Single phase DC/AC bi-directional converter with high-frequency isolation

Beristáin J. José A., Bordonau F. Josep, Busquets M. Sergi, Rocabert S. Joan and Murillo V. Ismael

Abstract— This paper introduces a comprehensive study of a dc/ac inverter with high-frequency isolation and bidirectional power flow capability. The topology is based on a high-frequency dc/ac converter, a high-frequency transformer, an ac/ac converter and a low-pass filter. In this scheme no additional dc-link stages are required. A LQR+I control approach and a modulation strategy for the commutation of the ac/ac converter switches is presented. Simulation and experimental verifications are provided.

Key words— High Frequency Isolation, Bi-directional power flow, soft commutation and renewable energy.

I. INTRODUCTION

Dc/ac inverter systems present a number of applications: induction motor drives, uninterruptible power supplies, photovoltaic energy systems, fuel cell systems, small wind power systems, etc. In many cases, isolation between the input and the output of the inverter is required, because of operating specifications or for security reasons. Significant contributions to conversion systems with HF (High Frequency) isolation can be found in [1]-[5]. The advantage of the idea studied in this paper is to have compact high-frequency isolation without any additional stage (usually a dc stage and a filter is required) and a simple control. The topology is divided in three parts: a high frequency dc/ac converter, a high-frequency transformer and an ac/ac converter.

A comprehensive study of the converter with galvanic isolation is presented in this work. The topology is used in [1],[4],[5]. A LQR+I control method that allows regulating the voltage and the output frequency is presented. The advantages of this structure are that it operates with output power up to 1 kW and has lower complexity (only two conversion stages are used, and without the need of dc-link filter). The LQR+I control provides an effective way to deal with multivariable controls typical in hybrid energy systems.

II. DESCRIPTION AND CIRCUIT CONFIGURATION

The objective of the single-phase HF-Link inverter is to generate a sinusoidal voltage with galvanic isolation and bidirectional power flow capability. The topology used in this work is presented in Fig.1.

A. Inverter description

The single-phase inverter generates a high-frequency ac voltage at the transformer primary. It generates a high-frequency PWM voltage by means of closed-loop bipolar control. Bipolar voltage is needed because of the use of a HF transformer.

Fig. 1 shows the basic configuration of the high-frequency link inverter. The devices S1-S4 form an inverter circuit that feeds the transformer with a high-frequency ac voltage providing isolation between the dc source and the load.

The devices S1-S2, S3-S4, S5-S6, and S7-S8 are bidirectional switches and form an ac/ac converter. When the energy flows from the dc source, the ac/ac converter operates as a positive or negative rectifier. The output filter eliminates the high frequency harmonics and delivers a sinusoidal voltage to the load. The load has been modeled as a resistor, but the results can be easily extended to other applications.

Table I outlines the 4 different dc/ac converter switching states and their associated output voltage presented at primary of the transformer, \( V_{ab} \).

Table II shows the 4 different ac/ac converter switching states and their associated output voltage presented at input of low-pass filter, \( V_{ef} \).
B. Modulation strategy

Different modulations strategies can be derived. In order to show the converter operation, a state vector modulation is chosen. State vector modulation is easily implemented in DSP devices.

Fig. 2 describes how the state vectors are defined in this system. The relative position of the reference vector in the right or left half-plane define if the \( V_1, V_0 \) or the \( V_2 \) state vectors are used, see how there are three different state vector for the converter.

The state vectors are defined as:

\[
V_1 = tr V_i + j0 \\
V_2 = -tr V_i + j0 \\
V_0 = 0 + j0
\]  

where

\( tr \) is the turn ratio of the HF transformer.

The projection of the output reference vector defines the duty-ratio \( d \) of the state vector. The zero vector is applied the rest of the period.

