A novel soft-switched single-phase grid-connected current-source inverter

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Abstract: This paper represents a novel soft-switched grid-connected current-source inverter topology and an efficient control strategy using switching flow graph theory. The switching flow graph technique is a unique diagrammatic model and a convenient strategy for analyzing PWM switching converters. All power switches operate at zero-current-switching (ZCS) turn-off and zero-voltage-switching (ZVS) turn-on. As a result, commutation and switching power losses will be declined; furthermore, higher efficiency is achieved. The proposed topology and control strategy for soft-switched grid-connected inverter is analyzed theoretically and demonstrated experimentally.

Keywords: DC-AC power converters; current-source inverter; soft-switching; grid-connected inverters; switching flow graph theory

1. Introduction

Grid-connected inverters for renewable energy systems are exponentially increasing and developing rapidly. Due to the limited availability of fossil fuels and the increasing global energy demands, the renewable energy resources such as solar energy or wind energy or other types of energy resources are the most promising solutions for these purposes. Most renewable energy resources have a significant drawback, since their produced power is unregulated and discontinuous.
In order to convert discontinuous output power from renewable energy resources to useful grid voltages, grid-connected inverters are used. Various converter topologies and inverter schemes have been proposed for single-phase grid-connected inverters (Botzel & Adams, 2013; Pierquet & Perreault, 2013; Prasanna & Rathore, 2013). Soft-switching techniques are used significantly to decline switching losses of power switches (Hartman Todorovic, Palmo, & Enjeti, 2008; Li & Wolfs, 2007; Rathore, Bhat, & Oruganti, 2008; Sachin Jain & Agarwal, 2008). Switching converters have nonlinear dynamic behavior (Pakdel & Jalilzadeh, 2016; Smedley, 1991). State feedback control structures are mostly used to control nonlinear systems. If a system is very simple, a small signal model of nonlinear systems can be obtained with linear control system theory. However, if the system is more complicated, this approach may not be successful. In this paper a new nonlinear modeling strategy i.e. the switching flow graph method is used to illustrate the nonlinear dynamic properties of grid-connected current-source inverter. This method exploits the state space averaging concept and linear circuit flow graph theory (Pakdel & Jalilzadeh, 2016; Smedley, 1991). A switching converter model is identical to ON-state when the switch is in the ON condition, and it is identical to OFF-state when the switch is in the OFF condition. Switching flow graphs can be used to identify transfer functions between arbitrary points in the system. The switching flow graph can easily be extracted from the switching converter circuit. The signals are illustrated by nodes which are connected with arrows together; moreover the signals flow only in the direction of the arrow. Each arrow has the gain demonstrated next to each arrow. The signal at the input of the node is the sum of all signals entering to the node. Nodes with only outputs are called source nodes and represent the independent variables. However, sink nodes, nodes with only inputs represent the dependent variables. In addition, mixed nodes include both inputs and outputs (Pakdel & Jalilzadeh, 2016). The procedure for implementation of switching flow graph is very easy and straightforward. First, all electrical variables i.e. voltages and currents related to all electrical elements are implemented as nodes in the switching flow graph. Next, the nodes are connected with arrows according to electrical rules between voltage and current of circuit elements. Once, all the nodes are connected conveniently the switching flow graph will be constructed (Pakdel & Jalilzadeh, 2016). The power converter represented in this paper illustrates a novel type of grid-connected current source inverter topology and applies a nonlinear control strategy using switching flow graph theory. The topology reaches high efficiencies with its continuous constant power operation. Moreover, zero-current-switching (ZCS) turn-off and zero-voltage-switching (ZVS) turn-on capabilities are maintained for all power switches.

