A Simplified DC-AC Converter with Feedback Current Control Model for PV Grid Connected System under Islanding Phenomena

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Abstract: This paper presents the proposed mathematical model of a dc-ac full-bridge switching converter with a feedback control for a PV grid connected system under islanding phenomena, employing piecewise functions. Each piecewise function ON and OFF interval is derived by using a state-space equation and solved by the Laplace Transform technique. The solution of whole time simulation can be calculated by iterative computation, using MATLAB/SIMULINK as the tool. Islanding phenomena on a PV grid connected system are experimented under 3 different resistive loads: 125%, 100% and 25% of inverter output and RLC when the grid system is disconnected.
The results are compared with the experiments, PSpice and the proposed method which show good agreement with them. In addition, it was found that the proposed model consumed much less computation time than PSpice and did not encounter any convergence problem.

**Keywords:** Islanding, dc-ac Full-Bridge Switching Converter, PV Grid Connected, Piecewise Function, PSpice and Laplace transformation.

**Nomenclature**

- CT = current transformer
- $L_f$ = inductive filter
- $C_f$ = capacitive filter
- $R_L$ = resistive load
- $C_L$ = capacitive load
- $L_L$ = inductive load
- $R_{1,2}$ = resistive for PI controller
- $R_{ref}$ = resistive for convert from current to voltage form
- $C$ = capacitive for PI controller
- $v_e$ = error voltage
- $V_p$ = peak amplitude of saw tooth signal
- $f_s$ = switching frequency in hertz
- $i_{Lf}$ = current flowing through the filter inductor
- $i_{ref}$ = current reference
- $v_O$ = output voltage
1. Introduction

In PV grid-connected systems, one of the major functions of an inverter is to sense the islanding condition and stop its operation. Islanding can occur if a portion of the grid system, which consists of generation and load, is isolated and continues to operate. During the occurrence of islanding, the grid side cannot control voltage and frequency in the island area, thus creating the possibility of equipment damage. Many control schemes have been devised to reliably sense islanding, such as conventional passive detection. Recent studies have focused on which factors influence islanding detection performance. For example, Kobayashi et al. [1] studied the optimum islanding prevention methods. They found that a ratio of PV penetration with distribution line capacity affected the accuracy of islanding detection. The greater the ratio, the greater the combination of islanding detection...
methods required. Gonzalez et al. [2] studied the impact of different multiple inverters and demonstrated that they would have difficulty identifying the absence of the grid.

Some previous work focused on the modeling and analysis of different switching converter topologies. With regarding to averaging approaches, a large-signal analysis was studied by several researchers [3-7]. Guinjoan et al. [8] proposed discrete-time approaches for two conduction modes including a stability graph study for the design of dc-dc switching regulators in large-signal applications. For steady-state analysis of a switching dc-dc converter, a general discrete formulation was proposed by Poveda and Martinez [9]. This method provided both sample and average values of state vector in two conduction modes. In addition, a generic and compact formulation of a unified state-space model which was described as a hybrid continuous-discrete model, or full discrete-time, was reported by Burdio and Martinez [10]. De Vicuna et al. [11] introduced a computer program based on a general nonlinear discrete formulation for large-signal analysis with two conduction modes. Both time-domain and state-trajectories simulation under different control strategies were provided by this program.

In this paper, the piecewise functions technique for a dc-ac full bridge switching converter and feedback control applied to a PV grid connected system under islanding phenomena is presented. With the switching converter in continuous mode, a general state-space model in each switching state is obtained. The solution of a state-space model is readily found by applying Laplace transform for each

piecewise function at ON and OFF intervals. Due to its cyclical operation in each stage of the switching converter, a piecewise function at ON and OFF intervals can be expressed in the solution of the present piecewise function is used as the initial value for subsequent piecewise functions. Computation can be achieved by an iteration method. This proposed model is used to analyze the dynamic response due to various load types (resistive load, R and the combination of resistive, inductive and capacitive in parallel connection, RLC) when the grid system is disconnected. In order to simplify the parameters for modeling, some basic assumptions have been neglected, such as the exclusion of parasitic elements effects (equivalent series inductance, ESL, of inductor winding resistance and core loss or equivalent series resistance, ESR, of filter capacitors). A current feedback control method is included for controlling the inductor current flowing through a filter. An experimental set-up and PSpice are undertaken to validate the proposed model.

