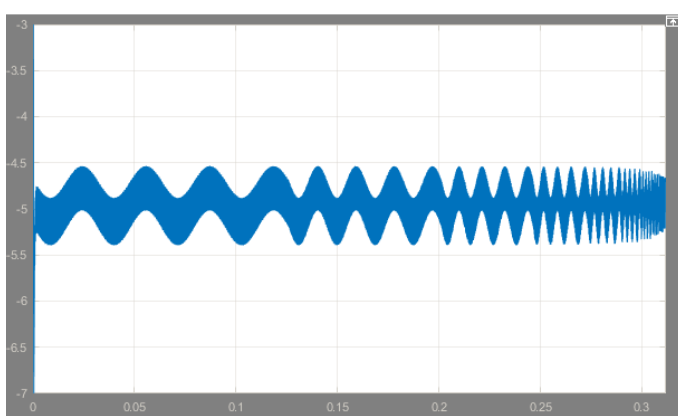

Fig. 17. Output response of buck-boost converter acting as inverting buck.

The estimated transfer function of the buck-boost converter, in case of inverting buck, from FRD is expressed by

$$G_{Buck-Boost}(s) = \frac{1.019\times10^{5}s - 3.64\times10^{9}}{s^{2} + 5.304\times10^{4}s + 2\times10^{8}} \tag{6}$$

The Bode plot of the estimated transfer function of the buck-boost converter matches exactly to the one obtained through frequency response data (see Fig. 18). This confirms the well-mapping of the frequency response data into the transfer function.

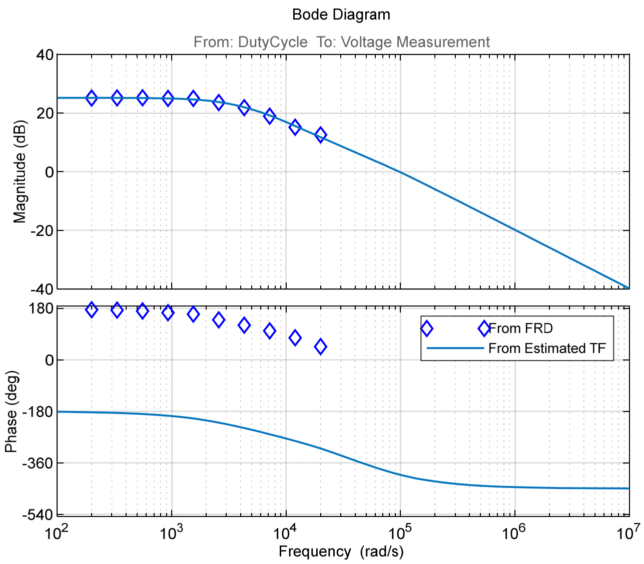

Fig. 18. Bode plot of FRD (blue line) and estimated transfer function (asterick red line).

2) Buck-Boost as An Inverting Boost

The buck-boost converter acts as an inverting boost converter when duty cycle lies between 0.5 and unity (in our case it is 0.7). The Bode plot obtained by FRD is shown in Fig. 19 whereas the output against the sinestream is shown in Fig. 20.

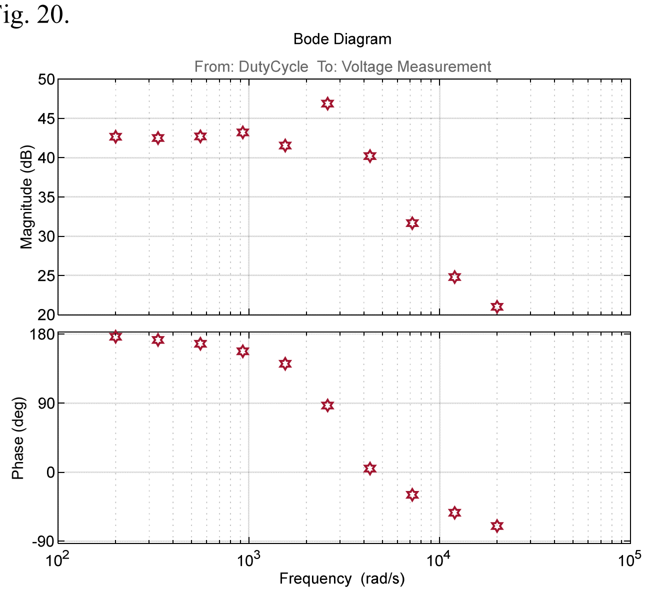

Fig. 19. Bode plot of frequency response data.

