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MATLAB-based Simplified Mathematical Modelling of Non-ideal Differential Mode Inverters

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***Abstract*: Power electronic converters use multifarious computer-aided software to simulate and analyze the converter dynamics. Simulink is a MATLAB-based graphical programming environment. It is frequently used for modeling, simulation and analysis of dynamic systems. The primary interface of Simulink consists of visual block diagram tools and a collection of customizable block libraries. Simulink provides a dedicated toolbox, "SimPowerSystems" to simulate power electronics converter circuits in a user-friendly manner. However, this paper presents a simplified mathematical model to simulate a power electronic system without using any dedicated toolbox (or library) of MATLAB. The simplified model decomposes the entire inverter system into simpler subsystems based on differential equations. The subsystem's output can be used as an input for another subsystem. This process is explained with the example of primitive (buck, boost, and buck-boost) converter-based non-ideal differential mode inverters (DMIs). The process avoids the use of discrete semiconductor devices from MATLAB. The performance of the proposed model is compared with the conventional model obtained using the "SimPowerSystems" toolbox. The derived model is implemented with two modulation schemes, continuous modulation scheme (CMS) and discontinuous modulation scheme (DMS).**

***Keywords*: Boost converter, buck converter, buck-boost converter, continuous modulation scheme, differential mode inverters, discontinuous modulation scheme, MATLAB Simulink, modeling, simulation-based design.**

I. INTRODUCTION

Practically the output voltage of a PV module is less. For example, a 400-W PV module provides a maximum power-point voltage of approximately 40 V[1]. An H-bridge inverter connected to this module cannot provide the single-phase-rated voltage of 120V. So, a boost converter is used between the input of the H-bridge inverter and the output of the PV module, which is a two-stage conversion process[2]–[4]. The two-stage conversion increases the losses and system cost with reduced efficiency. Ref. [3], [5]–[9] show differential mode inverters (DMIs), which convert the two-stage DC-AC conversion into a single-stage. DMIs are gaining popularity due to single-stage DC-AC conversion, high conversion efficiency, and energy density.

Computer simulation is a technique always used in power electronics to evaluate system dynamics and steady-state behavior before the hardware implementation of the system. Depending on cost, accuracy, memory allotment, speed, user interface, etc., all software have its merit and demerits [10]–[12]. Computer-based real-time-simulation software is also used to test hardware prototypes, called hardware-in-loop (HIL) [13], [14]. MATLAB is frequently used in power electronic converter simulation. MATLAB provides a dedicated toolbox, “SimPowerSystems”, to simulate power electronics converter circuits in a user-friendly manner. This toolbox contains power electronic switches, passive components, active sources, etc. It uses the "powergui" block to solve the complex algebraic loops, which sometimes may lead to convergence issues [15].

Moreover, the toolbox needs to be purchased separately from a control engineer's perspective. Therefore, there is a need to obtain the simplified MATLAB model, which can be easily implemented using MATLAB software's commonly used mathematical blocks. The simplified model does not require any passive and active electrical elements for the simulation purpose. Therefore, the simplified model is free from convergence and algebraic loop problems. This paper provides an approach through the example of non-ideal, single-stage DMIs without using the "SimPowerSystems" toolbox. The simplified model is designed in a modular way so that the voltage and current of each element can be accessed for further use. The simplified model can operate with any modulation schemes given in the literature [3], [7]. In this paper, the models are verified using two modulation schemes: CMS and DMS. The same results also have been obtained by comparing the performance results with the "SimPowerSystems" based model.

II. STATE-SPACE DESCRIPTION OF DIFFERENTIAL MODE INVERTERS

A single-phase DMI topology contains two similar DC-DC converter modules. A single module can be considered a single subsystem. It means decomposing a complete complex system into a simple subsystem is possible. Moreover, the inverter output voltage is similar for positive and negative load voltage cycles with 180^o phase-shift from each other[16], [17]. Fig. 1 shows the buck converter, boost converter, and buck-boost converter-based DMIs. Each DMI module contains inductor equivalent series resistance (ESR) r_L, capacitor ESR r_C, and ON-state resistance r_{SW}. Here DMIs are assumed to be operated in continuous conduction mode (CCM). Each module (or subsystem) behaves differently based on its provided duty cycle. Eq. (1)-(3) indicates the fundamental characteristic of

