A THREE-PHASE BOOST DC-AC CONVERTER

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Abstract

This paper describes a power conversion circuit configuration for three-phase boost dc-ac converter (inverter) based on the dc-dc boost converters. It naturally generates in a single stage three-phase ac voltages whose peak values are greater than the dc input voltage. This property is absent in the conventional three-phase inverter, as it inherently bucks. The proposed three-phase inverter comprises three dc-dc boost converters whose individual output voltages are modulated sinusoidally. Sliding mode controllers are designed to perform a robust control for the three boost dc-dc converters. Computer simulations and spectral analysis demonstrate the feasibility of the proposed three-phase inverter. The inverter is intended to be used in three-phase electric drives and uninterruptible power supply (UPS) systems.

Keywords: Boost converter, three-phase dc-ac converter, sliding mode control

1. Introduction

The generation of ac voltages whose amplitudes are greater than the input source voltage is among the basic prerequisites in many applications such as in three-phase electric drives and uninterruptible power supply (UPS) systems. This requirement is met in the conventional three-phase buck inverter, shown in Figure 1, when a dc- dc boost converter interfaces the input dc voltage source and the buck inverter; or when a line frequency transformer is placed between the inverter and the targeted load. This approach leads to high switching loss, costs, weight and low efficiency, depending on the power and voltage levels involved [1].

To alleviate the above shortcoming, this paper proposes a circuit topology for a three-phase boost inverter based on switch-mode dc-dc boost converters. It naturally generates three-phase ac voltages whose peak values are greater than the dc input voltage in a single stage. The idea of controlling the phase-shift between dc-dc boost converters in order to achieve a dc-ac converter is provided by the theory of phase-modulated inverters,

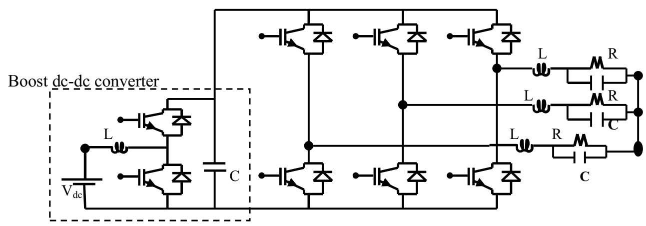

Figure 1: Circuit used to generate 3-phase ac voltages larger than the dc input.

which is presented in [2]. In this three-phase inverter topology, the constituting three boost dc-dc boost converters are driven by three 120 phase-shifted dc-biased sinusoidal references.

Boost converters possess the attributes of a nonlinear system; implying that controllers designed using small-signal linear model approach cannot show significant performance, since the operating points as well as the small-signal model parameters experience large variations, [3] [5]. The constituting three dc-dc boost converters of the proposed three-phase boost inverter should be able to follow independently three reference signals, displaced 120 from one another. This necessitates a nonlinear tracking controller for each of the dc-dc boost converters that can deal with variable operating point conditions. In this paper, sliding mode control approach is used to design three controllers; wherein the output voltages of the dc-dc boost converters faithfully track their respective set dc-biased sinusoidal reference signals.

Details on the analysis and simulations are provided in the subsequent sections; wherein simulations and spectral analyses are carried out for linear and nonlinear load conditions using SIMPLORER simulation package. Simulation results proved the feasibility of the proposed three-phase boost inverter configuration.

2. Configuration of Power Stage of the Proposed Three-Phase Boost Inverter

The power stage of each phase of the three-phase boost inverter is configured on the current bi-directional boost dc-dc converter, and the equivalent circuit of phase A is shown in Figure 2. Block diagram and circuit implementation of the three-phase boost inverter are shown in Figures 3 and 4 respectively.