The amplitude \( (m) \) of the output voltage is

\[ m = \sqrt{2} \ V_{o_{rms}} < tr \ V_i \]  

with \( f_o \) frequency

The reference vector is defined by:

\[
V_{ref} = m e^{j\omega t} \begin{cases} 
\theta = \omega t \\
\omega = 2\pi f_o
\end{cases}
\]  

Different state vector modulation strategies can be derived. The nearest two vectors are chosen to show the inverter operation. The duty ratio is defined as follows:

\[ d = d_1 + d_2 \]

If \( Sp=1 \) the nearest two vectors are \( V_1 \) and \( V_0 \) and

\[ d_1 = \frac{m \cos \theta}{tr \ V_i} \quad d_0 = 1 - d_1 \quad \text{and} \quad d_2 = 0 \]  

If \( Sp=0 \) the nearest two vectors are \( V_2 \) and \( V_0 \) and

\[ d_2 = \frac{m \cos \theta}{tr \ V_i} \quad d_0 = 1 - d_2 \quad \text{and} \quad d_1 = 0 \]  

In (3)-(4), the duty-ratios \( d_1 \) and \( d_2 \) define the projection of the reference vector (Fig. 2) for \( Sp=1 \) and \( Sp=0 \) respectively. The duty-ratio \( d_0 \) correspond to the zero vector. The HF inverter on the DC side is commanded by the duty-ratio \( d \).

C. Commutation strategy

The commutation strategy must satisfy some rules:

a. A short circuit of the dc source is not permitted.

b. The current through the inductors cannot be interrupted.

c. A commutation strategy verifying these rules and taking advantage of the possibilities for soft switching is proposed.

The commutation strategy for the dc/ac converter is defined by the modulation strategy. If the modulation is applied to the ac-ac converter, the commutation strategy for the dc-ac converter is
defined as in Fig. 3. If the modulation is applied to the dc-ac converter, the commutation strategy is defined as in Fig. 4.

The commutation strategy for the ac/ac converter is based on a four step technique [8]. The decision about how to commute the ac/ac converter is base on the modulation strategy.

In order to generate the control signals of the ac/ac converter four input signals are required: the inductor current sign \(i_L\), the output voltage sign \(S\), the transformer voltage \(V_{ab}\) and the pulse-width modulation signal associated to the duty-ratio \(d\) indicating the instantaneous value of the output voltage \(S\). The variable \(S\) is the switching function.

Fig. 5 shows one example of transition between \(S1\) ON to \(S1\) OFF.

A PLD implements the commutation sequence of the inverter and the ac/ac converter modulation and control scheme is implemented in a DSP.

Voltage spikes caused by the transformer secondary leakage inductance are clamped and recovered to the dc source by an energy feedback circuit presented in [4].

III. LARGE-SIGNAL AND SMALL-SIGNAL MODELS

Fig. 6 shows the switching model of the converter. The assumptions for the analysis are:

d. Ideal semiconductors.
e. Ideal HF transformer.
f. Ideal dc input source.
g. The losses in the system are neglected.
h. A resistive load is considered.
i. The switching frequency is significantly greater than the output fundamental frequency and the system cut-off frequencies.

The commutation function \(S_x(t)\) is used to define the switching state of each converter switch:

\[
S_x(t) = \begin{cases} 
0, & \text{switch open} \\
1, & \text{switch closed}
\end{cases}
\]

In order to avoid the short-circuit of the input capacitive filter and the open circuit of the primary (in Fig. 6), it is necessary to verify that:

\[
S_{x1} + S_{y1} = 1, \quad S_{y2} + S_{y3} = 1
\]

Additionally to avoid a short circuit in the secondary of the transformer and to avoid opening the output filter inductor, the following restrictions must be fulfilled:

\[
S_{y1} + S_{y1} = 1, \quad S_{y2} + S_{y2} = 1, \quad S_{y3} + S_{y3} = 1, \quad S_{y1} + S_{y2} = 1,
\]

\[
(S_{y1} - S_{y2}) + (S_{y3} - S_{y2}) = 1 \text{ and } (S_{y1} - S_{y2}) + (S_{y1} - S_{y3}) = 1
\]

If the particular case where \(V_{ab}\) is a pure square signal, the expression of the input voltage of the LC filter using switching functions (see Fig. 3) is:

\[
V_{ef} = (S_{x1} - S_{x2}) (S_{x3} - S_{x4}) tr V_i
\]

where \(tr\) is already defined as the turns ratio of the high-frequency isolation transformer.

Analyzing the circuit, the state equations are obtained.

\[
L \frac{di_L}{dt} = -V_o + V_{ef}
\]

\[
C \frac{dV_o}{dt} = i_L - \frac{V_o}{R}
\]

The state-space model of the system is expressed in (11)-(15). It represents the discrete time-variant large-signal model of the dc/ac converter.
Applying the DQ transformation \([7]\), resulting in \((18)\), where \((DQ)\) coordinates is obtained using the average method and variable assumed to be averaged.

