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Modeling and Simulation of DC-DC Boost Converter-Inverter System with Open-Source Software Scilab/Xcos

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Abstract: This paper proposes a mathematical modelling of DC-DC boost converter-inverter system and simulation work is carried out using Scilab/Xcos, which is free and open-source software. In this paper a two-stage DC-AC power conversion system is presented. This system consists of two converters, DC-DC boost converter and single-phase inverter. The boost converter converts input DC low voltage into high DC output voltage. The DC output from boost converter is converted into AC output voltage by an inverter. The mathematical model of a DC-AC boost converter-inverter system is presented with four different modes of operations. By using Kirchhoff's voltage and current law, the system mathematical model is derived from each operation mode. The mathematical model of the proposed system is represented and state-space matrix is derived. Moreover, the steady-state values of the system are also presented. The transient behaviors of the proposed mathematical model are validated with Xcos simulation results.

Keywords: DC-DC Boost Converter, Free and Open-Source, Mathematical Model, Simulation, Single-Phase Inverter

1. Introduction

The growing use of renewable energy sources brings new challenges to the energy conversion technology. One of these challenges is related to the fact that the output voltage of low voltage source (e.g. batteries, solar panels) need to be boosted and must be inverted to AC for practical applications. For many areas away from national grid, main energy source is DC power received from solar. Many industrial and household electrical devices use AC power. In application where the AC power is required, that DC power must be needed to change AC power.

Inverter must be used for changing of DC to AC. Inverter converts DC power to AC output 220V. When DC supply voltage is low, inverter must be connected with transformer to get 220V AC output from inverter. By connecting inverter with transformer produces AC output 220V, there exists transformer losses and costs. The aim to overcome this problem is input side of inverter must be connected with boost converter to boost input DC voltage. Boost converters are nonisolated power converters. They step-up low DC input voltage into high DC output voltage. The boosted DC output from boost converter is fed into inverter and converts that DC voltage into AC output voltage [1].

The boost converter-inverter system simulated with MATLAB for DC drive application is presented in [2]. Analysis of boost converter can be held by assuming that the components are ideal, but in practical, this assumption is not applicable. Because inductor, capacitor and semiconductor devices have nonideal effects. But more accurate model of the system is required, the parasitic components are needed to consider as in [3], [4]. High efficiency inverter connected with boost converter used in renewable application with low cost, simplified circuit configuration and improve efficiency have been proposed in [5]. Two-stage power conversion of boost converter and dual input inverter are connected to reduce power conversion losses and improve conversion efficiency have been discussed in [6]. Single-stage DC-AC power conversion using multi-loop controller to ensure a high dynamic performance is expressed in [7]. Small-signal modelling of two-stage inverter for battery application is derived and verified with simulation results have been discussed in [8]. Simulation of closed loop controlled DC-DC boost converter with inverter system using MATLAB/Simulink for small scale generation plant application has been discussed in [9].

There are many commercially available modelling and simulation software in the market such as PSim, MATLAB/Simulink, etc. Each software has its own merits. In this paper, Scilab/Xcos is chosen for simulation of the proposed system for the following reasons. It is one of open source software for scientific computation (OSSC) and provides powerful computation for engineering and scientific applications. Similar to MATLAB, it consists of Xcos (Scicos) toolbox which provides block diagram editor for constructing simulation model, dynamic system model and graphical design of a control system. Unlike MATLAB, Scilab is a freely distributed and open source software package and it is free of charge. Scilab 6.0.1 can be downloaded from the link [10].

Block diagram and subsystem of active disturbance rejection control system has been described and simulation on Xcos show good effectiveness of the control system has been expressed in [11]. The difference between two software environments, MATLAB and Scilab are described in [12]. Haofu Liao [13] expressed, Scilab or Xcos used computational function block (flags) to improve the computational efficiency of block. Mathematical model of induction motor is expressed in [14] and simulation is done with step-change in speed and load using Scilab/Xcos.

Modelling of Separately Excited DC Motor drive system using Scilab/Xcos tool and discuss the results in [15]. In the review of the previously mentioned works, simulation of boost converter-inverter system with Scilab/Xcos is not found in literature. In this paper, mathematical model of DC-DC boost converter-inverter system is represented and simulation work is done by using Scilab/Xcos.

The rests of the paper are structured as follows. In section 2, the mathematical model of the system using switched function is expressed. In section 3, simulation results and discussions are presented. Section 4 is the conclusion of the paper.

2. Mathematical Modeling of DC-DC Boost Converter-Inverter System

Section II consists of two subsections, mathematical model of the system and switched model of the system including steady-state equations.

2.1. Mathematical Model of the System

Figure 1 describes the proposed DC-DC boost converter-inverter system. The proposed system combines following three subsections.

(a) Boost Converter, this system consists of inductor (L), inductor parasitic resistance (r_L), switching device (Q_1), diode (Di), dc link capacitance (C_{dc}) and dc link resistance (R_{dc}). Where V_{in} is input voltage, i_{in} is inductor current, $q_1(t)$ is on/off input of Q_1 and v_{dc} is dc link voltage. The inductor stored and released energy when the switch is ON and OFF. The capacitor is used for filtering of ripple in the output voltage [16].

(b) Inverter composes of four switching devices, transistor Q_2 and $\overline{Q}_2$. $q_2(t)$ and $\overline{q}_2(t)$ are the ON/OFF control signals of transistor Q_2 and $\overline{Q}_2$.

(c) LC output filter is connected at the output of inverter. It consists of filter inductor (L_f), filter inductor resistance (r_L), filter capacitance (C_f) and output resistance (R_o). Where i_f filter current and output voltage of inverter is is v_o.