2. Proposed topology and control strategy

The circuit schematic in Figure 1 depicts proposed grid-connected current-source inverter which consists of a soft-switching resonant converter, a traditional current-source inverter, a filter, and an output transformer; moreover, they are connected in series electrically. This configuration may seem to have massive conduction losses. While, by using zero-current-switching condition for all power switches, the losses associated with this property can be greatly declined (Henze, Martin, & Parsley, 1988; Pakdel & Jalilzadeh, 2016). This paper illustrates that this proposed approach has high efficiency; furthermore, the techniques such as maximum power point tracking (MPPT) in photovoltaic power converts (Esram & Chapman, 2007), grid synchronization (Blaabjerg, Teodorescu, Liserre, & Timbus, 2006), and islanding detection techniques (Ye, Kolwalkar, Zhang, Du, & Walling, 2004) can conveniently be used within this proposed topology and control strategy. The switching flow graph
is applicable to study the dynamic behavior of the proposed soft-switched grid-connected inverter. The operation modes of the proposed soft-switched grid-connected current source inverter are illustrated in Figure 2. In operation mode I \((t = 0 - t_1)\), the power switch \(M_5\) is on and other power switches i.e. \(M_1, M_2, M_3\) and \(M_4\) are off; moreover, the capacitor \(C_8\) is charged through the power switch \(M_5\) and inductor \(L_3\) with the following equation:

\[
L_3 \frac{di}{dt} + \frac{1}{C_8} \int_0^{t_1} i \, dt = V_{dc}
\]  

(1)

In operation mode II \((t = t_1 - t_2)\), all power switches i.e. \(M_1, M_2, M_3, M_4\) and \(M_5\) are off; furthermore, the energy within inductor \(L_3\) is returned to the supply voltage through diodes \(D_{22}\) and \(D_{23}\). In addition, in this mode we have:

\[
L_3 \frac{di}{dt} = -V_{dc}
\]

(2)

In operation mode III \((t = t_2 - t_3)\), the power switches \(M_1, M_4\) and \(M_5\) are on; however, other power switches i.e. \(M_2\) and \(M_3\) are off, and the relation in this mode is according to the following equation:

\[
L_3 \frac{di}{dt} + L_2 \frac{di}{dt} + \frac{1}{C_2} \int_{t_2}^{t_3} i = V_{dc}
\]

(3)

In operation mode IV \((t = t_3 - t_4)\), all power switches are off; moreover, the relation in this mode is written as follows:

\[
L_3 \frac{di}{dt} = -V_{dc}
\]

(4)
In operation mode V \((t = t_4 - t_5)\), the power switches M\(_2\), M\(_3\), and M\(_5\) are on; however, other power switches i.e. M\(_1\) and M\(_4\) are off; moreover, the following equation is obtained:

\[
L_3 \frac{di}{dt} - L_2 \frac{di}{dt} - \frac{1}{C_2} \int_{t_4}^{t_5} i = V_{dc}
\]  

(5)

In operation mode VI \((t = t_5 - t_6)\), the power switches M\(_2\), and M\(_3\) are on; however, other power switches i.e. M\(_1\), M\(_4\), and M\(_5\) are off; furthermore, the following equation can be written:

\[
L_3 \frac{di}{dt} = -V_{dc}
\]  

(6)

Suppose the proposed switching converter operates at the following frequency:

\[
f_s(t) = \frac{1}{T_s(t)}
\]  

(7)

For simplifying the construction of control strategy, we assume switches M\(_1\) and M\(_4\) are ON, and switches M\(_2\) and M\(_3\) are OFF when \(0 < t < T_{on}\); moreover, switches M\(_1\), and M\(_4\) are ON, and switches M\(_2\) and M\(_3\) are OFF when \(T_{on} < t < T_s\). During time interval \(0 < t < T_{on}\), the converter is switched to the ON-state, and during time interval \(T_{on} < t < T_s\), the converter is switched to the OFF-state (Pakdel & Jalilzadeh, 2016). The switching flow graph of the proposed grid-connected inverter is shown in Figure 3. The switching functions \(k\) and \(\bar{k}\) are shown in Figure 4. The effective signal at the \(k\)-branch output is equal to the average value over a switch cycle (Pakdel & Jalilzadeh, 2016):

\[
y(t) = \frac{1}{T_s(t)} \int_{0}^{T_{on}(t)} x(t) \, dt \approx x(t) \frac{1}{T_s(t)} \int_{0}^{T_{on}(t)} \, dt = x(t) \frac{T_{on}(t)}{T_s(t)} = x(t) \, d(t)
\]  

(8)

The same equation can be applied for \(\bar{k}\)-branch. The input signal \(x(t)\) and output signal \(y(t)\), in this case, maintain the following relation (Pakdel & Jalilzadeh, 2016):

\[
y(t) = \frac{1}{T_s(t)} \int_{T_{on}(t)}^{1(t)} x(t) \, dt
\]

\[
\approx x(t) \frac{1}{T_s(t)} \int_{T_{on}(t)}^{1(t)} \, dt
\]

\[
= x(t) \frac{T_{off}(t)}{T_s(t)} = x(t) \, d'(t)
\]  

