Design of Grid Connected Three-phase Inverter with Series Resonant Filter and Reduced Control over Synchronization and Real and Reactive Power Injection

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Abstract—This paper investigates an inverter-topology with a series connected resonant filter for its integration with the existing power grid. It is found that such an inverter demands less control, yet it still effectively fulfills synchronization with an injection of pre-set real and reactive power into the grid. It can meet harmonics standards requirement with moderate amount of power injection into the grid. A windowed-sinc low-pass filter is introduced to extract the fundamental component of inverter terminal voltages for quick synchronization with the grid voltage and connecting the inverter to grid with the closing of circuit breaker.

Index Terms—grid-tie inverter, harmonics, resonant filter, synchronization

I. INTRODUCTION

There has been intensive research on grid-tied inverters, due to the booming of renewable energy generation[1-3]. Such inverters need to contain several basic control units including grid synchronization, current control and harmonics injection minimization[4-6]. There have been voltage source inverter (VSI) topologies based on LCL filters, and active filters etc, each of which needs complicated control algorithms. There has also been research on harmonic mitigation techniques [4-7]. In this paper, the authors introduce a simple, yet effective, inverter topology and its control algorithm that meets synchronization requirements, and mitigates harmonics injection requirement and real and reactive power injection requirement. Such a control algorithm is modified from the synchronous d-q frame based PQ closed-loop voltage oriented control and it does not need information of the impedance of the power grid with which it is connected.

Synchronization and connection of the inverter with the power grid is an important step in renewable energy applications [8-9]. In this paper, the authors introduce a windowed-sinc low-pass filter that can effectively extract the fundamental component of the output voltage at the inverter terminals, which is then compared with the voltage at the point of common coupling (PCC) for paralleling the inverter generation with the power grid[7-11]. It is found that such a filter is very effective in the proposed application.

This paper is organized as follows: In Section II, the single-phase topology of the inverter with series resonant filter is presented and its performance is studied in detail; Section III presents the overall system under study, containing grid connected three-phase inverter with series resonant filter, windowed-sinc filter design, and the results and discussion; Section IV concludes the paper.

II. PERFORMANCE OF SERIES RESONANT FILTER FOR VSI BASED INVERTER

Fig. 1 shows a single-phase series resonant filter for VSI inverter. To study the performance of such filter, one can build Eqns. (1) and (2). Then one can discretize them into (3) and (4). By using the iteration method, one can study the performance of the series-connected resonant filter. For the normal grid, the equivalent impedance at point of common coupling (PCC) is quite small. Hence when designing the LC resonant filter, one can choose a proper reactance \( \frac{1}{\omega L} \) at power frequency. At higher frequencies, \( \frac{\omega L}{\omega C} \) becomes larger and \( \frac{1}{\omega C} \) smaller. Provided that \( \frac{\omega L}{\omega C} \) becomes large enough at the third-order harmonic compared with equivalent source impedance \( Z_L \), the \( \frac{\omega L}{\omega C} - \frac{1}{\omega C} \) can share almost all harmonic voltage produced by the VSI based inverter. By doing so, the harmonic voltage injection into the system is contained.

\[
\begin{align*}
V_{PWM}(t) &= L \frac{di(t)}{dt} + v_c(t) + Ri(t) \\
&+ \frac{1}{L} v_{PWM}(t) - \frac{1}{C} v_c(t)
\end{align*}
\]

Figure 1. Series-connected resonant filter
\[ i(t) = C \frac{dv(t)}{dt} \]  

(2)

\[ i(j+1) = \Delta t \cdot \left[ v_{PWM}(j) - v_c(j) - Ri(j) \right] / L + i(j) \]  

(3)

\[ v_c(j) = [i(j) \cdot \Delta t / C] + v_c(j-1) \]  

(4)

In a current control based VSI inverter, the chosen inductance or capacitance has influence on harmonic components of the injected current. For the constant power control, the equivalent load seen by the inverter can be modeled by an impedance. If one assumes that only real power \( P \) is injected into grid, then the equivalent load impedance of the inverter is a resistor. Given the real power injected into grid and voltage at PCC, one can use \( V_{PCC}^2 / P \) to compute the equivalent resistance seen by the inverter.

In the following study, inductance is set equal to 30mH and capacitance 337.74µF.