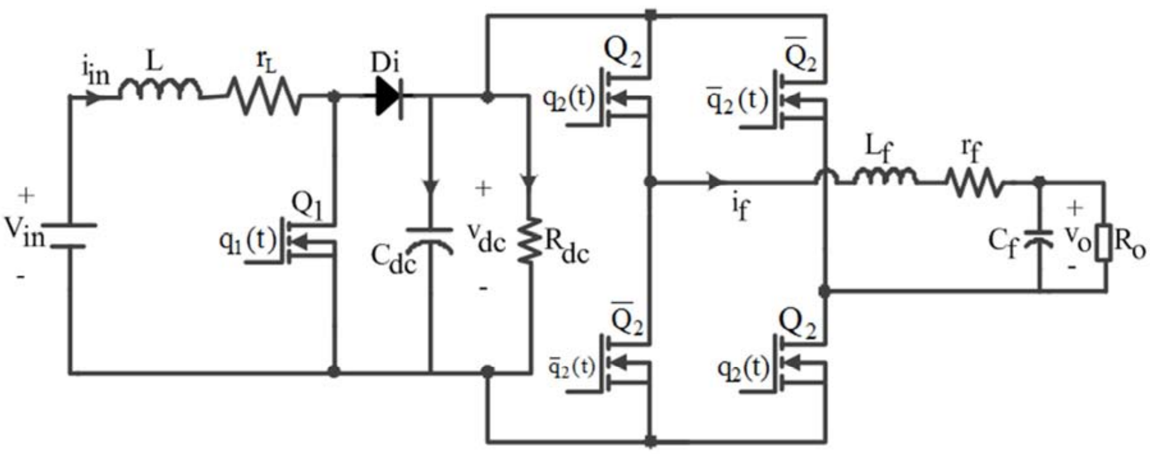

Figure 1. *Proposed DC-DC Boost Converter-Inverter System*。

In order to obtain mathematical model of the system, ideal switch topology is considered as shown in Figure 2. When switches conduct if q_1= 1 or q_2= 1 or switches do not conduct if q_1= 0 or q_2= -1.

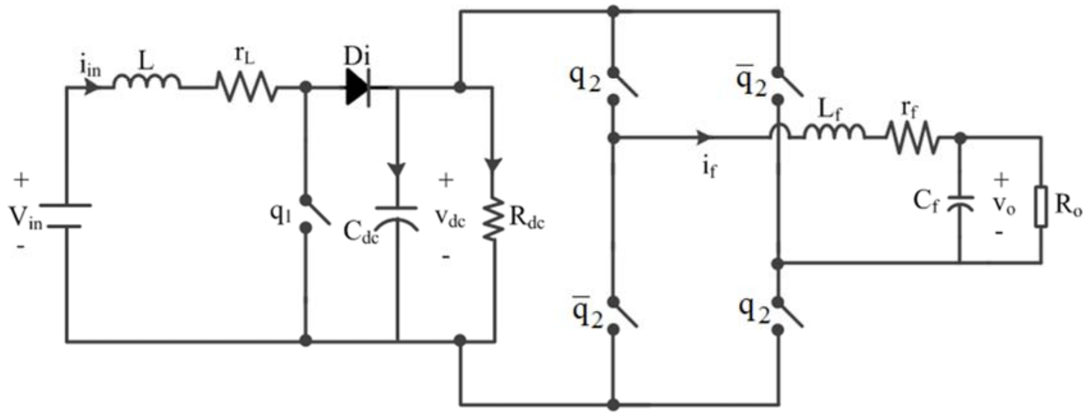

Figure 2. Equivalent Circuit Diagram of DC-DC Boost Converter-Inverter System.

Equivalent circuits of four different modes are represented to derive mathematical models of the system. The differential equations of the proposed system for four different modes are obtained by using Kirchhoff's voltage and current law.

Mode 1: Q1-OFF and Q2-ON

Figure 3 shows the equivalent circuit when $q_1 = 0$ and $q_2 = 1$.

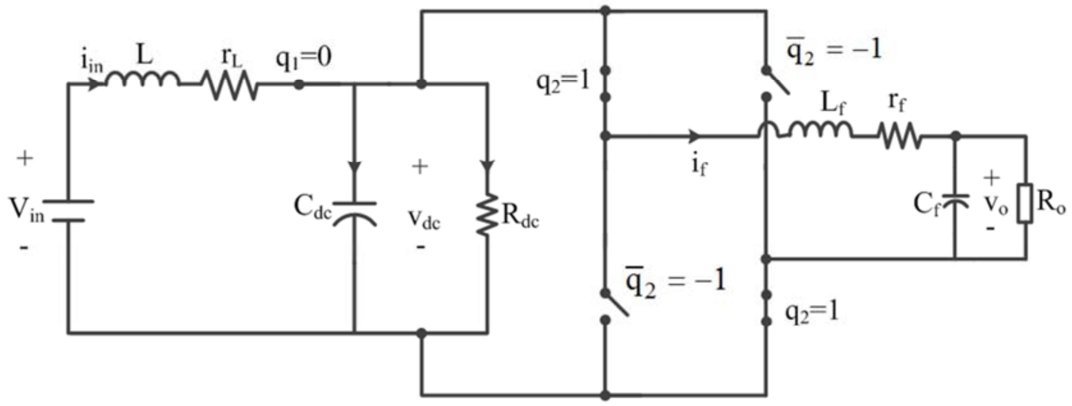

Figure 3. Equivalent Circuit of Mode 1.