2. The operation of PV grid-connected system

A general block diagram for a PV grid connected system with feedback current control and two PWM blocks (1) PWM (MPPT) for maximum power generation and (2) PWM (dc-ac) for dc-ac converter in current mode are shown in Fig.1. The main components are: (a) PV Panel generating direct current from sunlight, (b) dc-dc with isolated transformer designed for achieving the maximum power with PWM control produced by a simple method, namely Perturbation and Observation technique (P&O) \((dP / dv = 0)\) where P represents
the PV output power and $V$ the PV voltage; (c) dc-ac full bridge converter is used to generate ac waveform from dc signal with current-mode PWM scheme; (d) switching filter is used to eliminate the unwanted signal and (e) other parts, for example Phase Lock Loop (PLL) and load in parallel connection.

![Block Diagram of PV Grid-Connected System](image)

**Figure 1.** Block Diagram of PV Grid-Connected System.

The direct current and voltage from the PV panel are measured and formed as input for the MPPT block to generate a PWM signal for the dc-dc converter in order to operate at maximum power generation. The current amplitude at maximum operation from the MPPT block is multiplied with in-phase sinusoidal unit-vector waveform which is produced from the Phase Locked Loop (PLL) block. The result is designated as current reference signal. At the output of dc-ac converter stage, the actual current from the inductor current flowing through the filter is sensed and compared with the current reference, then the error is compensated for with the PI controller. This stage is called “error amplification”. Finally, this
output is compared with the saw-tooth signal to generate a PWM signal for the gate drive of dc-ac converter in the comparison stage.

3. Proposed model of the dc-ac full bridge switching converter

During one switching cycle of a switching converter, the operation consists of each piecewise function at ON and OFF intervals of time and then they repeat themselves periodically. Thus, it is straightforward to model this kind of operation by splitting the system into several sub-system topologies corresponding to time sub-intervals as piecewise functions. For the solution at a particular time, this consists of taking an initial value at a specific piecewise interval and solving it, then continuing to solve the next piecewise interval with the previous solution as the initial value. The main concept of the proposed model involves the substitution of the solution of the previous piecewise function as the initial condition of the next piecewise function. The overall view of the proposed model, dc-ac converter and feedback current control, are depicted in the flow chart shown in Fig. 2.

To develop a model in this study, a dc-ac full-bridge switching converter is used, with a feedback current control scheme consisting mainly of power stage and control loop stage as shown in Fig. 3. A pair of switching converters, S1-S3 and S2-S4, are operated alternately each half cycle of a switching period with its duty cycle
The duty cycle \( d \) is the ratio of the ON time \( (t_{on}) \) to the switching period \( (T) \), 
\[ d = \frac{t_{on}}{T} = t_{on}f_s \] 
as plotted in Fig. 4.

Figure 2. Flow chart for proposed model.

Figure 3. A dc-ac full-bridge switching converter with current control scheme.
As an initial step, the state equations which describe the individual switched circuit of a multi-topological circuit are noted. In this study, the inverter operates in continuous conduction mode. Thus, two switched circuits can be identified, one for the ‘switch-on’ interval (S1 and S3 ON) and the other for the ‘switch-off’ interval (S1 and S3 OFF). Two state equations can be derived by applying Kirchoff’s voltage and current laws. The state equation forms are written as [12-14]:

For $d$ interval

$$\dot{x} = A_1 x + B_1 v$$ \hspace{1cm} (1)

The solution in the general form for time domain is

$$x(t_n') = f(x(t_n), d) .$$

and $1-d$ interval

$$\dot{x} = A_2 x + B_2 v$$ \hspace{1cm} (2)

Similarly, the solution is $x(t_{n+1}) = f(x(t_n'), d)$ .