DMIs, as shown in Fig. 1. Based on the (1)-(3), the simple subsystem can be interconnected to make the complex system (DMIs).

$$v_o = v_{o1} - v_{o2} \tag{1}$$

$$i_o = i_{o1} = -i_{o2} \tag{2}$$

$$v_{o1} = r_{C1} i_{C1} + v_{C1} \tag{3}$$

Fig. 2 shows the mathematical model of second-order (from the module perspective) DMIs. Here d_1, d_2 are the duty cycle of the first and second module switch, as shown in Fig.2(b). S_1-S_4 shows gate pulses of the desired duty cycle for the particular switch, where $S_2=\overline{S}_1$ and $S_3=\overline{S}_4$. Other variables in Fig. 2 have the same meaning as in Fig.1.

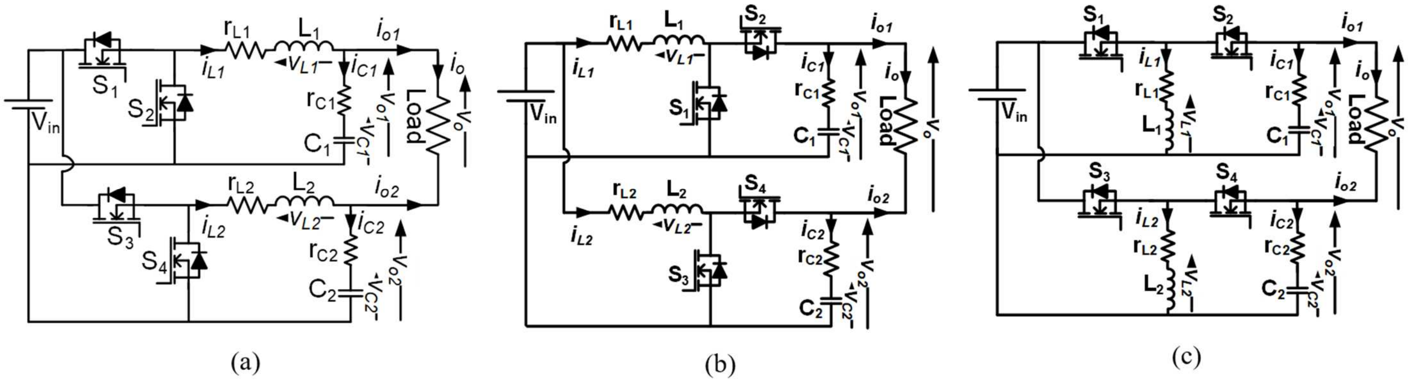

Fig. 1 (a) Buck, (b) boost and (c) buck-boost DC-DC converter-based DMI

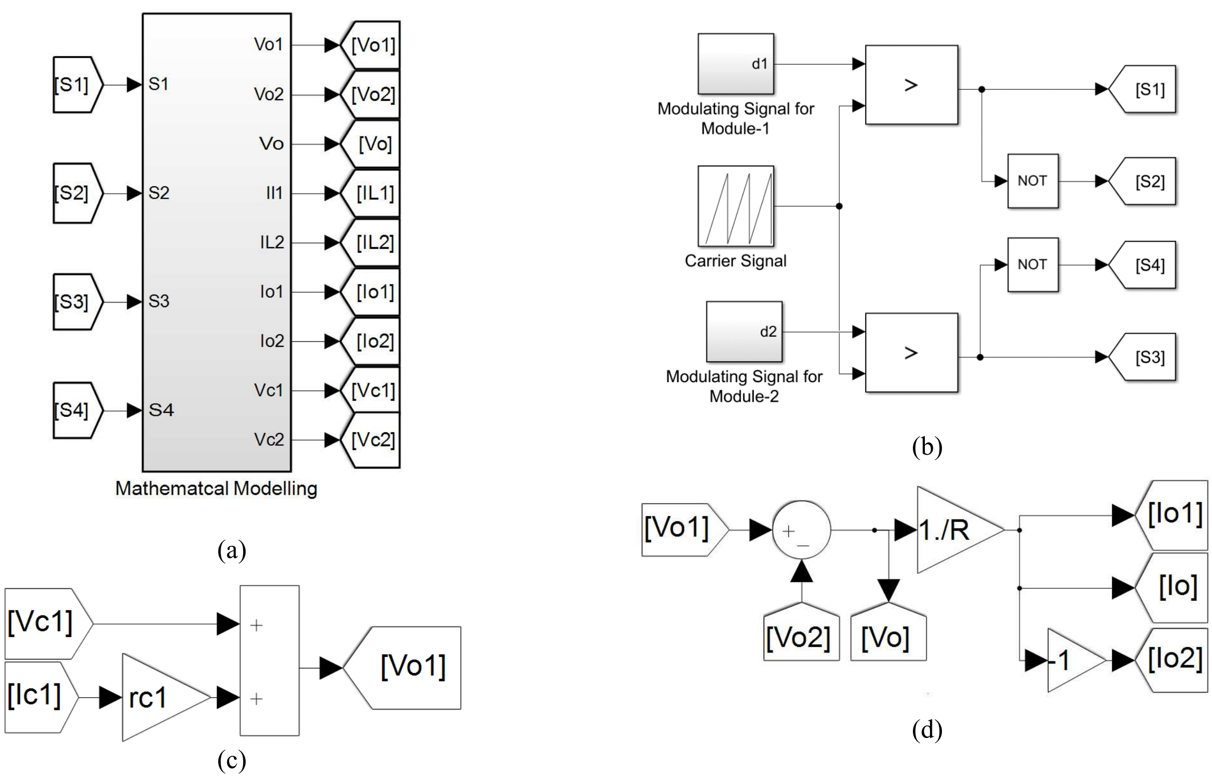

Fig. 2 Generalized (a) subsystem of DMI, (b) generation of duty cycle, (c) generation of module voltage, (d) generation of load voltage

Based on the inductor volt-second and capacitor charge-second balance[18], module output voltage (V_{o1}, V_{o2}) and current (I_{o1}, I_{o2}) can be found in terms of its module parameter. Eq. (4)-(9) shows the first module parameter in terms of V_{o1} and I_{o1}. Eq. (4) and (5) show the relation for buck converter-based DMI. Similarly, (6), (7) and (8), (9) show the relation for the boost and buck-boost-based DMIs module, respectively. Here all the upper-case alphabetical latter show the steady-state value of the variables.