The mathematical model of Figure 3 is represented by the following differential equations (1)-(4):

$$L\frac{di_{in}}{dt} = V_{in} - i_{in}r_L - v_{dc} \tag{1}$$

$$C_{dc}\frac{dv_{dc}}{dt} = i_{in} - i_f - \frac{v_{dc}}{R_{dc}} \tag{2}$$

$$L_f\frac{di_f}{dt} = v_{dc} - i_f r_f - v_o \tag{3}$$

$$C_f\frac{dv_o}{dt} = i_f - \frac{v_o}{R_o} \tag{4}$$

Mode 2: Q1-OFF and Q2-OFF

Figure 4 shows the equivalent circuit whenq$_1$=0 and q$_2$=-1.

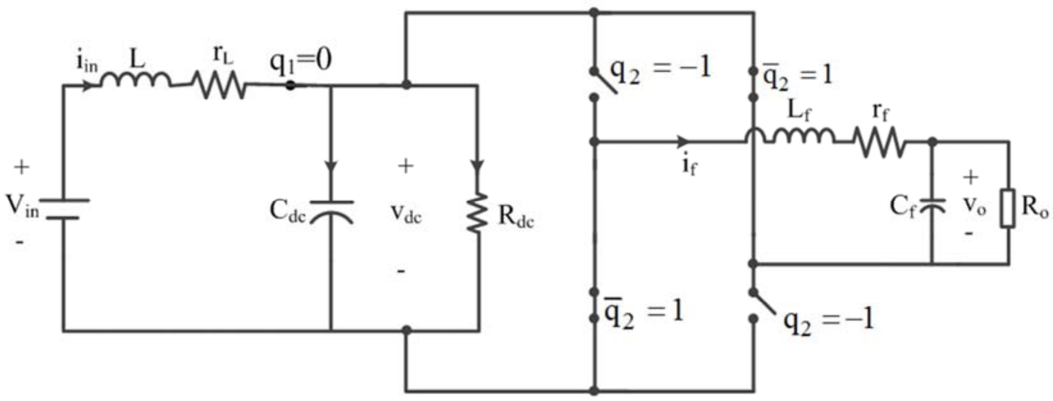

Figure 4. Equivalent Circuit of Mode 2.

The mathematical model of Figure 4 is represented by the following differential equations (5)-(8):

$$L\frac{di_{in}}{dt} = V_{in} - i_{in}r_L - v_{dc} \quad (5)$$

$$C_{dc}\frac{dv_{dc}}{dt} = i_{in} + i_f - \frac{v_{dc}}{R_{dc}} \quad (6)$$

$$L_f\frac{di_f}{dt} = -v_{dc} - i_f r_f - v_o \quad (7)$$

$$C_f\frac{dv_o}{dt} = i_f - \frac{v_o}{R_o} \quad (8)$$

Mode 3: Q1-ON and Q2-ON

Figure 5 shows the equivalent circuit when q_1=1 and q_2=1.

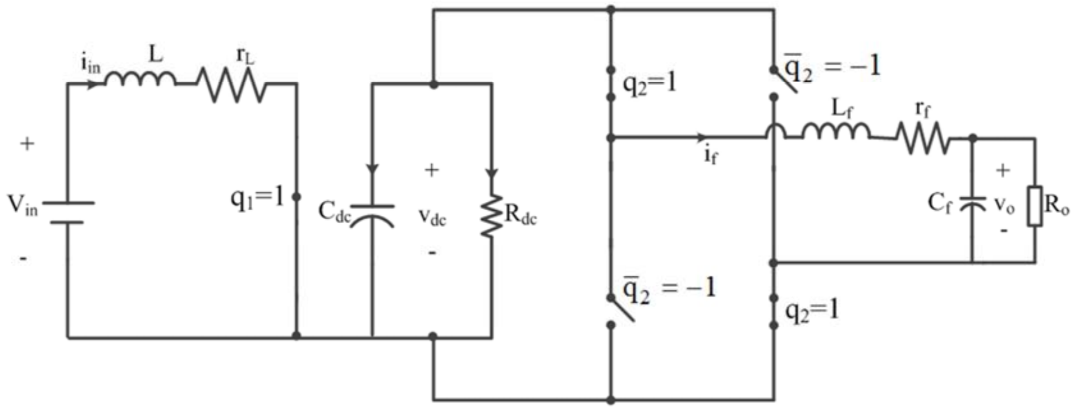

***Figure 5.** Equivalent Circuit of Mode 3.*

The mathematical model of Figure 5 is represented by the following differential equations (9)-(12):

$$L\frac{di_{in}}{dt} = V_{in} - i_{in}r_L \quad (9)$$

$$C_{dc}\frac{dv_{dc}}{dt} = -i_f - \frac{v_{dc}}{R_{dc}} \quad (10)$$

$$L_f\frac{di_f}{dt} = v_{dc} - i_f r_f - v_o \quad (11)$$

$$C_f\frac{dv_o}{dt} = i_f - \frac{v_o}{R_o} \quad (12)$$

Mode 4: Q1-ON and Q2-OFF

Figure 6 shows the equivalent circuit when q_1=1 and q_2=-1.