(9)
where \( d(t) \) and \( d'(t) \) are the averages of the switch functions \( k(t) \) and \( \bar{k}(t) \) respectively, and are the duty ratio of corresponding switches; thus the following equations are valid (Pakdel & Jalilzadeh, 2016):

\[
d(t) = \frac{T_{ON}(t)}{T_S(t)}
\]  

(10)

\[
d'(t) = \frac{T_{OFF}(t)}{T_S(t)}
\]

(11)

\[
d'(t) = 1 - d(t)
\]  

(12)

Therefore, the models for the switching branches are represented with block diagrams as shown in Figure 5.

3. Simulation results
Simulation of proposed topology and control strategy for the grid-connected current-source inverter is depicted in Figure 6. The following parameters and circuit element values have been used in simulation study: \( L_j = L_p = 100 \mu H, C_j = 2.2 \mu F, C_p = 100 nF, C_o = 1 \mu F, f_s = 20 \) kHz. Also, the output transformer has the following parameters: \( L_m \) (magnetizing inductance) = 0.1 H, \( N_p = 50 \) and \( N_s = 500 \). The proposed control strategy is directly extracted from switching flow graph which is shown in Figure 3.

To illustrate and evaluate the proper operation of the proposed control strategy and to investigate soft switching operation of power devices, drain current and voltage across drain and source of power MOSFETs are shown in simulation studies. To reach these purposes a control method using signal flow graph of proposed grid-connected current-source inverter -which is an effective tool for nonlinear behavior evaluation of power switching converters- is constructed as illustrated in Figure 6. The voltage across capacitor \( C_j \) is depicted in Figure 7.
4. Experimental results
To illustrate the performance and appropriate functionality of the proposed grid-connected current-source inverter as described in this paper, a prototype platform has been designed; furthermore, a photograph of the proposed soft-switched inverter can be seen in Figures 8 and 9.

Figure 8. A photograph of the proposed grid-connected inverter.
As shown in Figure 9, the proposed soft-switched grid-connected current source inverter can easily give off light to a compact fluorescent light (CFL) bulb. Measured waveforms of PWM gate signals for power switch driving circuits using a digital oscilloscope is shown in Figure 10. Also, the voltage waveform across capacitor $C_2$ has been illustrated in Figure 11.
The current flowing through switch $M_1$ and $M_5$ as well as their corresponding gate control signals are shown in Figures 12 and 13, respectively. As depicted in mentioned figures, zero-current-switching (ZCS) condition is satisfied for power switches $M_1$ and $M_5$.

Figure 12. ZCS turn-off and ZVS turn-on condition for power switch $M_1$ (yellow: $M_1$ gate signal, turquoise: $M_1$ current).

Figure 13. ZCS turn-off and ZVS turn-on condition for power switch $M_5$ (yellow: $M_5$ gate signal, turquoise: $M_5$ current).

Figure 14. Efficiency comparison of the proposed soft-switched grid-connected inverter and traditional hard-switching PWM inverter.
The efficiency comparison diagram of the proposed soft-switched grid-connected inverter and traditional hard-switching inverter is illustrated in Figure 14. As depicted, the proposed converter has an efficiency of 94% at rated power.

5. Conclusion
The soft-switched grid-connected current-source inverter design and implementation presented in this paper have demonstrated a new topology and control strategy using switching flow graph theory. In addition, the proposed current source inverter maintains soft-switching ZVS turn-on and ZCS turn-off for all power devices; moreover, simulation results using PSIM software have been presented to validate the proposed analysis and design. The presented prototype verifies the functionality and performance of the design and analysis. Experimental results show the accuracy of the analysis and high performance of the proposed topology and control strategy.

Funding
The authors received no direct funding for this research.

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Citation information
Cite this article as: A novel soft-switched single-phase grid-connected current-source inverter, M. Pakdel & S. Jalilzadeh, Cogent Engineering (2017), 4: 1357866.

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Batzel, T. D., & Adams, K. (2013). Variable timing control for grid-connected current-source inverter, M. Pakdel & S. Jalilzadeh, Cogent Engineering (2017), 4: 1357866.

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