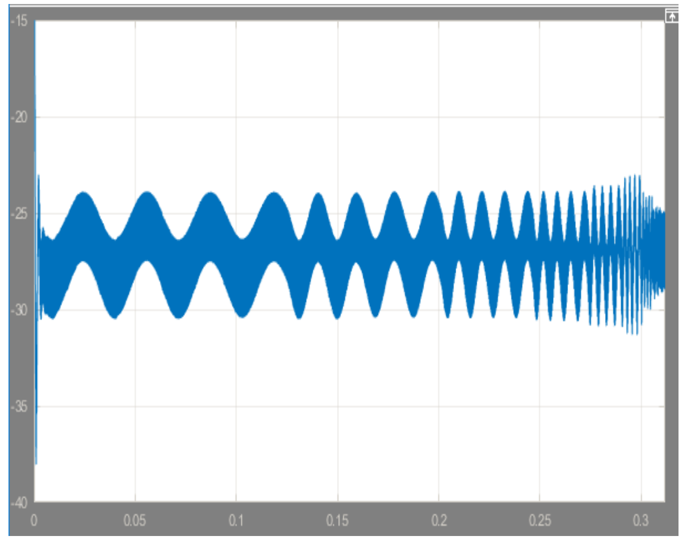

Fig. 20. Output response of buck-boost converter acting as inverting boost.

The estimated transfer function of the buck-boost converter, in case of inverting boost, from FRD is expressed by

$$G_{Buck-Boost}(s) = \frac{1.851\times10^{5}s - 1.081\times10^{9}}{s^{2} + 1985s + 8.747\times10^{6}} \tag{7}$$

The Bode plot of the estimated transfer function of the buck-boost converter matches exactly to the one obtained through frequency response data (see Fig. 21). This confirms the well-mapping of the frequency response data into the transfer function.

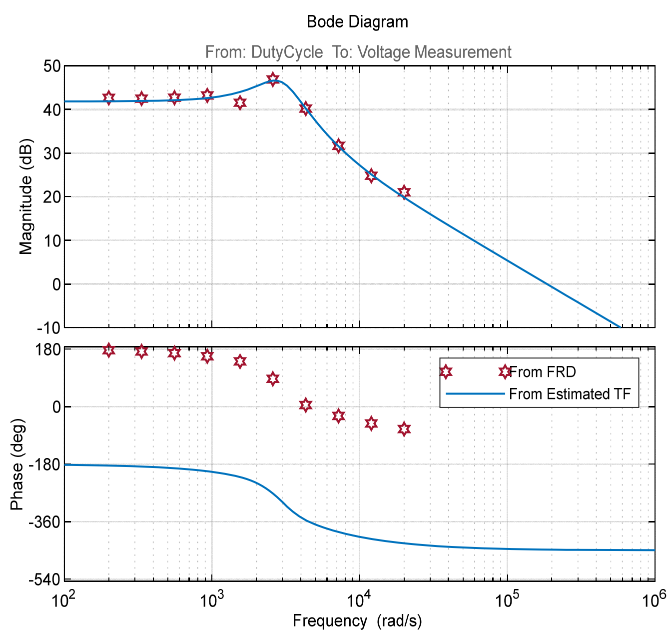

Fig. 21. Bode plot of FRD (blue line) and estimated transfer function (asterick red line).

In summary, the estimated transfer functions of three converters named buck, boost and buck-boost are tabulated in Table II.

