EFFECTIVE CURRENT CONTROL DESIGN AND ANALYSIS OF SINGLE PHASE INVERTER FOR POWER QUALITY IMPROVEMENT

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ABSTRACT
Using an effective Predictive Current Control strategy to a single phase voltage source inverter and to analyze its performance for various parameters variations is the main objective of this paper. An improved performance of the proposed predictive current control method has been analyzed with various conditions is carried out such as steady state, transient state, non sinusoidal references, input frequency variations, sampling frequency variations, current reference amplitude variations and filter inductance variations, that offers excellent reference tracking with less current harmonic distortion for all conditions. The control algorithm and inverter model was developed in Matlab/Simulink software.

Keywords: Voltage Source Inverter (VSI), current control, Pulse Width Modulation (PWM), Model Predictive Control (MPC), Total Harmonic Distortions (THD).

1. INTRODUCTION
Nowadays, the voltage source inverter is common topologies have been used in wide diversity of applications and give more attention of the researchers to control and conversion of power. For a grid connected inverter, the power quality mainly depends on performance of the current controller’s in inverter.

The development of PWM techniques is the most popular control technique for grid-connected inverters. As compared with the open loop voltage PWM converters, the current-controlled PWM has several advantages such as fast dynamic response and inherent over-current protection [1]. Several control techniques that have been developed till now to control the current in inverter.

In the Ref [1-16] a Variaty of available current control techniques and its advantages and disadvantages are discussed.

Nowadays, Predictive current control technique has been used for control the current of three phase inverter[27], three phase four-leg inverter[24], three-phase two-level and three-level neutral-point-clamped inverter[29],[30], cascaded H-Bridge inverter[31], single phase boost rectifier[32], multilevel converter[33], matrix converter[34] and corresponding their application such as Active-Front-End Rectifier[18],[19], Distributed Generation Systems[20], Active Filters and Power Conditioning[23, 24], Non-Conventional Renewable Energy[20], uninterruptible power supplies (UPS) [25], drives [22], and power factor correction [26].

This current control method used in various wide power converters and the control scheme is to predict the future load current in terms of the measured actual load current and predicted load voltages.

Compared with the Classic Linear PI-PWM the MPC offers many advantages such as good reference tracking and minimum output distortion [24, 22]. In the all above mentioned strategies are only considering three phase inverter, multilevel inverter, matrix converter for various conditions is described. But the detailed investigation of single phase two level two-leg inverter for various conditions is not being described.

In this paper, we use improved current controller used to control the current of single phase inverter for various condition are evaluated through simulation results. This paper is organized as follows. In Section II, the mathematical model of the converter-load system is presented, followed by the explanation of the proposed control strategy in Section III. In Section IV, Experimental results are presented. Finally in Section V appropriate conclusions are drawn.

2. POWER CONVERTER MODEL

Figure-1. Voltage source inverter power circuit.

The power circuit of the converter considered in this work is shown in Figure-1. It is a two leg two level inverter operated by two control signals named S_a and S_b, form a total of 4(2²) switching state, and the inverter consisting of two controlled switches in each leg (S_1, S_3) and (S_2, S_4). The switching states of converter are determined by the control signals S_a and S_b as follows:

\[ S_a = \begin{cases} 
1 & \text{if } S_1 \text{ on and } S_3 \text{ off} \\
0 & \text{if } S_1 \text{ off and } S_3 \text{ on} 
\end{cases} \tag{1} \]

\[ S_b = \begin{cases} 
1 & \text{if } S_2 \text{ on and } S_4 \text{ off} \\
0 & \text{if } S_2 \text{ off and } S_4 \text{ on} 
\end{cases} \tag{2} \]
The voltages in each leg of the two leg inverter, measured from negative point of DC-Link N, that can be represented as

\[
\begin{bmatrix}
    v_a N \\
    v_b N
\end{bmatrix} = v_{dc} \begin{bmatrix}
    S_a \\
    S_b
\end{bmatrix}
\]  