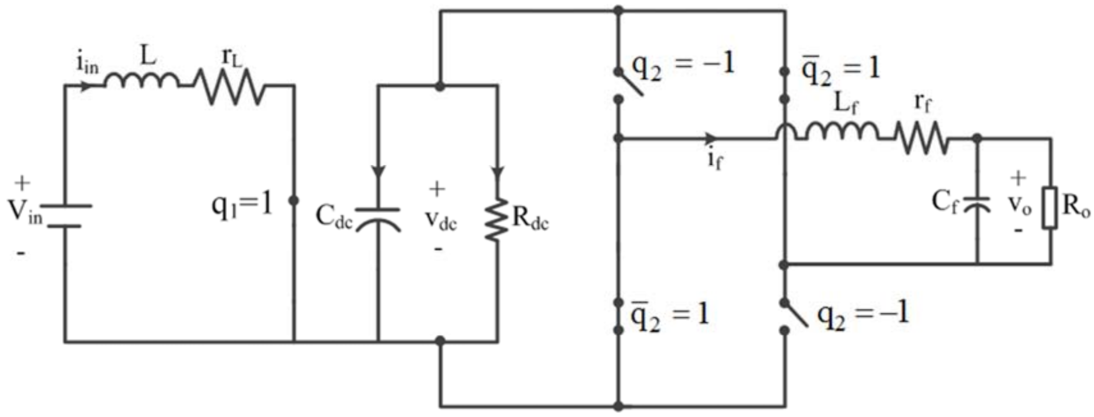

***Figure 6.** Equivalent Circuit of Mode 4.*

The mathematical model of Figure 6 is represented by the following differential equations (13)-(16):

$$L\frac{di_{in}}{dt} = V_{in} - i_{in}r_L \quad (13)$$

$$C_{dc}\frac{dv_{dc}}{dt} = i_f - \frac{v_{dc}}{R_{dc}} \quad (14)$$

$$L_f\frac{di_f}{dt} = -v_{dc} - i_f r_f - v_o \quad (15)$$

$$C_f\frac{dv_o}{dt} = i_f - \frac{v_o}{R_o} \quad (16)$$

2.2. Switched Function Model of the System

To obtain the dynamic model of the system, equivalent circuit with switches as shown in Figure 2 is considered. Whereas, $q_1 \in \{0,1\}$ and $q_2 \in \{1,-1\}$ are the input switch positions. The switched models of the system can be represented as in (17)-(20):

$$L\frac{di_{in}}{dt} = V_{in} - i_{in}r_L - (1-q_1)v_{dc} \tag{17}$$

$$C_{dc}\frac{dv_{dc}}{dt} = (1-q_1)i_{in} - q_2 i_f - \frac{v_{dc}}{R_{dc}} \tag{18}$$

$$L_f\frac{di_f}{dt} = q_2 v_{dc} - i_f r_f - v_o \tag{19}$$

$$C_f\frac{dv_o}{dt} = i_f - \frac{v_o}{R_o} \tag{20}$$

In order to obtain the steady-state equation of the system, the average model of the system is used. The switch positions q_1 and q_2 are replaced by average positions d_1 and d_2 in equations (17)-(20). The average switched models of the system are shown in (21)-(24):

$$\frac{d\bar{i}_{in}}{dt} = \frac{1}{L}\left[V_{in} - \bar{i}_{in}r_L - (1-\bar{d}_1)\bar{v}_{dc}\right] \tag{21}$$

$$\frac{d\bar{v}_{dc}}{dt} = \frac{1}{C_{dc}}\left[(1-\bar{d}_1)\bar{i}_{in} - \bar{d}_2\bar{i}_f - \frac{\bar{v}_{dc}}{R_{dc}}\right] \tag{22}$$

$$\frac{d\bar{i}_f}{dt} = \frac{1}{L_f}\left[\bar{d}_2\bar{v}_{dc} - \bar{i}_f r_f - \bar{v}_o\right] \tag{23}$$

$$\frac{d\bar{v}_o}{dt} = \frac{1}{C_f}\left[\bar{i}_f - \frac{\bar{v}_o}{R_o}\right] \tag{24}$$

$d_1 = D_1 + \tilde{d}_1$ and $d_2 = D_2 + \tilde{d}_2$, $\tilde{d}_1 \ll D_1$ and $\tilde{d}_2 \ll D_2$ thus $\tilde{d}_1$ and $\tilde{d}_2$ are neglected according to small ripple approximation. d_1 and d_2 are equal D_1 and D_2. The system equilibrium condition can be represented by (25) – (28):

$$0 = \frac{1}{L}\left[V_{in} - I_{in}r_L - (1-D_1)V_{dc}\right] \tag{25}$$

$$0 = \frac{1}{C_{dc}}\left[(1-D_1)I_{in} - D_2 I_f - \frac{V_{dc}}{R_{dc}}\right] \tag{26}$$

$$0 = \frac{1}{L_f}\left[D_2 V_{dc} - I_f r_f - V_o\right] \tag{27}$$

$$0 = \frac{1}{C_f}\left[I_f - \frac{V_o}{R_o}\right] \tag{28}$$

In matrix form, equations (25)-(28) can be represented as follow,

$$\begin{pmatrix} r_L & (1-D_1) & 0 & 0 \\ (1-D_1) & -1/R_{dc} & -D_2 & 0 \\ 0 & D_2 & -r_f & -1 \\ 0 & 0 & 1 & -1/R_o \end{pmatrix}\begin{pmatrix} I_{in} \\ V_{dc} \\ I_f \\ V_o \end{pmatrix} = \begin{pmatrix} \mathrm{V_{in}} \\ 0 \\ 0 \\ 0 \end{pmatrix} \tag{29}$$

By solving (29), the steady-state matrix is obtained as (30).