$$\langle v_{L1} \rangle_{avg} = 0 = d_1 V_{in} - \left(r_{SW1} + r_{L1} \right) I_{L1} - V_{o1} \tag{4}$$

$$\langle i_{C1} \rangle_{avg} = 0 = I_{L1} - I_{o1} \tag{5}$$

$$\langle v_{L1}\rangle_{avg} = 0 = V_{in} - I_{L1}\left(r_{SW1} + r_{L1}\right) - \overline{d}_1 V_{o1} \quad (6)$$

$$\langle i_{C1}\rangle_{avg} = 0 = -I_{o1} + \overline{d}_1 I_{L1} \quad (7)$$

$$\langle v_{L1}\rangle_{avg} = 0 = d_1 V_{in} - I_{L1}\left(r_{SW1} + r_{L1}\right) - \overline{d}_1 V_{o1} \quad (8)$$

$$\langle i_{C1}\rangle_{avg} = 0 = -I_{o1} - \overline{d}_1 I_{L1} \quad (9)$$

Based on (4)-(9), Fig.3 shows the mathematical model for calculating inductor, capacitor voltages, and currents for the buck, boost, and buck-boost converter-based DMIs modules. A similar analysis can be done for the second module of DMI, which follow (10)-(15) in the same sequence as (4)-(9). Similar to Fig.3, which is formulated for the first module, a subsystem can also be formulated for the second module of DMI. However, the formulation of the second DMI module is not shown here due to limited space constraints.