Where $x =$ state variable vector

$A =$ state coefficient matrix
\( \mathbf{v} = \) source vector

\( \mathbf{B} = \) source coefficient matrix

Therefore, the solution of one switching period is expressed with the combination of \( d \)-interval in Eq. (1) and \( 1-d \) interval in Eq. (2). The result is:

\[
x(t_{n+1}) = \mathbf{f}(x(t_n), d)
\]  

(3)

To analyze the behavior of a dc-ac full-bridge switching converter with a PV grid-connected system under islanding phenomena, we have to split this circuit into three sections, for power stage: (a) resistive load, \( R \) and (b) a combination of resistive, inductive and capacitive load, \( RLC \) and control stage and (c) feedback current control.

(a) Power stage for resistive load

The power stage is illustrated in Fig. 3 where the resistor is connected in parallel as load. The state equation of each switched circuit (ON and OFF interval) is then described. Inductor current flow through a filter \( (i_{L_f}) \) and load voltage \( (v_o) \) are considered as state variables in this study.

For switch \((S1, S3)\)-on interval \( t_n \leq t < t_n' \), two state equations in matrix form are

\[
\begin{bmatrix}
\frac{di_{L_f}}{dt} \\
\frac{dv_o}{dt} \\
\end{bmatrix} = \begin{bmatrix}
0 & -1 \\
\frac{1}{L_f} & -1 \\
\frac{1}{C_f} & \frac{1}{R_L C_f} \\
\end{bmatrix} \begin{bmatrix} i_{L_f} \\
v_o \\
\end{bmatrix} + \begin{bmatrix}
\frac{1}{L_f} \\
0 \\
\end{bmatrix} [v_s]
\]  

(4)
For switch (S1, S3)-off interval \( t_n^0 \leq t < t_{n+1} \), it produces two state equations as follows:

\[
\frac{di_Lf}{dt} = \begin{bmatrix}
0 & -\frac{1}{L_f} \\
\frac{1}{C_f} & -\frac{1}{R_L C_f}
\end{bmatrix} \begin{bmatrix} i_Lf \\ v_o \end{bmatrix} + \begin{bmatrix} -\frac{1}{L_f} \\ 0 \end{bmatrix} [v_s] \tag{5}
\]

The state-space equation of the switch-on and-off interval is solved by using the Laplace transformation, then the partial fraction technique is applied taking the inverse Laplace transform. The solution is

\[
i_{Lf}(t) = K_{1R-on} + \frac{K_{3R-on}}{\omega} - \frac{K_{2R-on} \sigma}{\omega} e^{-\sigma(t-t_n)} \sin \omega(t-t_n)
+ K_{2R-on} e^{-\sigma(t-t_n)} \cos \omega(t-t_n) \tag{6}
\]

\[
v_o(t) = K_{4R-on} + \frac{K_{6R-on}}{\omega} - \frac{K_{5R-on} \sigma}{\omega} e^{-\sigma(t-t_n)} \sin \omega(t-t_n)
+ K_{5R-on} e^{-\sigma(t-t_n)} \cos \omega(t-t_n) \tag{7}
\]

where \( \sigma = \frac{1}{2C_f R_L}, \omega = \sqrt{\frac{1}{L_f C_f} - \sigma^2} \)

\[
K_{1R-on} = \frac{v_s}{R_L}, \quad K_{2R-on} = i_{Lf}(t_n) - \frac{v_s}{R_L}
\]

\[
K_{3R-on} = \frac{i_{Lf}(t_n)}{R_L C_f} - \frac{v_o(t_n)}{L_f} + \frac{v_s}{R_L} \left( \frac{R_L}{L_f} - 2\sigma \right), \quad K_{4R-on} = v_s
\]

\[
K_{5R-on} = v_o(t_n) - v_s, \quad K_{6R-on} = \frac{i_{Lf}(t_n)}{C_f} - 2v_s \sigma
\]

Following this, inserting \( t = t_n^0 \) and \( t_n^0 - t_n = dT = t_{on} \) in switch-on interval into Eq. (6) and (7), we can obtain the value of \( i_{Lf} \) and \( v_o \) at the end of switch-on interval as expressed:
\[ i_{L_f}(t_n') = K_{1R-on} + \frac{K_{3R-on} - K_{2R-on} \sigma}{\omega} e^{-\sigma(dT)} \sin \omega(dT). \]

\[ + K_{2R-on} e^{-\sigma(dT)} \cos \omega(dT) \]  
(8)

\[ v_o(t_n') = K_{4R-on} + \frac{K_{6R-on} - K_{5R-on} \sigma}{\omega} e^{-\sigma(dT)} \sin \omega(dT) \]

\[ + K_{5R-on} e^{-\sigma(dT)} \cos \omega(dT) \]  
(9)