$$\begin{bmatrix} I_{in} \\ V_{dc} \\ I_f \\ V_o \end{bmatrix} = \begin{bmatrix} \dfrac{(R_{dc}D_2^2 + R_o + r_f)}{((R_{dc}D_2^2 + R_o + r_f)r_L + R_{dc}R_o + R_{dc}r_f - 2R_{dc}R_oD_1 - 2R_{dc}D_1r_f + R_{dc}R_oD_1^2 + R_{dc}D_1^2r_f)} \\ \dfrac{(R_{dc}R_o + R_{dc}r_f - R_{dc}R_oD_1 - R_{dc}D_1r_f)}{((R_{dc}D_2^2 + R_o + r_f)r_L + R_{dc}R_o + R_{dc}r_f - 2R_{dc}R_oD_1 - 2R_{dc}D_1r_f + R_{dc}R_oD_1^2 + R_{dc}D_1^2r_f)} \\ \dfrac{(R_{dc}D_2 - R_{dc}D_1D_2)}{((R_{dc}D_2^2 + R_o + r_f)r_L + R_{dc}R_o + R_{dc}r_f - 2R_{dc}R_oD_1 - 2R_{dc}D_1r_f + R_{dc}R_oD_1^2 + R_{dc}D_1^2r_f)} \\ \dfrac{(R_{dc}R_oD_2 - R_{dc}R_oD_1D_2)}{((R_{dc}D_2^2 + R_o + r_f)r_L + R_{dc}R_o + R_{dc}r_f - 2R_{dc}R_oD_1 - 2R_{dc}D_1r_f + R_{dc}R_oD_1^2 + R_{dc}D_1^2r_f)} \end{bmatrix} V_{in} \tag{30}$$

3. Simulation Results and Discussion

Simulation works and related results are provided in this section.

3.1. Simulation with Scilab/Xcos

Scilab provides a large number of toolboxes for developing and simulation models of several types. The DC-DC boost converter-inverter system (21)-(24) is represented by using the blocks from Xcos toolbox. Simulation work is important for researchers because it can study dynamic performance of system without any charges. When the system undergoes changes or disturbances, the changes in system dynamic parameters can be easily seen. By doing simulation, it can save time and costs and can easy to study the dynamic changes before practical constructing.

The average duty cycle command of DC-DC boost converter is $D_1 = 0.7$. The duty cycle command for reference sine wave of inverter is 0.8. The rms value of D_2 for inverter is 0.8/1.414. The inverter is intended to generate output voltage of 220 V (rms) and if the power rating is set at 2200 W, the value of load resistance is 22 Ω. The parameters of the system used in simulation are expressed in Table 1.

Table 1. *Parameters of the Proposed System.*

Parameters	Variables	Values
Supply voltage	Vin	120 [V]
Boost converter frequency	f	2000 [Hz]
Inductor	L	2 [m H]
Inductor resistance	r_L	0.2 [Ω]
DC link capacitance	C_{dc}	1.41 [m F]
DC link resistance	R_{dc}	1000 [Ω]
Duty-cycle	D_1	0.7
	D_2 (rms)	$0.8/\sqrt{2}$
Output filter capacitance	C_f	22 [μ F]
Output filter inductance	L_f	2 [m H]
Resistance of output filter inductor	r_f	0.2 [Ω]
Load resistance	R_o	22 [Ω]
Output power	P_o	2200 [W]
Inverter output frequency	f	50 [Hz]

Based on (21), the input current block diagram can be created as shown in Figure 7.

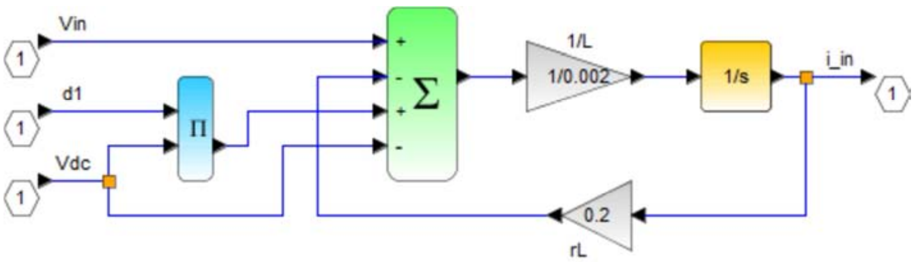

Figure 7. *Block Diagram of Input Current.*

Using (22), the DC-link voltage block diagram can be created as shown in Figure 8.

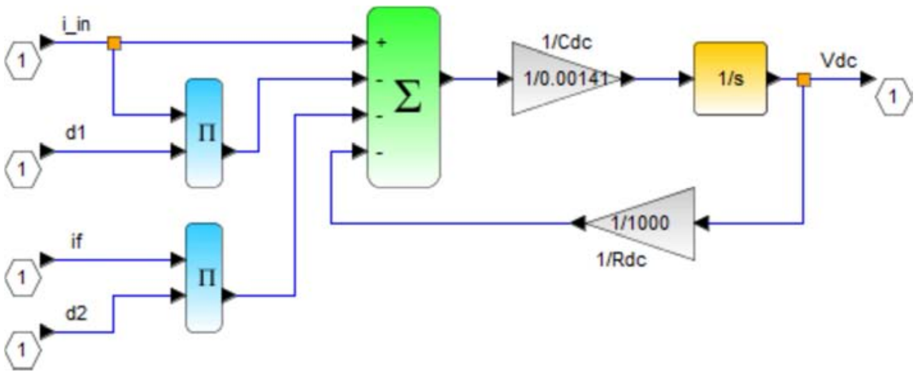

Figure 8. *Block Diagram of DC Link Voltage.*

The output filter current block diagram can be created by using (23) as shown in Figure 9.

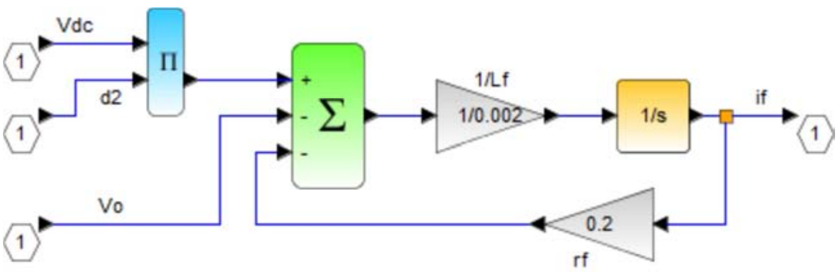

Figure 9. *Block Diagram of Output Filter Current.*

Based on (24), the inverter output voltage block diagram can be created as shown in Figure 10.