Fig. 2 shows the PWM voltage \( v_{PWM}(t) \) for the study of harmonics across the equivalent load calculated by \( V_{PCC}^2 / P \). Fig. 3 and 4 are the results with equivalent load resistance of 20Ω. The total harmonic distortion is 12.19%. Fig. 5 and 6 are the results with load resistance of 2Ω. The total harmonic distortion is 1.22%. One can see that such a series-resonant-filter based VSI inverter topology is very suitable for the application of a large amount of power generation under which the harmonics requirement set by standard, can be satisfied with a small inductance value. To supply low power into grid, the required inductance is high in order to meet this harmonics requirement.

Fig. 7 shows the relationship between total harmonic distortion (THD) and power injected into power grid, from which one can see that for a given inverter system with fixed parameters of inductance and capacitance, the THD decreases with the increase of power injection into grid. With the increase in inductance and corresponding decrease in capacitance, the THD decreases. Hence, it allows such a system to be used for smaller power injection conditions, yet it still meets the THD requirement. If one considers the bulkiness of the inductor, then one can see that an inverter with a series resonant filter is the most suitable for high power applications such as above 25kW renewable generation, in which the required inductance is less than 10mH and THD can be satisfied with a significant margin.

III. THREE-PHASE VSI INVERTER WITH SERIES-CONNECTED RESONANT FILTER

The overall system of the three-phase inverter with series-connected resonant filter is shown in Fig. 8. In the system, there is one three-phase load, which consumes...
10kW real power and 0VAr reactive power. The source internal impedance is very small and it is set as a swing source. Between the source and point of common coupling (PCC) there is a line impedance in each phase, each being formed by a 0.2Ω resistor in series with a 3mH inductor. Initially, the breaker is in the open position. The synchronisation algorithm is implemented, as described later in this paper.

Fig. 9 an illustrates that the grid voltage at PCC is taken as the reference signal, and reference voltages $v_{gd}$ and $v_{gq}$ are computed. Fig. 9b shows that the three-phase currents out of inverter are measured and converted into $i_d$ and $i_q$, then converted into $i_d'$ and $i_q'$. $i_d'$ and $i_q'$ are compared with their respective reference signals $i_d^*$ and $i_q^*$, which are obtained by (6) with targeted real and reactive power injection into the grid. The differences between $i_d'^*$ and $i_d'$, and $i_q'^*$ and $i_q'$ are fed into a simple controller: proportionality controller. The outputs from the controller are added with $v_{gd}$ and $v_{gq}$ references. Next $v_a$, $v_b$, and $v_c$ are obtained and converted into three-phase reference voltages. These reference voltages are compared with a 1kHz triangular waveform. Finally, six gate signals are produced to control the inverter.

\[
\begin{pmatrix}
i_d'^* \\
i_q'^*
\end{pmatrix} = \frac{1}{v_{gd}^2 + v_{gq}^2} \begin{pmatrix}
v_{gd} & -v_{gq} \\
v_{gq} & v_{gd}
\end{pmatrix} \begin{pmatrix}
P \\ Q
\end{pmatrix}
\]  

(6)

By doing so, the inverter voltage is attempting to follow the voltage at PCC after the system is powered up. After the circuit breaker is closed,

\[
s_1 = v_{gd} + k_p \cdot \left( i_d' - i_d \right) \cdot \text{BreakerC}
\]  

(7)

\[
s_2 = v_{gq} + k_p \cdot \left( i_q' - i_q \right) \cdot \text{BreakerC}
\]  

(8)

Where BreakerC=0 before synchronization and BreakerC=1 after the breaker is closed or the system is synchronized.

Hence before circuit breaker is closed,

\[
s_1 = v_{gd}
\]  

(9)

\[
s_2 = v_{gq}
\]  

(10)

Then control of power injection into the grid is fulfilled after the breaker is closed.

To make an effective synchronization, in the authors’ work, a windowed-sinc low pass filter is introduced to extract the fundamental component of inverter terminal voltages. Three-phase voltage sensors are installed at the output of the inverter. Outputs from the sensors are then fed into the controller where the windowed-sinc filter is part of it.