Since K-values are a function of \( x(t_n) \), we can write the general form of the difference equation in the switch-on interval, which involves the value of \( x(t_n) \) as initial value and \( d \). The equation is:

\[ x(t_n') = f(x(t_n), d) \]

(10)

For switch (S1, S3)-off interval \( t_n' \leq t < t_{n+1} \), in this interval, \( x(t_n') \) value, which is the solution value of the previous interval or switch-on interval, is determined as the initial value. Similar to the switch-on interval, the expression of the solution from Eq. (5) can be obtained:

\[ i_{L_f}(t) = K_{1R-off} + \frac{K_{3R-off} - K_{2R-off} \sigma}{\omega} e^{-\sigma(t-t_n')} \sin \omega(t-t_n') \]

\[ + K_{2R-off} e^{-\sigma(t-t_n')} \cos \omega(t-t_n') \]  
(11)

\[ v_o(t) = K_{4R-off} + \frac{K_{6R-off} - K_{5R-off} \sigma}{\omega} e^{-\sigma(t-t_n')} \sin \omega(t-t_n') \]

\[ + K_{5R-off} e^{-\sigma(t-t_n')} \cos \omega(t-t_n') \]  
(12)

where

\[ K_{1R-off} = -\frac{v_s}{R_L}, \quad K_{2R-off} = i_{L_f}(t_n') - \frac{v_s}{R_L} \]

\[ K_{3R-off} = \frac{i_{L_f}(t_n')}{R_L C_f} - \frac{v_o(t_n')}{L_f} + \frac{v_s}{R_L} (2\sigma - \frac{R_L}{L_f}), \quad K_{4R-off} = -v_s \]

\[ K_{5R-off} = v_o(t_n') + v_s, \quad K_{6R-off} = \frac{i_{Lf}(t_n')}{C_f} + 2v_s\sigma \]

In this interval, we substitute \( t = t_{n+1} \) then, \( t_{n+1} - t_n' = (1 - d)T = t_{off} \) into Eq. (11) and (12), then we can obtain the value of \( i_{Lf} \) and \( v_o \) at the end of switch-off interval as:

\[
i_{Lf}(t_{n+1}) = K_{1R-off} + \frac{K_{3R-off} - K_{2R-off}\sigma}{\omega} e^{-\sigma(1-d)T} \sin \omega(1-d)T \cdot e^{-\sigma(1-d)T} \cos \omega(1-d)T
\]

\[ v_o(t_{n+1}) = K_{4R-off} + \frac{K_{6R-off} - K_{5R-off}\sigma}{\omega} e^{-\sigma(1-d)T} \sin \omega(1-d)T \cdot e^{-\sigma(1-d)T} \cos \omega(1-d)T \]

From Eq. (13) and (14), the general form of the difference equation in the switch-off interval can be expressed

\[ x(t_{n+1}) = f(x(t_n'), d) \]  

To determine the general form of difference equation in one switching period, the \( x(t_n') \) value of switch-on interval and \( x(t_{n+1}) \) value of switch-off interval are combined by substituting \( x(t_n') \) in Eq. (15) with Eq. (10). Thus, the general form of the difference equation is:

\[ x(t_{n+1}) = f(x(t_n), d) \]