(3)

where \(V_aN\) and \(V_bN\) are the voltage at the points ‘a’ & ‘b’ with respect to negative point of DC-Link N. The voltage applied to the load is potential difference between points ‘a’ & ‘b’ (or) potential difference between \(V_aN\) and \(V_bN\). This can be written as

\[V_i = (v_a N - v_b N) \quad \text{or} \quad V_i = v_{dc} \begin{bmatrix}
    S_a - S_b
\end{bmatrix}
\]

(4)

Then the output voltages can be related to the switching state vector \(S_i\) by

\[V_i = v_{dc} \begin{bmatrix}
    1 & 0 \\
    0 & -1
\end{bmatrix} \begin{bmatrix}
    S_a \\
    S_b
\end{bmatrix}
\]

(5)

where \(V_i\) is the output voltage (or) voltage vector generated by the switching states \(S_i\) with \(i = 0, \ldots, 4\).

The load current can be represented by the following equation

\[iL = i_R + \frac{di}{dt}
\]

(7)

Where \(i_L\) is the load current, \(i_R\) is the source current and \(i\) the load inductance. \(V\) is the voltage generated by the inverter.

### Table-1. Switching states with their corresponding voltage vectors.

<table>
<thead>
<tr>
<th>Switching state</th>
<th>(S_a)</th>
<th>(S_b)</th>
<th>(V_{dc})</th>
<th>(V_{dc})</th>
<th>(V_{dc})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>(V_{dc})</td>
<td>0</td>
<td>(V_{dc})</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>1</td>
<td>(V_{dc})</td>
<td>(-V_{dc})</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
<td>(V_{dc})</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1</td>
<td>(V_{dc})</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### Figure-3. Space vector diagram of inverter output voltage.

\[V_i = \begin{bmatrix}
    1 & 0 \\
    0 & -1
\end{bmatrix} \begin{bmatrix}
    i_a \\
    i_b
\end{bmatrix}
\]

(6)

The load current can be represented by the following equation

\[V = (R_f + R) i + L \frac{di}{dt}
\]

(7)

Where \(R_f\) filter leakage inductance is \(R\) is the load resistance \(L\) is the load inductance, \(V\) is the voltage generated by the inverter.

### 3. MODEL PREDICTIVE CURRENT CONTROL

a) Predictive current control technique

The proposed current control scheme is shown in Figure-4. It uses the discrete-time model of inverter and load for predicting the load current at a future sample instant for each of the available output voltage vector that can be generated by the inverter. The quality function or cost function or error between the reference and predicted values is calculated. The switching state that minimizes \(g\) is selected and applied during the next sampling period. The model needs input voltage and actual load currents at instant of \(k\). By using the system input voltage to generate voltage vectors, which is given to the predictive model to predict the inverter future current.

The current references are generated according to the application we are using. In this system a simple
designing and analysis of the inverter. So that the references are user defined. By changing the reference it can be used for any applications.

A discrete-time form of the load current for a sampling time \( T_s \) can be used to predict the future value of load current by using measurement of load current and supply voltage at the sampling instant \( k \).

Approximating the derivative \( \frac{di}{dt} \) by

\[
\frac{di}{dt} = \frac{i(k) - i(k-1)}{T_s}
\]  

(8)

Substituting equation (8) in equation (7) the following expression as

\[
v = (R_f + R) i + L \frac{i(k) - i(k-1)}{T_s}
\]

(9)

Then the load current at instant \( k \) as

\[
i(k) = \left[1 - \frac{(R_f + R)T_s}{L}\right] i(k-1) + \frac{T_s}{L} v(k)
\]

(10)

Shifting the discrete-time one step forward in the future load current can be determined by

\[
i(k+1) = \left[1 - \frac{(R_f + R)T_s}{L}\right] i(k) + \frac{T_s}{L} v(k+1)
\]

(11)

Where \( R \) and \( L \) are the load resistance and inductance, respectively \( T_s \) is the sampling time, \( i(k) \) is the measured load current, and \( v(k+1) \) is the inverter predicted voltage is the decision variable to be calculated by the controller.