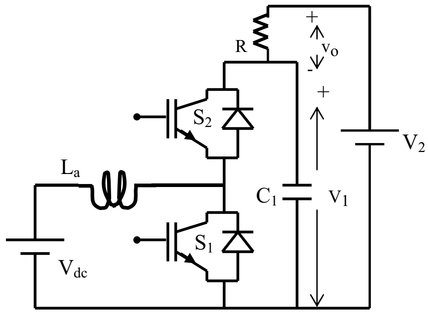

Figure 2: Equivalent circuit of phase A

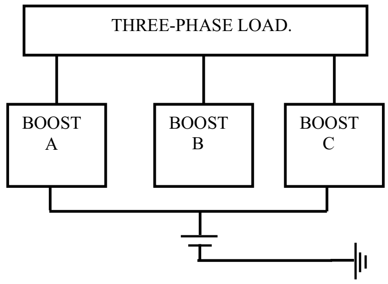

Figure 3: Block diagram of the three-phase boost inverter

In Figure 3, the three dc-dc boost converters produce dc-biased (unipolar) sinusoidal outputs; which are modulated 120 from one another. Consequently, dc-dc boost converter can be modeled with ideal ac and dc voltage sources, which are in series as shown in Figure 5.

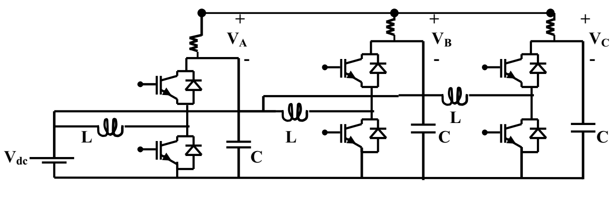

Figure 4: Proposed three-phase boost inverter.

It can be easily shown that:

$$\begin{aligned} V_{AB} &= \sqrt{3}V_m sin(\omega t + 30) \\ V_{BC} &= \sqrt{3}V_m sin(\omega t - 90) \\ V_{CA} &= \sqrt{3}V_m sin(\omega t + 150) \end{aligned} \quad (1)$$

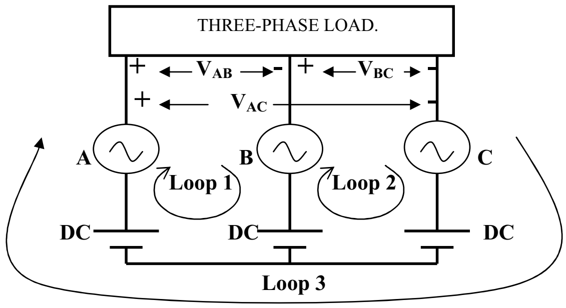

Figure 5: The three dc-dc boost converters model.

Therefore, the line voltages in the load terminals of the proposed three-phase boost inverter are balanced three-phase voltages.

3. SLIDING MODE CONTROLLER

The sliding mode control has been presented as a good alternative to control of switching power converters, [6] [7]. The main advantage of sliding mode control over classical linear control scheme is its insusceptibility to parameter variations that lead to invariant dynamics and steady-state response in the ideal case, [1]. In this paper, a sliding mode controller is designed and applied to control the output voltages of the proposed three-phase boost inverter; wherein the output voltages of the constituting dc-dc boost converters have to track desired sinusoidal dc-biased references.

System description of the proposed inverter topology:

In operation, each of the three current bidirectional dc-dc boost converters works independently. Assuming that all circuit components are ideal and that the converters operate in a continuous conduction mode, equivalent circuit of phase A leg of the three-phase boost inverter, shown in Figure 2, is used in the modeling and control strategy development. Figure 2 works in two topological modes for a period of operation; as shown Figure 6.

The state-space modeling of the equivalent circuit with state variables i_{L1} and V_1 is

$$\begin{aligned} \begin{bmatrix} \frac{di_{L1}}{dt} \\ \frac{di_{L1}}{dt} \end{bmatrix} &= \begin{bmatrix} \frac{R_a}{L_a} & \frac{-1}{L_a} \\ \frac{-1}{C_1} & \frac{-1}{R_1 C_1} \end{bmatrix} \begin{bmatrix} i_{L1} \\ V_1 \end{bmatrix} \\ &+ \begin{bmatrix} \frac{V_1}{L_a} \\ \frac{-i_{L1}}{C_1} \end{bmatrix} \gamma + \begin{bmatrix} \frac{V_{dc}}{L_a} \\ \frac{-V_2}{R_1 C_1} \end{bmatrix} \\ \Longrightarrow \dot{x} &= AX + B\gamma + C \end{aligned} \quad (2)$$

Where γ is the state of the switches given in equation 3; x and $\dot{x}$ are the state vectors and their time derivatives, respectively.