(b) Power stage for RLC loads

For RLC loads, the combination of R, L and C are connected in parallel as load, as in Fig. 3. To simplify the state equation, a filter
capacitor \( (C_f) \) and a load capacitor \( (C_L) \) are summed up and called \( C_{new} \). An inductor current flow through a filter \( (i_{Lf}) \), inductor current flow through load \( (i_{LL}) \) and load voltage \( (v_o) \) are chosen as state variables. The state equations of d and 1-d interval are expressed respectively:

\[
\begin{bmatrix}
\frac{di_{Lf}}{dt} \\
\frac{di_{LL}}{dt} \\
\frac{dv_{o}}{dt}
\end{bmatrix} =
\begin{bmatrix}
0 & 0 & \frac{-1}{L_f} \\
0 & \frac{-1}{L_L} & 0 \\
\frac{1}{C_{new}} & \frac{-1}{R_L C_{new}} & 0
\end{bmatrix}
\begin{bmatrix}
i_{Lf} \\
i_{LL} \\
v_o
\end{bmatrix} +
\begin{bmatrix}
\frac{1}{L_f} \\
0 \\
0
\end{bmatrix}
\begin{bmatrix}
v_s
\end{bmatrix}
\]

(17)

\[
\begin{bmatrix}
\frac{di_{Lf}}{dt} \\
\frac{di_{LL}}{dt} \\
\frac{dv_{o}}{dt}
\end{bmatrix} =
\begin{bmatrix}
0 & 0 & \frac{-1}{L_f} \\
0 & \frac{-1}{L_L} & 0 \\
\frac{1}{C_{new}} & \frac{-1}{R_L C_{new}} & 0
\end{bmatrix}
\begin{bmatrix}
i_{Lf} \\
i_{LL} \\
v_o
\end{bmatrix} +
\begin{bmatrix}
-1 \\
0 \\
0
\end{bmatrix}
\begin{bmatrix}
v_s
\end{bmatrix}
\]

(18)

Similar to R load, Eq. (17) and (18) are solved by taking the Laplace transformation and re-arranging it to a partial fraction, then taking the inverse Laplace. The solution of S1 and S3 ON, d interval is:

\[
i_{Lf} \left( t' \right) = K_{1RLC-on} + K_{2RLC-on}dT
\]

\[
+ \frac{K_{4RLC-on} - K_{3RLC-on}\sigma_1}{\omega_{RLC}} e^{-\sigma_1(dT)} \sin \omega_{RLC}(dT)
\]

\[
+ K_{3RLC-on} e^{-\sigma_1(dT)} \cos \omega_{RLC}(dT)
\]

(19)

\[
i_{LL} \left( t' \right) = K_{5RLC-on} + K_{6RLC-on}dT
\]

\[
+ \frac{K_{8RLC-on} - K_{7RLC-on}\sigma_1}{\omega_{RLC}} e^{-\sigma_1(dT)} \sin \omega_{RLC}(dT)
\]

\[
+ K_{7RLC-on} e^{-\sigma_1(dT)} \cos \omega_{RLC}(dT)
\]

(20)
\[ v_o(t_n') = K_{9RLC-on} + \frac{K_{11RLC-on} - K_{10RLC-on} \sigma_1}{\omega_{RLC}} e^{-\sigma_1(dT)} \sin \omega(dT) \]
\[ + K_{10RLC-on} e^{-\sigma_1(dT)} \cos \omega_{RLC}(dT) \]  
\[ (21) \]

Where \[ \sigma_1 = \frac{1}{2C_{new}R_L}, \quad \omega_{RLC} = \sqrt{\frac{L_f + L_L}{L_fL_fC_{new} - \sigma_1^2}} \]

\[ K_{1RLC-on} = \frac{L_fL_LC_{new}}{L_f + L_L}(i_{Lf}(t_n) + \frac{v_s}{R_LC_{new}L_f} + \frac{i_{LL}(t_n)}{C_{new}L_f} - \frac{K_{2RLC-on}}{R_LC_{new}}) \]

\[ K_{2RLC-on} = \frac{v_s}{L_f + L_L} \]

\[ K_{3RLC-on} = i_{Lf}(t_n) - K_{1RLC-on} \]

\[ K_{4RLC-on} = \frac{i_{Lf}(t_n)}{R_LC_{new}} + \frac{v_s}{L_f} - \frac{K_{1RLC-on}}{R_LC_{new}} + K_{2RLC-on} \]

\[ K_{5RLC-on} = \frac{L_fL_LC_{new}}{L_f + L_L}(i_{Lf}(t_n) + \frac{i_{LL}(t_n)}{C_{new}L_f} - \frac{K_{6RLC-on}}{R_LC_{new}}) \]