If the switching period is \(T_s\), then the moving average of any variable \(x\), called \(\hat{x}\) is defined as:

\[
\hat{x}(t) = \frac{1}{T_s} \int_{t-T_s}^{t} x(\tau) d\tau
\]

The duty cycle is defined as (17):

\[
d = S = \frac{1}{T_s} \int_{t-T_s}^{t} (S_{op} - S_{ip})(S_{oc} - S_{ic}) d\tau
\]

The averaged state-space equation in Direct-Quadrature (DQ) coordinates is obtained using the average method and applying the DQ transformation \([7]\), resulting in \((18)\), where \(\omega = 2\pi f\) and \(f\) is the output voltage frequency. The averaged time-invariant large-signal model is in \((18)\). For notation simplicity, from now on, all the time-domain variables are assumed to be averaged.

\[
\begin{bmatrix}
\frac{d}{dt} \hat{i}_{Ld} \\
\frac{d}{dt} \hat{i}_{Lq} \\
\frac{d}{dt} \hat{v}_{od} \\
\frac{d}{dt} \hat{v}_{oq}
\end{bmatrix} =
\begin{bmatrix}
0 & -\frac{1}{L} & 0 & 0 \\
\omega & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\frac{1}{C} & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\hat{i}_{Ld} \\
\hat{i}_{Lq} \\
\hat{v}_{od} \\
\hat{v}_{oq}
\end{bmatrix} +
\begin{bmatrix}
\frac{trV_i}{L} & 0 \\
0 & \frac{trV_i}{L} \\
0 & 0 \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
\hat{d}_d \\
\hat{d}_q
\end{bmatrix}
\]

IV. CONTROL SCHEME

For closed-loop control, a linear quadratic regulator [LQR+I] in the DQ domain is proposed \([6],[7]\).

LQR+I is used for closed-loop control since it allows obtaining an optimum multivariable controller and since all the state variables that are used for feedback can be easily sensed. The scheme is shown in Fig. 6.

The cost function for the design of the LQR regulator defines a trade-off between the output voltage error, the integral of the output voltage error and the control variables effort in order to avoid saturation. Indeed, three variables have been taken into account in the multivariable cost function.

V. SIMULATION AND EXPERIMENTAL RESULTS

A Simulation was done with the following specifications: output voltage \(V_o = 110 \text{ Vrms}\), input voltage \(V_i = 24 \text{ Vdc}\), output power \(P_{\text{max}} = 160 \text{ W}\), output voltage frequency \(f = 50 \text{ Hz}\), \(f_s=20\text{kHz}\), \(L=2\text{mH}\) and \(C=10\text{uF}\).

The large-signal model in \((14)\) allows simulating the converter. The operation output voltage and inductor current in closed-loop are shown in Figs. 8, 9.

An experimental prototype has been implemented using functional modules. It is shown in Fig. 10. Experiments have been performed in order to verify the characteristics of the proposed circuit.
The experimental conditions are:

- $V_i = 24\text{V}_{\text{dc}}$,
- $V_o = 110\text{V}_{\text{rms}}$,
- $P_{\text{omax}} = 160 \text{ W}$,
- $f = 50\text{Hz}$,
- $f_s = 20\text{kHz}$,
- $t_r = 8.33$,
- $L = 2\text{mH}$, and
- $C = 10\mu\text{F}$.

Fig. 11 includes the output voltage and inductor current during the start-up of the converter. The results show that the response is very fast.

Figs. 12 and 13 show the evolution of the output voltage and the inductor current during a load transient. The results show that the response is very fast and there is no overshoot.
VI. CONCLUSIONS

This paper presents a comprehensive study of a dc/ac inverter with high-frequency isolation and bidirectional power flow capability. The benefits of this topology are: reduced number of conversion stages, no dc-link required, and bidirectional operation capability. The LQR+I control approach for a dc/ac topology with high-frequency isolation is presented. The LQR+I is an effective way to implement a multivariable control. Simulations of the proposed control method have proven its good performance in terms of response time and overshoot. The experimental results correlate perfectly with the model and its performance with small overshoot and very low steady-state error. These results show the benefits of the LQR+I control technique.

REFERENCES