$$\gamma = \begin{Bmatrix} 1 \longrightarrow S_1\text{ON}, & S_2 \text{ OFF} \\ 0 \longrightarrow S_1\text{OFF}, & S_2 \text{ ON} \end{Bmatrix}$$

Sliding mode controller design:

In order to apply sliding mode control to a system, a sliding surface should be defined. The sliding surface consists of a linear combination of the errors of state variables; which are defined as difference between each variable and its reference.

$$S(i_{L,1}, V_1) = K_1\varepsilon_1 + K_2\varepsilon_2 \quad (3)$$

Where K_1 and K_2 are proper gains; ε_1 and ε_2 are error variables given by:

$$\begin{aligned} \varepsilon_1 &= i_{L,1} - i_{L,ref} \\ \varepsilon_2 &= V_1 - V_{ref} \end{aligned} \quad (4)$$

The corresponding control scheme is shown in Figure 7.

State of the switch, γ, is controlled by the hysteresis block, H_1, which maintains the variable $S(i_{L1}, V_1)$ near zero. The existence condition of the control signal can be expressed in the form of equation (5), [1]:

$$\begin{aligned} &\frac{K_1}{L_1}[V_{dc} - V_{ref} - R_a i_{L,ref}] + \frac{K_2}{C_1 R_1}[V_2 - V_{ref} - R_1 i_{L,ref}] > 0 \\ &\frac{K_1}{L_1}[V_{dc} - R_a i_{L,ref}] + \frac{K_2}{C_1 R_1}[V_2 - V_{ref}] < 0 \end{aligned} \quad (5)$$

Moreover, the sufficient condition to steer toward the sliding surface for all initial states is that the coefficient K_1 and K_2 be non-negative, [1].

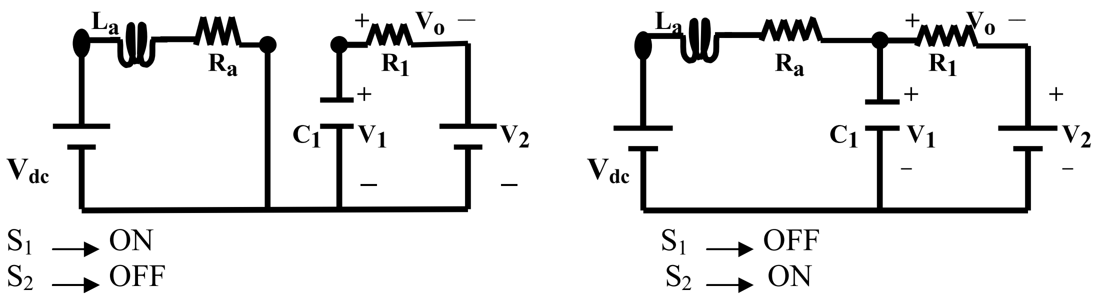

Figure 6: Topological modes of operation of each leg in the three-phase inverter.

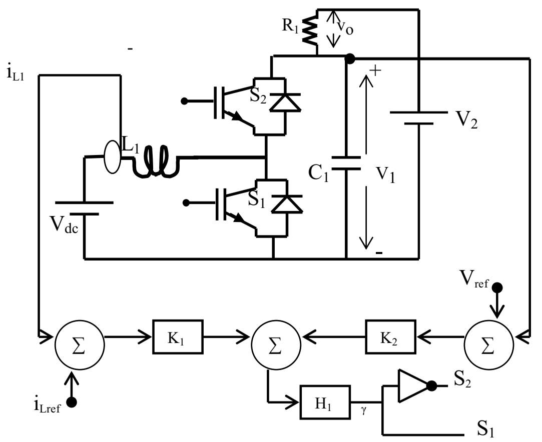

Figure 7: Sliding mode controller scheme.

4. SIMULATION RESULTS

Simulations of the proposed three-phase inverter configuration are carried out under two loading conditions: three-phase 30Ω resistive load and a 2msec three-phase fault applied to the output of the inverter. For the first loading condition, the inductor currents and output voltages of the three dc-dc boost converters are shown in Figures 8 and 9 respectively. The line voltages of the three-phase inverter and the corresponding phase A frequency spectrum are displayed in Figures 10 and 11 respectively. When a 2msec three-phase fault is applied to the output of the proposed inverter, displays of the inductor currents; line voltages of the three-phase inverter and the corresponding phase A frequency spectrum are shown in Figures 12, 13 and 14 respectively. It can be seen that the sliding mode controller resumes the output voltages quickly.