\[ K_{6RLC-on} = \frac{v_s}{L_f + L_L} \]

\[ K_{7RLC-on} = i_{LL}(t_n) - K_{5RLC-on} \]

\[ K_{8RLC-on} = \frac{i_{LL}(t_n)}{R_LC_{new}} + \frac{v_o(t_n)}{L_L} - \frac{K_{5RLC-on}}{R_LC_{new}} - K_{6RLC-on} \]

\[ K_{9RLC-on} = \frac{v_sL_L}{L_f + L_L} \]

\[ K_{10RLC-on} = v_o(t_n) - K_{9RLC-on} \]

\[ K_{11RLC-on} = \frac{i_{LL}(t_n) - i_{Lf}(t_n)}{C_{new}} - \frac{K_{9RLC-on}}{R_LC_{new}} \]

From Eq. (19), (20) and (21) we can write the general form of the difference equation in the switch-on interval as follows:
The solution of $S1$ and $S3$ OFF, $1-d$ interval is:

$$i_{Lf}(t_{n+1}) = K_{1RLC-off} + K_{2RLC-off} (1-d)T$$

$$+ \frac{K_{4RLC-off} - K_{3RLC-off} \sigma_1}{\omega_{RLC}} e^{-\sigma_1 (1-d)T} \sin \omega_{RLC} (1-d)T$$

$$+ K_{3RLC-off} e^{-\sigma_1 (1-d)T} \cos \omega_{RLC} (1-d)T$$  \hspace{1cm} (23)$$

$$i_{LL}(t_{n+1}) = K_{5RLC-off} + K_{6RLC-off} (1-d)T$$

$$+ \frac{K_{8RLC-off} - K_{7RLC-off} \sigma_1}{\omega_{RLC}} e^{-\sigma_1 (1-d)T} \sin \omega_{RLC} (1-d)T$$

$$+ K_{7RLC-off} e^{-\sigma_1 (1-d)T} \cos \omega_{RLC} (1-d)T$$  \hspace{1cm} (24)$$

$$v_o(t_{n+1}) = K_{9RLC-off} + \frac{K_{11RLC-off} - K_{10RLC-off} \sigma_1}{\omega_{RLC}} e^{-\sigma_1 (1-d)T} \sin \omega_{RLC} (1-d)T$$

$$+ K_{10RLC-off} e^{-\sigma_1 (1-d)T} \cos \omega_{RLC} (1-d)T$$  \hspace{1cm} (25)$$

where

$$K_{1RLC-off} = \left(\frac{L_f}{L_f + L_L}\right) \left(\frac{i_{Lf}(t_{n}')}{C_{new}L_L} - \frac{v_s}{R_LC_{new}L_f} + \frac{i_{LL}(t_{n}')}{C_{new}L_f} - \frac{K_{2RLC-off}}{R_LC_{new}}\right)$$

$$K_{2RLC-off} = \frac{-v_s}{L_f + L_L}$$

$$K_{3RLC-off} = i_{Lf}(t_{n}') - K_{1RLC-off}$$

$$K_{4RLC-off} = \frac{i_{Lf}(t_{n}')}{{R_LC}_{new}} \frac{v_s}{L_f} - \frac{v_o(t_{n}')}{{L_f}} - \frac{K_{1RLC-off}}{R_LC_{new}} + K_{2RLC-off}$$

$$K_{5RLC-off} = \left(\frac{L_f}{L_f + L_L}\right) \left(\frac{i_{Lf}(t_{n}')}{C_{new}L_L} + \frac{i_{LL}(t_{n}')}{C_{new}L_f} - \frac{K_{6RLC-off}}{R_LC_{new}}\right)$$

$$K_{6RLC-off} = \frac{-v_s}{L_f + L_L}$$
From Eq. (23), (24) and (25), we can write the general form of the difference equation in the switch-off interval. It is:

\[ x(t_{n+1}) = f(x(t_n), d) \]  \hspace{1cm} (26)