$$\langle v_{L2}\rangle_{avg} = 0 = d_2 V_{in} - \left(r_{SW2} + r_{L2}\right) I_{L2} - V_{o2} \quad (10)$$

$$\langle i_{C2}\rangle_{avg} = 0 = I_{L2} - I_{o2} \quad (11)$$

$$\langle v_{L2}\rangle_{avg} = 0 = V_{in} - I_{L2}\left(r_{SW2} + r_{L2}\right) - \overline{d}_2 V_{o2} \quad (12)$$

$$\langle i_{C2}\rangle_{avg} = 0 = -I_{o2} + \overline{d}_2 I_{L2} \quad (13)$$

$$\langle v_{L2}\rangle_{avg} = 0 = d_2 V_{in} - I_{L2}\left(r_{SW2} + r_{L2}\right) - \overline{d}_2 V_{o2} \quad (14)$$

$$\langle i_{C2}\rangle_{avg} = 0 = -I_{o2} - \overline{d}_2 I_{L2} \quad (15)$$

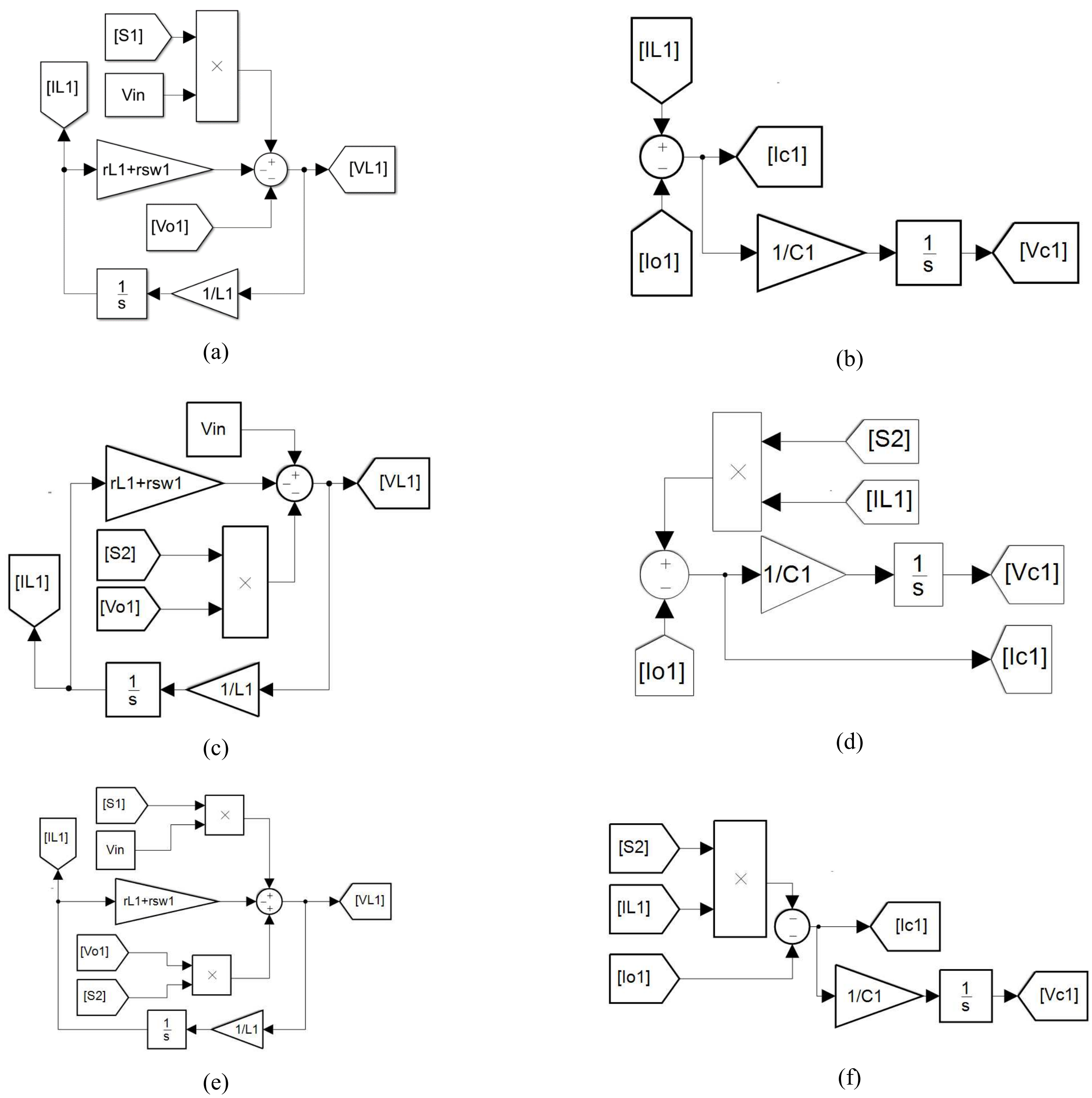

Fig. 3 Mathematical model based on (a)-(b) eq. (4)-(5) for buck converter, (c)-(d) eq. (6)-(7) for boost converter, (e)-(f) eq. (8)-(9) for buck-boost converter-based DMIs