TABLE II

ESTIMATED TRANSFER FUNCTIONS OF SWITCHING CONVERTERS

Converter	Estimated Transfer Function
Buck	$G_{Buck}(s)=\dfrac{2.198\times10^{9}}{s^{2}+2975\,s+1.105\times10^{7}}$
Boost	$G_{Boost}(s)=\dfrac{-3.151\times10^{5}s+2.637\times10^{8}}{s^{2}+\;3282\,s+2.789\times10^{6}}$
Buck-Boost as Inverting Buck	$G_{Buck-Boost}(s)=\dfrac{1.019\times10^{5}s-3.64\times10^{9}}{s^{2}+5.303\times10^{4}s+2\times10^{8}}$
Buck-Boost as Inverting Boost	$G_{Buck-Boost}(s)=\dfrac{1.851\times10^{5}s-1.081\times10^{9}}{s^{2}+1985\,s+8.747\times10^{6}}$

IV. ADDITIONAL SIMULATION RESULTS

For the sake of validating the transfer functions of the converters estimated through proposed identification technique, additional MATLAB/Simulink based simulation results are presented. Open-loop response for the circuits and their estimated transfer functions is observed. From Figs. 22 to 27, it can be observed that the estimated transfer functions show the same step response as that of their circuits from which they are derived. This further validates that the estimated transfer functions well-model the circuits.

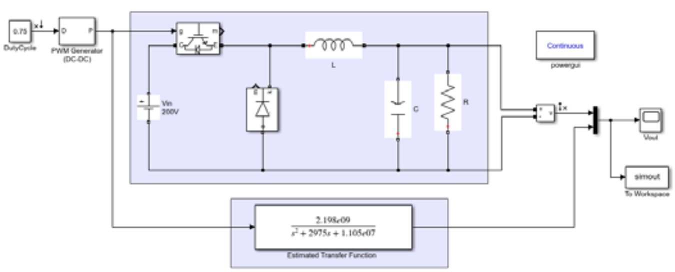

Fig. 22. Simulink model containing buck converter circuit and its estimated transfer function.

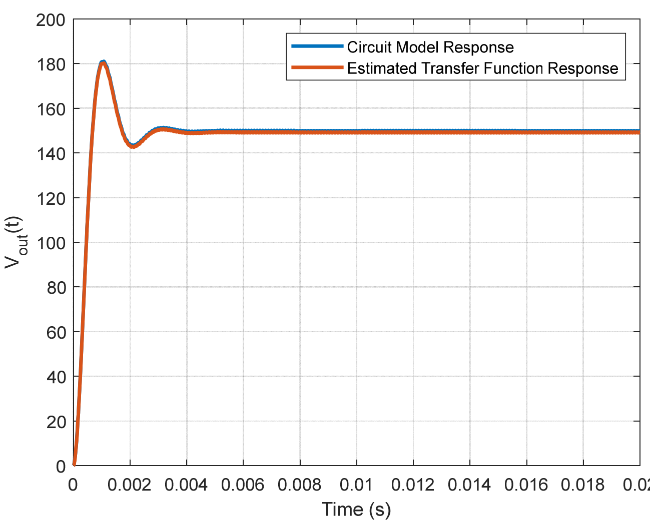

Fig. 23. Response shown by buck converter circuit and its estimated transfer function.

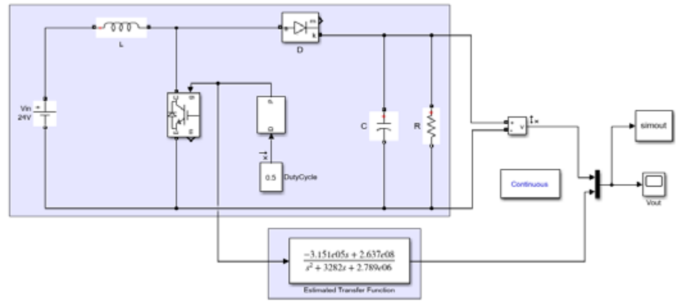

Fig. 24. Simulink model of boost converter.