The cost function is error between the reference current and the measured load current at the next sampling instant can be expressed as follows

\[
g = \left|i'(k+1) - i(k+1)\right|
\]

(12)

where, \( i'(k+1) \) is the reference current vector and \( i(k+1) \) is predictive load current vector. In this work, the absolute error is used for computational simplicity. Other quality functions such as error squared could also be used, that can be expressed as follows

\[
g = (i'(k+1) - i(k+1))^* (i'(k+1) - i(k+1))
\]

(13)

Finally the corresponding switching state is given to the inverter.

b) Proposed algorithm

Step 1: Parameter initialization

Set supply voltage \( V_{dc} = 100 \), Load Resistance \( = 10 \), Load inductance \( = 24 \) mH, Initial cost function \( g_{\text{opt}} = \infty \), Initial voltage vector \( = V_1 \), and Switching State \( = S_1 \)

Voltage vector \( = V_i \) /*voltage vector

\[
V_i = V_{dc} \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \cdot \begin{bmatrix} S_1 \end{bmatrix}^* /
\]

Switching State \( = S_i /* Switching State: 10; 0 1; 0 0 ; 1 1 */

Step 2: Current prediction

for \( i = 1 \) to \( n /* n: \) number of switching state */

Current prediction in \( k+1 \) instant

\[I_k1 = (1 - (R_f + R)Ts/L)i_{\text{meas}} + Ts/L*(v_o1)\]; /* using measured current and previous voltage vector*/

vector \( v(i) */

Step 3: Calculate the cost function (G)

/* cost function (G) : \( g = (\text{abs}(\text{real}(i_{\text{ref}} - ik1))) */

Selection of the optimal cost function and switching state value

if \( g > g_{\text{opt}} \)

\( g_{\text{opt}} = g; /* update the optimal cost function */

\( x_{\text{opt}} = i; /* update the optimal switching state */

End

Update the optimal voltage vector in the equation---

\[S_a = S (x_{\text{opt}}, 1);
\]

\[S_b = S (x_{\text{opt}}, 2);
\]

Send the optimal switching signal to the inverter.

Send the optimal switching signal to the inverter.

4. SIMULATION RESULTS

The Control of single phase voltage source inverter has been designed and developed in the laboratory to validate the performance of inverter. To validate the proposed current control strategy, for the single phase
inverter is evaluated by simulation by using Mat lab/Simulink software and simulation is done using Intel core i3-2350M Processor 2.30GHz computer system. To analyze and to improve the performance of the proposed predictive control method the various cases are considered, such as of steady state, transient state, supply frequency variations, sampling frequency variation, Reference Amplitude variations and filter inductance variation are carried out. Specification parameters of single phase voltage source inverter

<table>
<thead>
<tr>
<th>Variable description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vdc - DC supply voltage</td>
<td>100 V</td>
</tr>
<tr>
<td>Lf - Filter inductance</td>
<td>24 mH</td>
</tr>
<tr>
<td>Rf - Filter leakage resistance</td>
<td>0.05 Ω</td>
</tr>
<tr>
<td>Rl - Load resistance</td>
<td>10 Ω</td>
</tr>
<tr>
<td>Ts - Sampling Time</td>
<td>50µs</td>
</tr>
<tr>
<td>f - Rated Frequency</td>
<td>50Hz</td>
</tr>
</tbody>
</table>

a) Steady state analysis
The performance of proposed predictive control in steady state operation for resistive load is 10 ohm and filter inductance is 24mH. The amplitude of reference current is set as 2A, frequency is 50Hz and DC-Link voltage to be kept at 100V.

In Figure-4 shows that actual load current to track their references with less ripple content.

b) Transient analysis
The transient state analysis for the model, a amplitude of reference current step changes from 4A to 2A with frequency is 50Hz that is shown in Figure-6, where good dynamic response of the load currents is observed with low harmonic distortion with fast rise time and no overshoot. The load is the same as of the steady-state analysis discussed earlier.

c) Analysis with non sinusoidal reference
In this Third, fifth, seventh and ninth harmonic references are given separately with amplitude of 10 A; The load Resistance = 0.5ohm; Filter inductance =24mH are used.