III. SIMULATION RESULTS

Traditionally literature contains two modulation schemes for the DMIs, namely, CMS and DMS. The presented model has been simulated with both modulation schemes as presented in Fig. (4), and Fig. (5). For the verification of the mathematical model following parameters are used by each primitive converter-based DMIs: Each DMI uses common parameters as:

Input voltage V_{in} = 80 V, load voltage (V_o) frequency 50Hz, load resistance R= 28.8Ω, switching frequency f_{SW}=25kHz.

For buck converter: V_o (RMS)= 40 V, L/r_L =11.52 mH/0.5 Ω, C/r_C=0.34 μF/0.1 Ω, r_{sw}= 0.1 Ω.

For boost converter: V_o (RMS)= 110 V, L/r_L = 2.50 mH/ 0.15 Ω, C/r_C= 20 μF/0.1 Ω, r_{sw}= 0.15 Ω.

For buck-boost converter: V_o (RMS)= 110 V, L/r_L=11.52 mH/ 0.1 Ω, C/r_C= 20 μF/0.1 Ω, r_{sw}= 0.15 Ω.

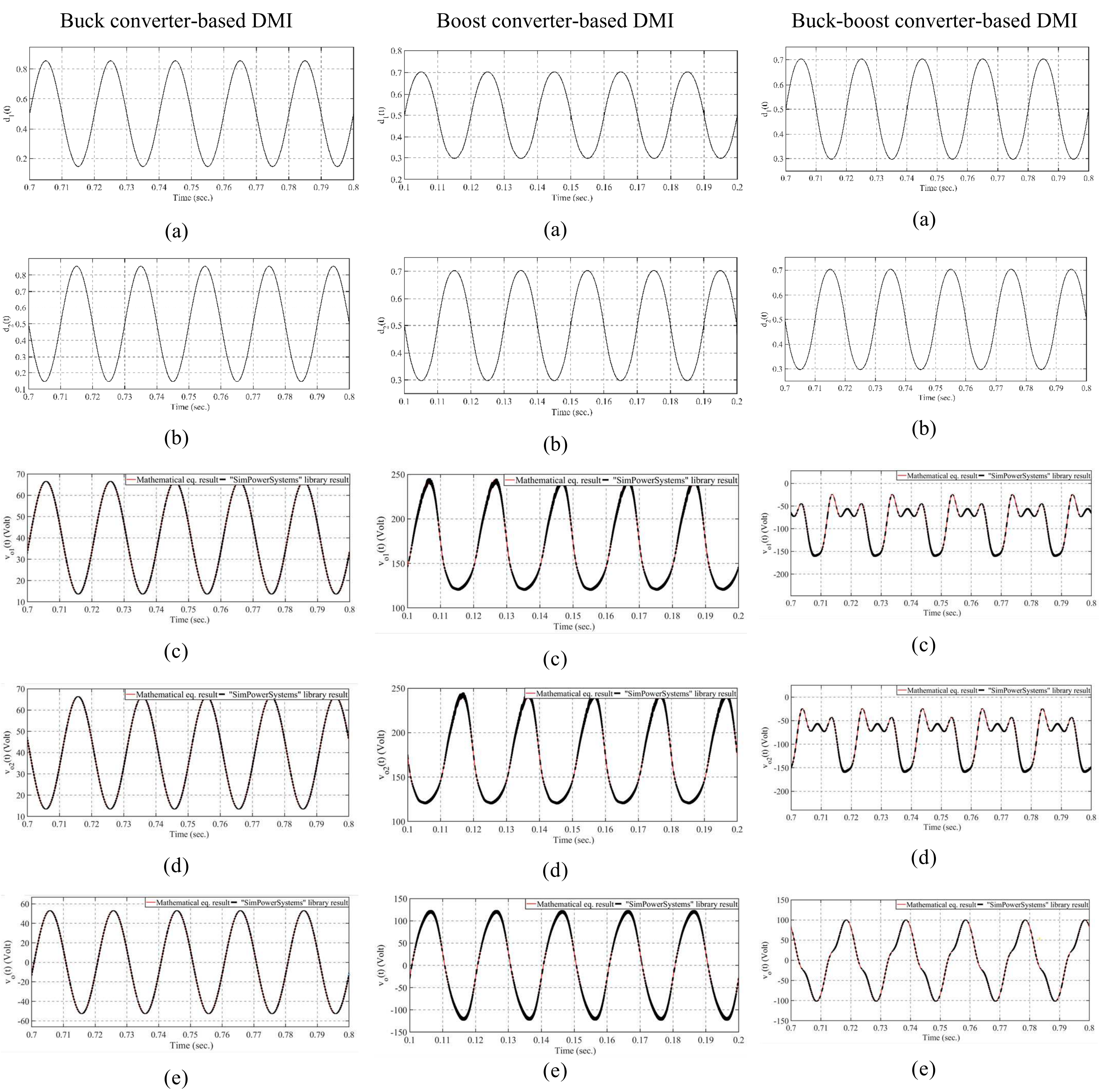

Fig. 4 Simulation results for (a) first module duty cycle, (b) second module duty cycle, (c) first module output voltage, (d) second module output voltage, (e) load voltage for buck converter, boost converter, and buck-boost converter based DMI using CMS