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5. Conclusion

In this paper, a six-switch configuration for a three-phase boost inverter is proposed; this inverter produces, in a single power stage, a three-phase ac voltage with magnitude greater than the input dc voltage. The proposed inverter consists of three reference follower dc-dc boost converters that generate three sinusoidal output voltages. Robust tracking control for these converters is achieved with applied sliding mode controllers. Simulation results and frequency spectral display show the feasibility of the proposed three-phase inverter configuration; as well as controllers operation.

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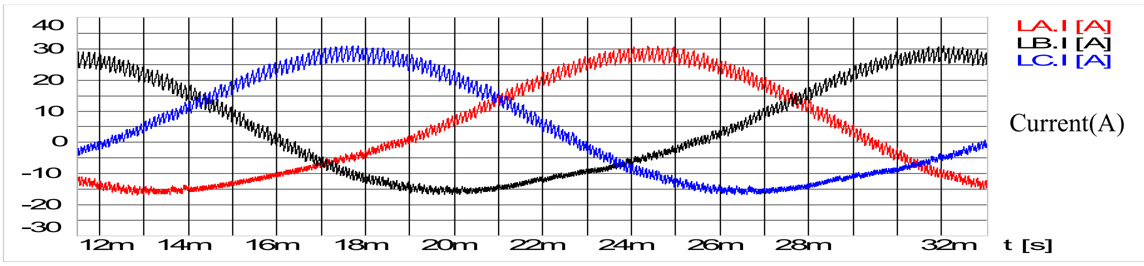

Figure 8: Inductor currents of the three dc-dc boost converters for 3-phase resistive load.

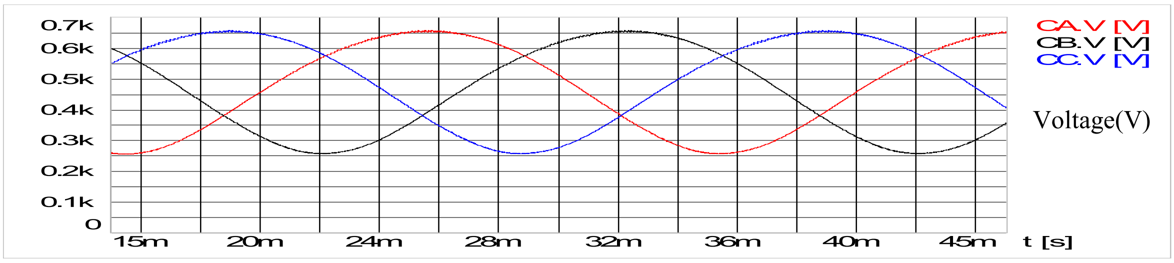

Figure 9: Output voltages of the three dc-dc boost converters.

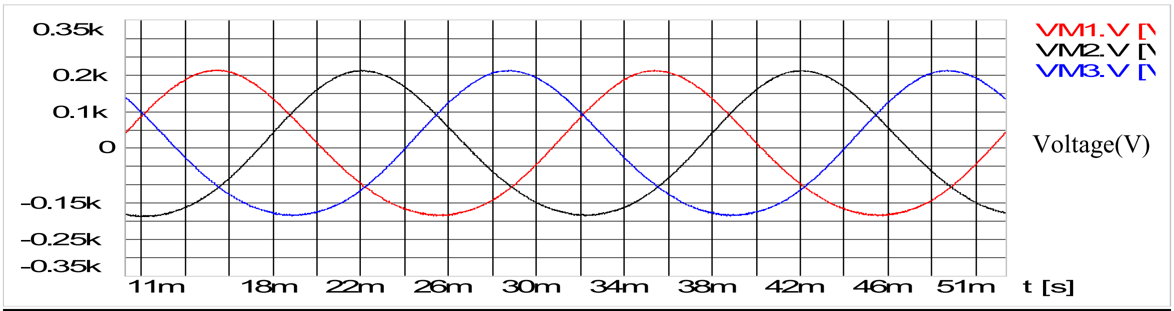

Figure 10: Output line voltages of the proposed three-phase boost inverter.