To obtain the general form of difference equation in one switching period, the \( x(t_n') \) value of switch-on interval and \( x(t_{n+1}) \) value of switch-off interval are combined by substituting \( x(t_n') \) into Eq. (26) with Eq. (22). Thus, the general form of difference equation is

\[ x(t_{n+1}) = f(x(t_n), d) \] \hspace{1cm} (27)

(c) Feedback current control stage

In this study, a feedback current control technique is implemented by controlling inductor currents flowing through filters corresponding to a reference voltage. As a result, the output current is in phase with grid voltages and produces a good power factor. As shown in Fig. 3, the lower part is a feedback current control loop stage consisting of sensing of inductor current flowing through a filter \( i_{L_f} \) and...
converted to voltage ($v_{ilf}$) form by multiplying with a resistor, then this voltage is compared with sinusoidal reference value. This stage is called error amplification. Then the error amplification is compensated with a PI controller. The result is designated as the error voltage ($v_e$). Finally, the error voltage is compared with the sawtooth signal to generate the PWM signal. To model the dc-ac full-bridge switching converter and produce the output voltage in sinusoidal waveform, we have to set up a duty cycle ($d$) with a variation in terms of a sinusoidal waveform around an average level of 0.5 as shown in Fig. 5 (a).

![Diagram](image)

**Figure 5.** (a) $d$ function waveform (b) output voltage waveform ($v_o$).

Written in equation form, the waveform appears as follows [15].

$$d(t) = 0.5 + m(\sin(\omega t))$$ (28)
where \( m \) is a modulated duty cycle variation. The factor of 0.5 is determined from the relationship of the voltage conversion ratio of the dc-ac full bridge switching converter which is \( \frac{v_o}{v_s} = 2d - 1 \).

Therefore, if \( v_s \) is dc source and \( d \) is represented by Eq. (28), then the output voltage \( (v_o) \) can produce the sinusoidal waveform across the x-axis as shown in Fig. 5 (b). The term \( m(sin(\omega t)) \) can be represented as \( \frac{v_o(t)}{V_p} \). Thus, we can substitute it into Eq. (28) and obtain

\[
d(t) = 0.5 + \frac{v_e(t)}{V_p}
\]  

(29)

As shown in Fig. 6, we can calculate \( v_e(t) \) with a basic Op-amp circuit calculation as shown below:

\[
v_e(t) = v_{ref} \left(1 + \frac{R_2}{R_1}\right) - v_{i_{Lf}} \left(\frac{R_2}{R_1}\right) - \frac{1}{C R_1} \int v_{i_{Lf}} dt + \frac{1}{C R_1} \int v_{ref} dt
\]  

(30)

Where \( v_{ref} = i_{ref} R_{ref} \)

![Figure 6. Error amplification circuit with PI controller.](image)

We can obtain the duty cycle \( (d) \) by substituting \( v_e(t) \) from Eq. (30) into Eq. (29). Therefore, to study dc-ac full-bridge switching converter under islanding phenomena, we can constitute an equation
by using Eq. (16), (27) and (29) for power stage of R load, RLC and duty cycle \((d)\) from a feedback current control stage, respectively. The solution for such a model can readily be handled using simple numerical iteration methods with sampling time by using embedded MATLAB function on MATLAB/SIMULINK with the passive islanding method and PLL block [16] as shown in Fig. 7.

Figure 7. The proposed model on MATLAB/SIMULINK.

4. Comparison of results between experiment, PSpice and the proposed modeling

The objectives of the experiment on the dc-ac full-bridge switching converter under islanding phenomena are to verify the proposed modeling as presented in the previous section. Fig. 8 shows the islanding testing circuit. The open circuit breaker is controlled
by using a computer linked to the desired quadrant of grid voltage. The dc input of the inverter is fixed to be a dc source. A-2 kW inverter purchased locally is used in this experiment.

Initially, the grid system is connected to the inverter and then removed intentionally in order to form an islanding condition. For the experiment, the inverter is automatically stopped with its own islanding detection. The islanding detection for the proposed model and PSpice have been implemented with the passive detection method such as over/under voltage frequency and phase jump. To avoid the malfunction of islanding detection, the inverter will be delayed 2-3 cycles before shutdown. Figs. 9-11 show the comparison results for various resistive load types: large loads, balance loads and light loads which are set to 125%, 100% and 25% of inverter output respectively. The grid voltage is plotted as reference in upper trace and lower trace for load voltage.