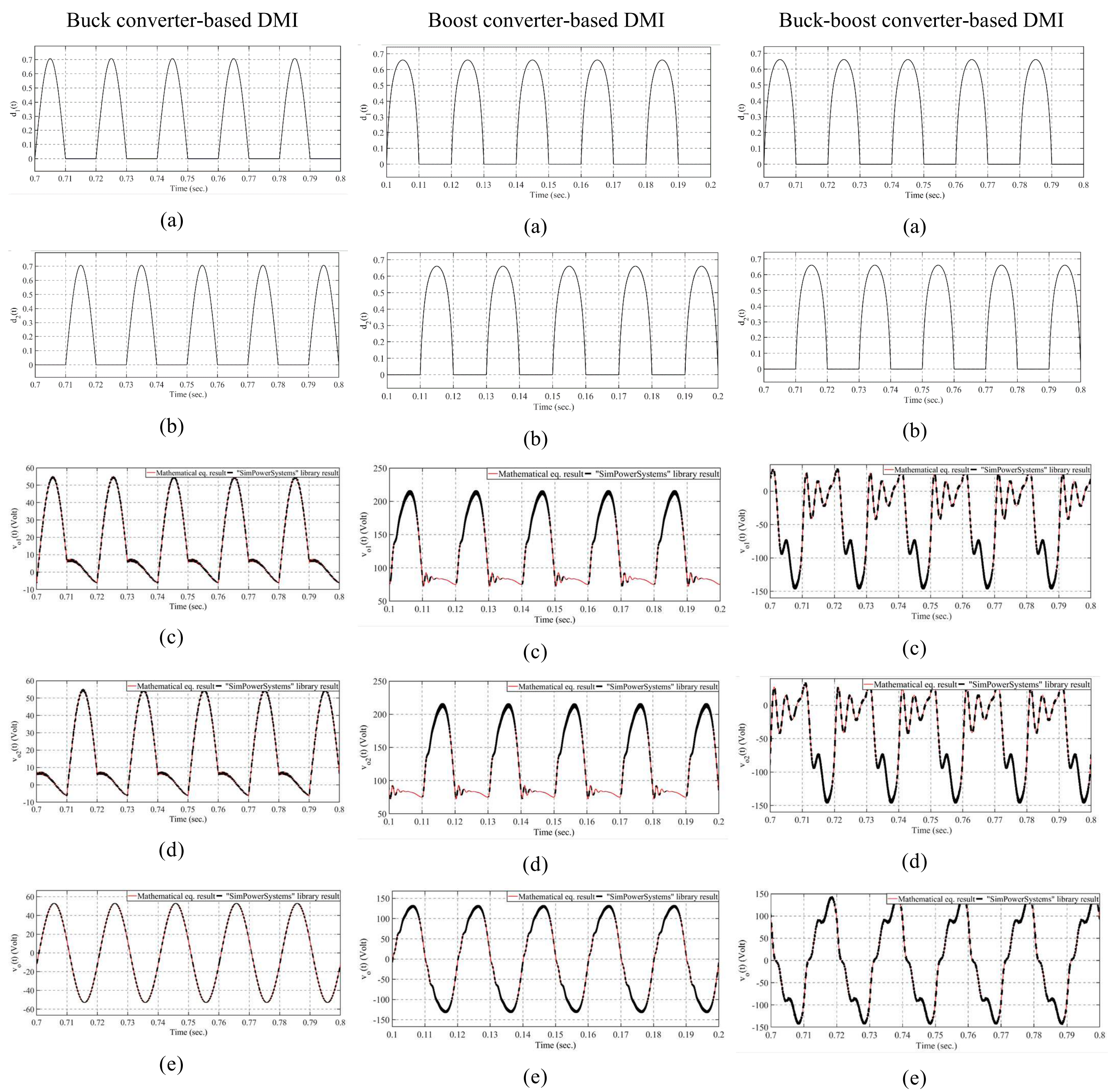

Fig. 5 Simulation results for (a) first module duty cycle, (b) second module duty cycle, (c) first module output voltage, (d) second module output voltage, (e) load voltage for buck converter, boost converter, and buck-boost converter based DMI using DMS

Fig.4(a) and Fig.4(b) show the duty cycle of the first and second modules, respectively for DMIs with CMS. Fig.4(c) and Fig.4(d) show the module voltages to generate the AC output voltage as Fig.4(e). Fig.4(e) shows that the instantaneous output voltage of buck converter-based DMI cannot be more than its input voltage. For getting the output voltage greater than the input voltage buck converter-based DMI requires a two-stage conversion process. To convert two-stage conversion into single-stage, boost converter-based DMI is used. Boost converter-based DMI provides huge module voltage, but it also gives high voltage stress to the output capacitor of the boost converter module. To decrease the module output capacitor voltage stress, buck-boost converter-based DMI is used. Buck-boost converter-based DMI produces the same level of AC output voltage as boost converter-based DMI. Moreover, it reduces the output capacitor voltage stress. Fig.4(e) also shows the effect of inverting and non-inverting DC-DC converters by pointing out the negative module voltage of buck-boost converter-based DMI. The use of inverting DC-DC converter shows the 180^o phase shift in AC output voltage compared to a non-inverting DC-DC converter-based DMI. Similar to the simulation results of DMIs with CMS, Fig.5 shows the simulation results of DMIs with DMS (in the same sequence as Fig. 4).