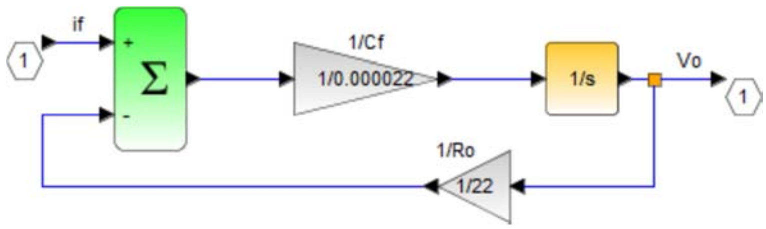

Figure 10. *Block Diagram of Output Voltage of Inverter.*

By combining the above four block diagrams, the following overall system is obtained. When applying duty cycle commands as inputs and the system is run with Scilab, the output state variables i_{in}, v_o, i_f and v_{dc} are obtained.

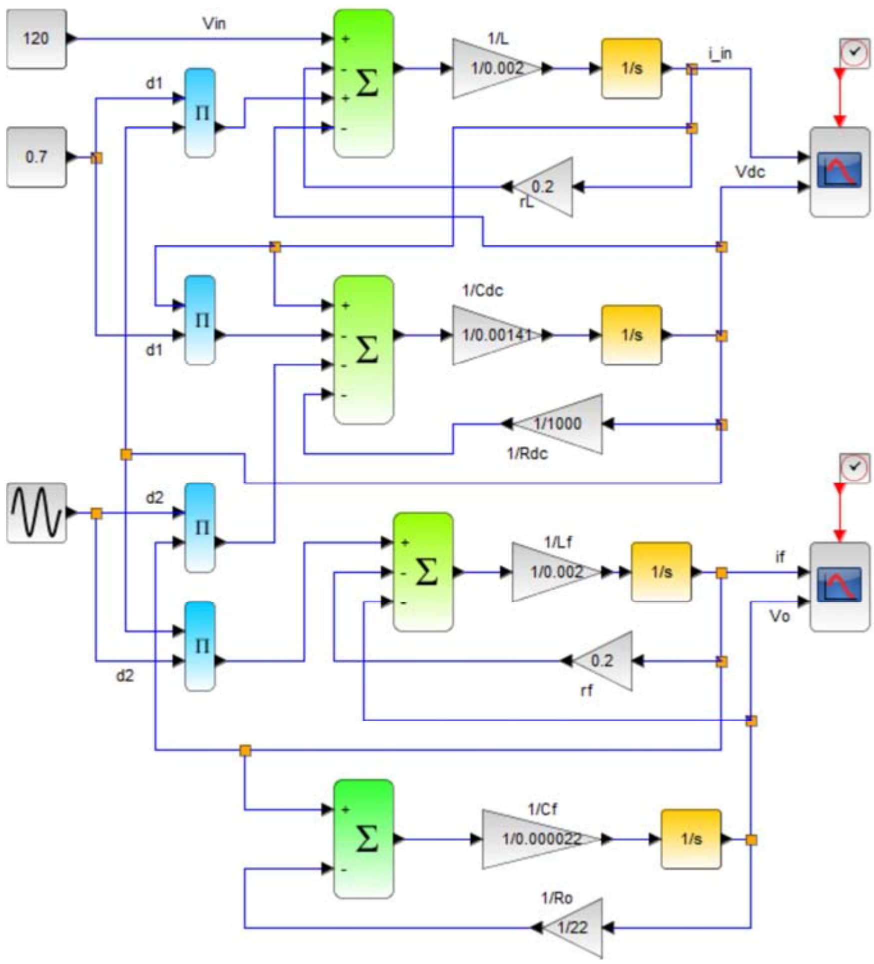

Figure 11. *Overall System Block Diagram of Boost Converter-Inverter System.*

3.2. Discussion on Simulated Results

Table 2 presents the numerical values of the equilibrium points of i_{in} , v_{dc} , i_f and v_o when the values of DC link resistor R_{dc} and output resistor R_o changed at D_1=0.7 and $D_2=0.8/\sqrt{2}$. The simulation results are shown in Figure 12-14 and discussed the results.

TABLE 2. *Simulation Results at the Equilibrium Points.*

Equilibrium Points	Simulation 1 R_{dc}=1000Ω, R_o=22Ω	Simulation 2 R_{dc}=10Ω, R_o=22Ω	Simulation 3 R_{dc}=1000Ω, R_o=1000Ω
i_{in}	19.87730	121.6318	1.7549
v_{dc}	386.7485	318.9121	398.8301
i_f	9.8564	8.1375	0.2256
v_o	216.8397	178.8057	225.6013