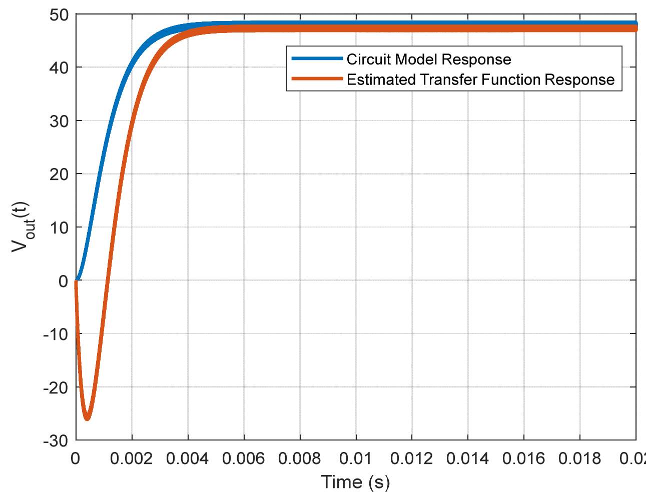

Fig. 25. Response shown by boost converter.

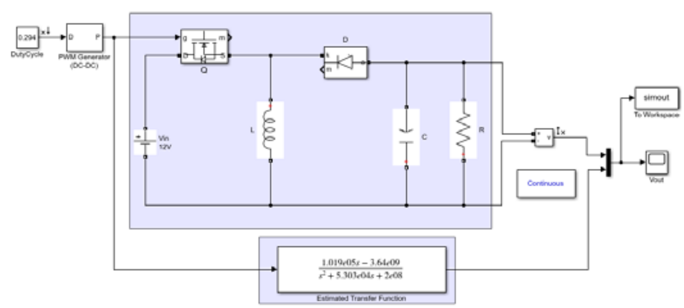

Fig. 26. Simulink model of buck-boost converter.

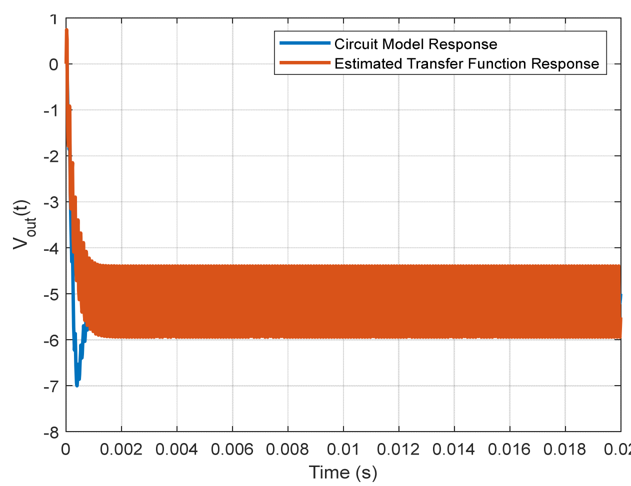

Fig. 27. Response shown by buck-boost converter.

V. CONCLUSIONS

In past the non-parametric identification of switching converter has not been discussed in detail. It is due to lack of knowledge about potential of fast frequency response measurement and analysis. Besides this, frequency response measurement requires modern knowledge regarding identification and restriction of practical implementation. Here we have used Sine Sweep Method (SSM) by means of which proposed converters from frequency response data has been identified accurately. Using frequency response estimation technique, the transfer functions of all converters have been identified successfully. The proposed technique is numerically verified and validated in MATLAB Simulink Environment. Cross Correlation method has been used in past to identify the switching converters but it causes error to identification results especially when considering finite length of signal. Now Sine Sweep Method is introduced in this research to nullify the inaccuracies on frequency response measurement. The proposed method can be applied both in development phase and production of switching converters. Here the main critical thing is to select the suitable range of amplitude an applying too much greater value can cause non-linear distortions. In future the controller can be designed to find suitable excitation amplitude about the converter under experiment.

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