Figure 8. Islanding Test Circuit.
Figure 9. Comparison of results for resistive load of 125% inverter output.
Figure 10. Comparison of results for resistive load of 100% inverter output.
Figure 11. Comparison of results for a resistive load of 25% inverter output.
The comparisons of results indicate that the proposed modeling was close to the experiment and PSpice. When the grid is trip, the islanding detection from the proposed model can cease to energize within 2-3 cycles which is similar to experiment and PSpice. There are some small differences due to parasitic element effects which were not considered in the proposed modeling. The ratio of load consumption and output inverter affect the amplitude of load voltage. The greater the ratio, the less load voltage amplitude, is similar to the study of Achim Woyte et al. [17]. It was found that for resistive loads of 100% and 125% inverter output, the inverter behaves as current source. Its load voltage can give a perfect sinusoidal waveform. For resistive load of 25% inverter output, it operates as a voltage source without current control. Thus the load voltage is distorted. In Fig. 12, the results during islanding phenomena for RLC loads connected in parallel at resonance are compared. It can be observed that the amplitude and frequency of load voltage remain constant. This is the reason why such cases are difficult to detect using the passive detection method. The results show close agreement between the experiment and the proposed modeling in terms of phase and amplitude.

Nevertheless, when compared to PSpice simulation, the proposed model, which is based on iterative computation, consumes much less for computation time, see Table 1. Another advantage of the proposed model is that it does not encounter any convergence problem, which is often the case for PSpice.
N. Chayawatto, K. Kirtikara, V. Monyakul, C. Jivacate and D. Chenvidhya

(a) Experiment

(b) Pspice

(c) The proposed model
Figure 12. Comparison of results for RLC load resonance case.

Table 1. Comparison of the time for simulation between PSpice and the proposed model.

<table>
<thead>
<tr>
<th>P_{\text{load}}(\text{pu.})</th>
<th>PSpice(\text{second})</th>
<th>The proposed model (second)</th>
<th>Load type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>103</td>
<td>5</td>
<td>R</td>
</tr>
<tr>
<td>1.0</td>
<td>175</td>
<td>5</td>
<td>R</td>
</tr>
<tr>
<td>1.25</td>
<td>170</td>
<td>5</td>
<td>R</td>
</tr>
<tr>
<td>1.0</td>
<td>200</td>
<td>6</td>
<td>RLC</td>
</tr>
</tbody>
</table>

5. Conclusions

The piecewise function technique employed to derive a model for a dc-ac full bridge switching converter, used with a PV grid-connected system, is presented in this paper. The analysis of a large signal model under islanding phenomena, due to load variation of R and RLC connection, can be easily obtained using the state equation technique over a switching period and determining the ON and OFF interval in each switching period as a piecewise function. The Laplace transformation technique is applied for solving the state space equation. Moreover, the feedback current control technique is implemented by setting up the duty cycle with sinusoidal terms around a constant value of 0.5. The final solution for the whole time simulation can be easily handled by numerical iteration methods on MATLAB/SIMULINK at fast speed and with the absence of any convergence problem. Comparisons of results are made among the experiments, PSpice and the proposed method. The study shows that the proposed modeling gives good agreement with the experiment
and PSpice. The small differences encountered were due to parasitic element effects.

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Appendix (data in this study)

\[
\begin{align*}
L_f &= 2 \text{ mH} \\
C_f &= 6.8 \mu \text{F} \\
R_L &= 19,24 \text{ and } 97 \text{ ohms (125\%, 100\% and 25\% of output inverter)} \\
C_L &= 2.66 \mu \text{F} \\
L_L &= 3.55 \text{H} \\
R_1, R_2 &= 10k, 25k \\
C &= 470 \mu \text{F} \\
V_p &= 6 \text{ V} \\
f_s &= 10 \text{ kHz} \\
v_S &= 450 \text{ Vdc} \\
V_{\text{ref}} &= 1.5 \text{ Vac (Rref = 1 ohm)} \\
r &= 0.1
\end{align*}
\]
References