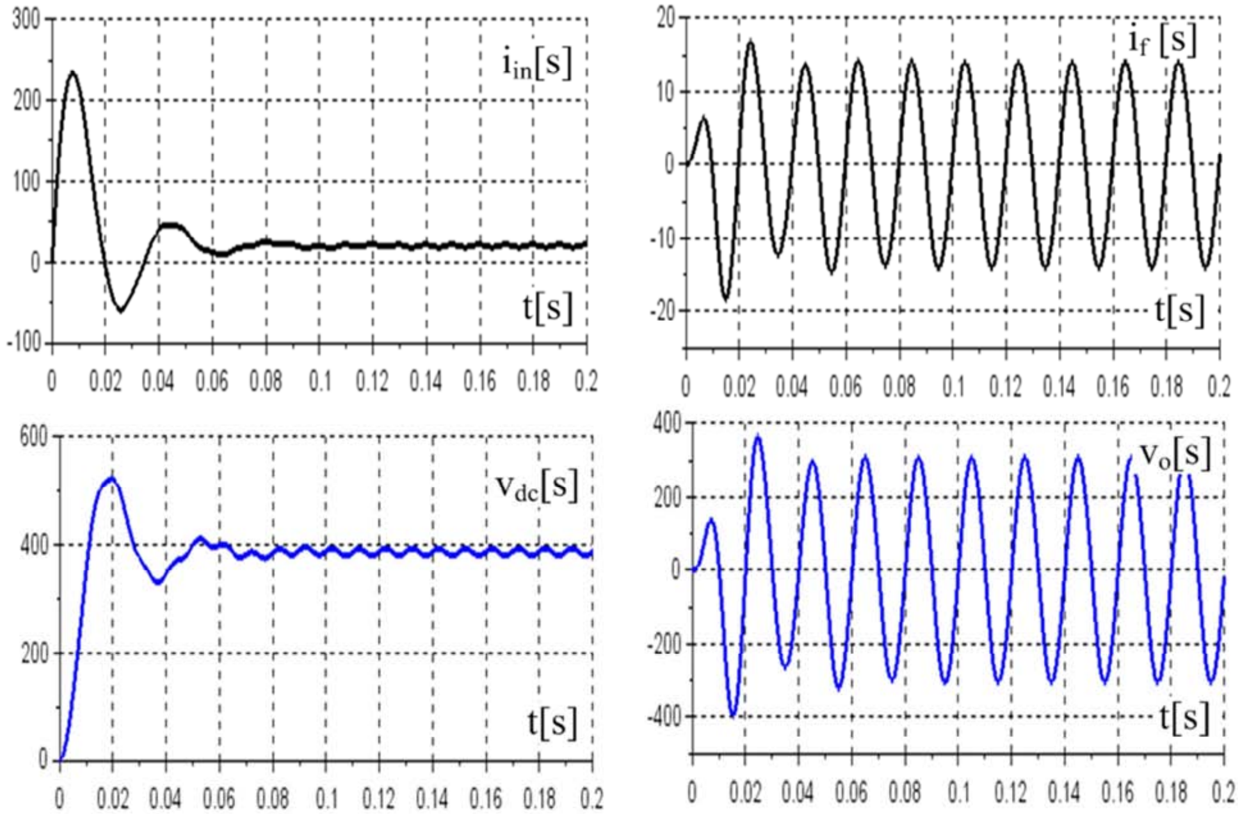

Figure 12. *Simulation Results at R_{dc}=1000Ω and R_o=22Ω.*

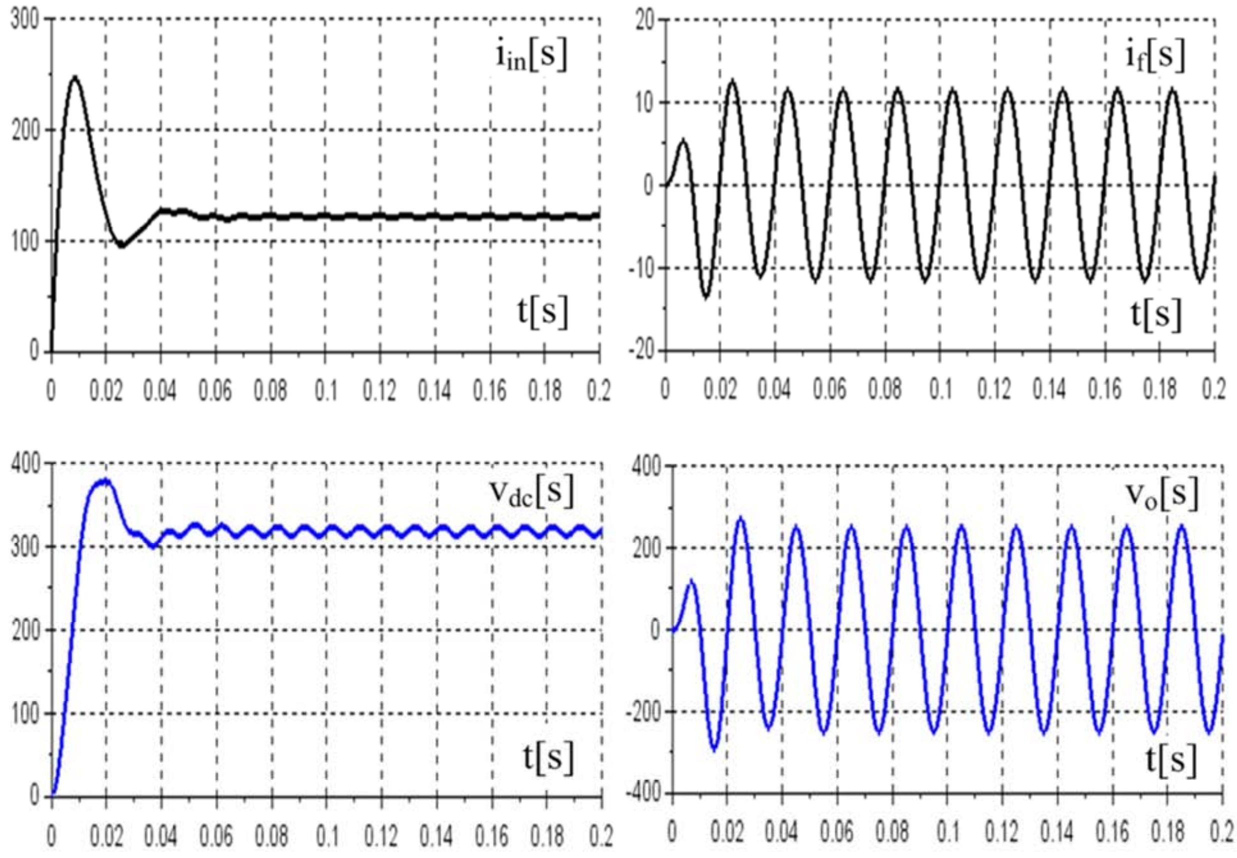

Figure 13. *Simulation Results at R_{dc}=10Ω and R_o=22Ω.*

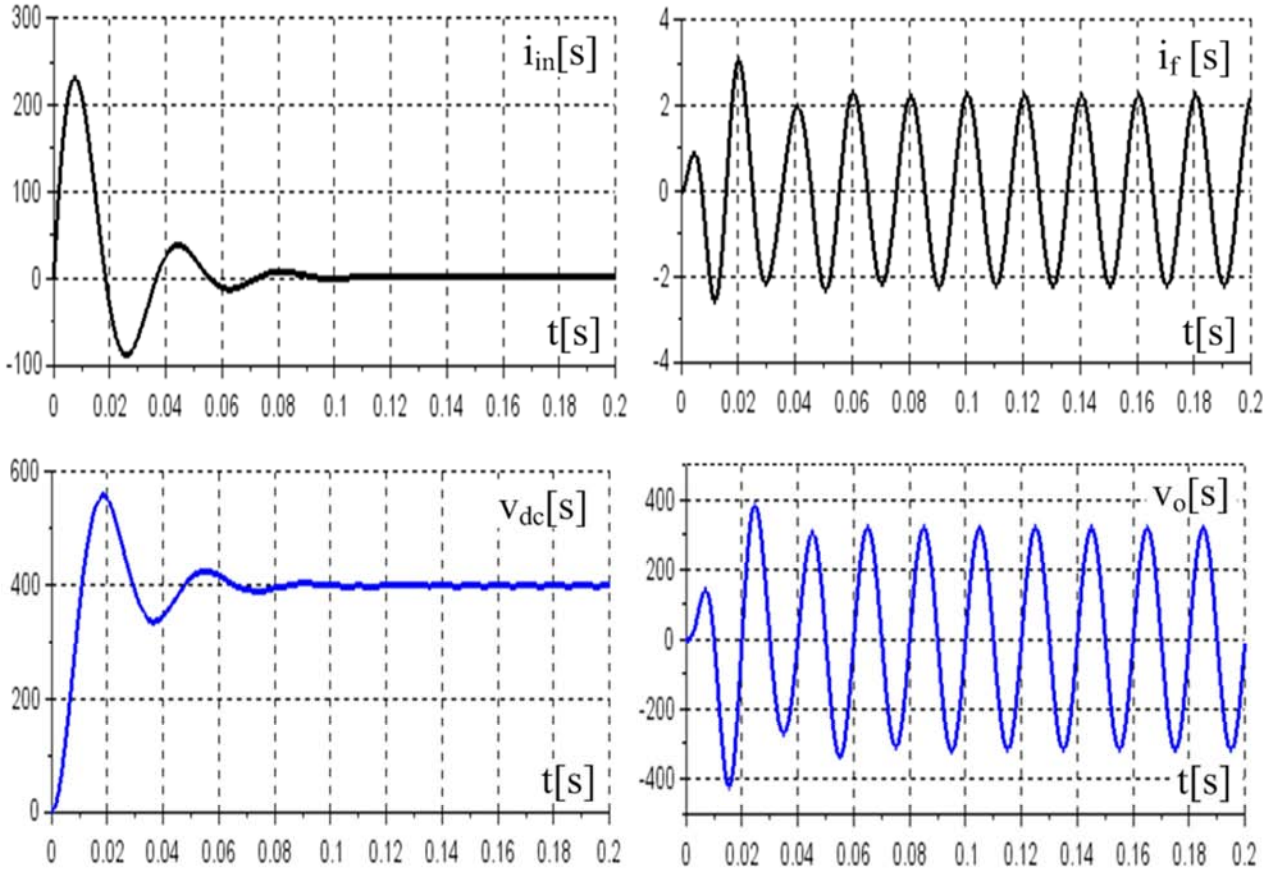

Figure 14. *Simulation Results at R_{dc}=1000Ω and R_o=1000Ω.*

The changes in simulation results of i_{in}, v_{dc}, i_f and v_o can easily be seen in Figure 12-14. Where the value of DC-link resistor decreases, the value of input current dramatically increases with more ripple. The increase in the value of input current damages the devices used in the system. During this condition, the inverter output voltage also decreases. When the value of DC-link resistance is kept constant and load resistance is large nearly opened-circuit, input current value is very small and DC-link voltage changes little. This is due to the existence of DC-link resistor. It protects the sudden increase in DC link voltage when large load resistance changes. The ripple of input current and DC-link voltage are lesser than in simulation-3 as compared with simulation-1. The DC-link voltage fluctuation is more obvious in loaded condition. This is because of power transferred of inverter. The ripple frequency of DC-link voltage fluctuation is twice the output voltage frequency of inverter.

4. Conclusions

In this paper, the configuration of DC-DC boost converter-single phase inverter system has been presented. Mathematical modeling and simulation results of the proposed system have been represented. Simulations of the system have been done by using Scilab/Xcos. The mathematical derivations and analysis have been confirmed with simulation results. As a new user, when using Scilab/Xcos in faces some unfamiliar problems. But it is free and open source but its computations are reliable solutions. The simulation results are validated with the equilibrium values of table II. As future work, it is intended to control DC-link voltage of DC-DC boost converter-inverter system.

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