The expected maximum output voltage (peak of AC load voltage) is 56.56V and 155.56 V for buck and boost (and buck-boost) converter-based DMI respectively. However, due to the internal ESR of various inductors and capacitors with switch ON resistance, the peak load voltage is reduced as shown in simulation results Fig.4 and Fig.5. The simulation results also indicate the effect of various non-idealities, which varies based on the modulation scheme used in DMIs. The effect on the maximum value depends on the maximum required duty cycle in the particular modulation scheme. Moreover, the shape of particular waveforms depends on the nature of the duty cycle used in the modulation scheme.

A comparison of Fig.4 and Fig.5 shows that in each DMI, module voltage is higher with CMS for generating the same load voltage than DMS. Also, the module switching cycle with DMS is half compared to CMS. Both the points mentioned earlier make the DMIs more efficient with DMS compared to CMS. However, due to nonlinearity of the duty cycle in DMS increases the controller job in a closed-loop system [7]-[8], [19].

IV. CONCLUSION

The process for the decomposition of a complex system in a simple subsystem has been shown. The simple subsystem formation shows the process's simplicity, which helps to find out the dynamics of a complete complex system. The simulation results validate the design of non-ideal DMIs. Results also validate the mathematical results and show the simplicity of the approach in designing the non-ideal fourth-order system without using the "SimPowerSystems" library. Mathematical models can be used in the feedback control design. Results also indicate the independence of particular simulation software for finding model dynamics. The same approach is also applicable to higher-order DMI.

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