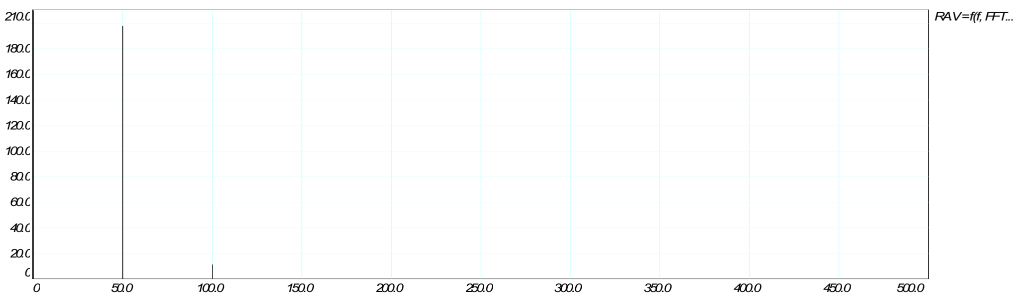

Figure 11: Frequency spectrum of line A voltage.

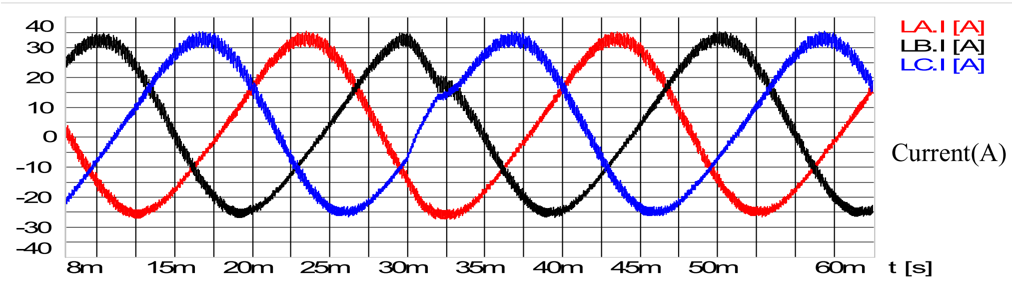

Figure 12: Inductor currents of the three dc-dc boost converters when a 3-phase fault occur.

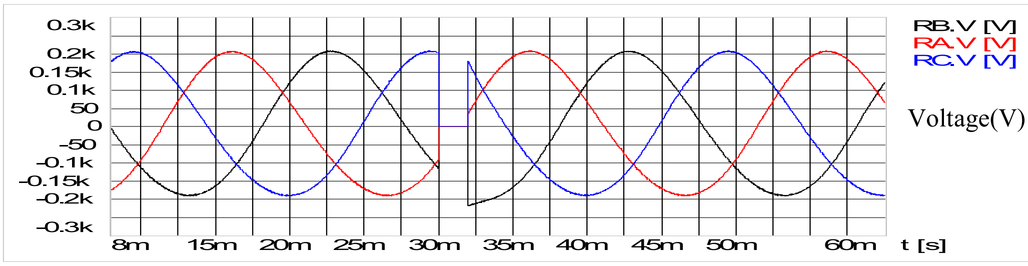

Figure 13: Output line voltages of the proposed three-phase boost inverter for a 3-phase fault.

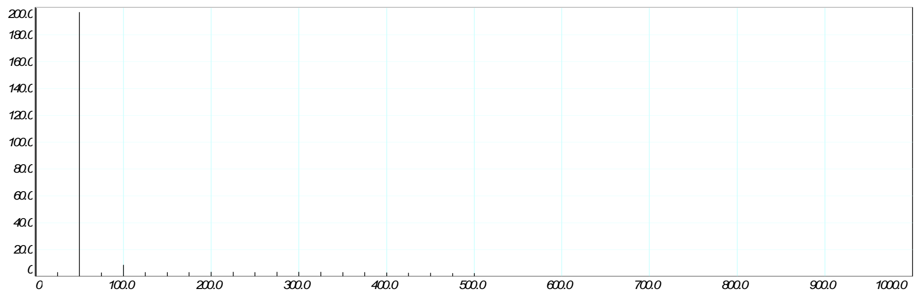

Figure 14: Frequency spectrum of line A voltage when a 3-phase fault occur.

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