The results are indicated in Figure-7. where a good tracking of the load current to its references are observed, which demonstrates that this control strategy can be applied effectively in a single phase voltage source converter operating as an active filter.

d) Analysis with input frequency variations
In this analysis the Reference frequency F = (50-20-70) Hz, Ref current =4 A , and the load is the same as of the steady-state analysis discussed earlier.

In Figure-8. Simulation result with input frequency variations.
In the Figure-8 shows that good reference tracking with frequency variations and fast response is observed.

e) Sampling frequency variation

The effect of varying the sampling time was tested with different load inductance values, in that the load current THD and Switching frequency of controller are varies with the sampling time variations.

The simulation result is depicted in Figure-9 that shows the THD of the load current is minimum and switching frequency is maximum at higher sampling frequency or small sampling time, and also it shows that THD of the load current is reducing from 12 mH value of the load inductance to 72mH. After increasing the inductance the THD is going to reach maximum value. Similarly the switching frequency of the controller is increase from 12mH to 36mH of load inductance and reducing for increasing the load inductance. A switching frequency have a significant relation to the THD is high when THD is low value.

where THD1 indicate with the sampling time(Ts) of 100μs, THD2 for 50μs and THD3 for 20μs. And fsw1 indicate with the switching frequency of the controller is 100μs, fsw2 for 50μs and fsw3 for 20μs respectively.

f) Current reference amplitude variations

The effect of varying the reference amplitude was tested with different filter inductance values, in that the load current THD and Switching frequency of controller are varies with the reference amplitude variations.

Figure-11 and 12 shows that variation of load current THD and switching frequency for different current reference amplitude. where THD-1 indicate with the sampling time(Ts) of 50μs and reference amplitude of 1A, THD-2, THD-3, THD-4, THD-5, THD-6, THD-7, THD-8, THD-9 and THD-10 for the
sampling time ($T_s$) of 50 $\mu$s and for reference amplitude of 2A, 3A, 4A, 5A, 6A, 7A, 8A, 9A and 10A respectively.

Similarly $f_{sw-1}$ indicate with the sampling time ($T_s$) of 50 $\mu$s and reference amplitude of 1A, $f_{sw-2}$, $f_{sw-3}$, $f_{sw-4}$, $f_{sw-5}$, $f_{sw-6}$, $f_{sw-7}$, $f_{sw-8}$, $f_{sw-9}$ and $f_{sw-10}$ for the sampling time ($T_s$) of 50 $\mu$s and for reference amplitude of 2A, 3A, 4A, 5A, 6A, 7A, 8A, 9A and 10A respectively. Where y-axis in Figure-12 indicates the switching frequency of the controller in terms of kHz. The current reference amplitude from 1A to 4A, the THD values are gradually decreasing from 15.68 % to 0.58 %, and switching frequency of the controller are gradually increasing from 0.35 kHz to 3.21 kHz. And the current reference amplitude from 4 A to 10A, the THD values gradually increasing from 1.74 % to reach 12.88% of THD, and switching frequency of the controller are gradually decreasing from 3.5 kHz to 0.18 kHz.

g) Controller operation with filter parameter variations

In the second case (CCF: changes to the controller and filter), the correct values of the load are given to the controller for the purpose of comparison. Both the cases are investigated in terms of % THD and Switching frequency.

A comparison of them is depicted in Fig 13 and 14. where only a small difference is observed in THD and switching frequency of the controller for different filter inductance variations. With this, the proposed control strategy can operate efficiently even under filter inductance variations.

5. CONCLUSIONS

In this paper the current control of single phase two-level two-leg voltage source inverter has been presented.

The control algorithm has been evaluated with seven different cases through simulation results. The result shows that good performances of the current tracking ability in all conditions with less harmonic distortion and the advantage of proposed technique are related to simplicity, design and modeling. With this the current control technique is a very good alternative solution to classical current control techniques.

In further research on control technique with cost function values variations in control algorithm and to compare with conventional current controllers.

REFERENCES