The kernel of the windowed-sinc filter is given below[9]

\[
h(i) = K \frac{\sin[2\pi f_c(i - M / 2)]}{i - M / 2} - 0.5 \cos(2\pi i / M) + 0.08 \cos(4\pi i / M)
\]  

(13)

Where $f_c$ is the cutoff frequency, expressed as a fraction of the sampling rate, a value between 0 and 0.5. The sample number kernel is determined by $M$, which must be an even integer. The sample number $i$ is an integer that runs from 0 to $M$, resulting in $M+1$ total points in the filter kernel. The constant $K$ is chosen to provide unity gain at zero frequency. To avoid a divide-by-zero error, for $i=M/2$, use $h(i)=2\pi f_c K$.

In our modeling, the sample frequency is 50kHz. Hence the designed windowed-sinc filter has the kernel as shown in Fig.10.

![Figure 8. Overall inverter system under study.](image)

![Figure 9. Computation of reference voltage for gating signal generation.](image)

Fig. 10. The kernel of the windowed-sinc filter with a sample rate of 50kHz.
This windowed-sinc low-pass filter performs well for signals with no DC bias. The output voltages from the inverter contain a lot of harmonic components but they do not have a DC component. Hence the chosen windowed-sinc low-pass filter suits in this case, and can effectively and quickly extract the fundamental components of the inverter voltage.

Initially the breakers are in the open position. The control algorithm controls the inverter to synchronize the output voltage of the inverter with those of the grid. The following algorithm is implemented to judge whether synchronization has been reached:

\[
E_{av} = \sqrt{\frac{1}{m} \sum (v_a - v_{av})^2}
\]
\[
E_{bv} = \sqrt{\frac{1}{m} \sum (v_b - v_{bv})^2}
\]
\[
E_{cv} = \sqrt{\frac{1}{m} \sum (v_c - v_{cv})^2}
\]

where \(v_a, v_b, v_c\) are the fundamental components of the output voltages at inverter terminals extracted by the windowed-sinc filter and \(v_{av}, v_{bv}, v_{cv}\) are the three-phase grid voltages and \(m\) is the number of points per cycle. The summation is for one-cycle data.

Only when all three errors are less than pre-set values, the breaker is closed. The synchronization and paralleling of the inverter with the power grid through the closure of the breaker take a short time, around 0.04s, as can be seen in Fig. 11.

Fig. 11, 12 and 13 show the inverter currents, load currents and source currents. From Fig. 11, one can see that the currents injected into the grid produce an almost sinusoidal waveform with minor distortion, whose harmonic components are shown in Fig. 14, from which it can be seen that the harmonic component is almost negligible. Fig. 12 is the three-phase load current. The three-phase load is set as unity power factor load. Hence, it does not absorb reactive power. The reactive power from the inverter is injected into the grid and balanced by the source. Since the set real power is 20kW and reactive power is -10kVAR by the inverter and load real power consumption is 10kW, the extra 10kW real power from inverter and reactive power from it are pumped into source. Fig. 13 is the current into the source that facilitates these real and reactive powers flowing into the source.

Fig. 15 is the calculated reference voltages \(v_{gd}\) and \(v_{gq}\), from which one can see that they quickly dwell at their respective final values 3.7812V and -602.494V. Then one can compute real and reactive power generated by the inverter and flowing into the grid through PCC point as

\[
P = v_{gd}i_d + v_{gq}i_q = 20.00\text{kW}
\]

\[
Q = -v_{gd}i_q + v_{gq}i_d = -10.096\text{kVAR}
\]

They are almost the same as 20kW and -10kVAR, the settings for the inverter. This shows that the overall circuit works effectively.
Fig. 18 shows the three-phase voltage at the inverter terminal and their fundamental components. The PCC phase-a voltage and the fundamental component of the phase-a voltage at the inverter terminal are shown in Fig. 19. From these two figures, one can see that before the closure of the circuit breaker, the fundamental component of the inverter voltage traces that of PCC voltage very quickly. Once errors calculated by (14) through (16) are less than 5 (a pre-set value), the breaker is closed. Then the inverter terminal voltage experiences a short-time mild disturbance, which lasts less than two cycles. Finally, the inverter terminal voltages dwell at their steady-state values.

Fig. 20 and 21 show the harmonic components of the voltage at inverter terminal and PCC point. One can see that the harmonic components of voltage generated by the inverter have been filtered out by the resonant inverter effectively, leaving negligible components at PCC, as can be seen from Fig. 21.

The control and filter algorithms are implemented in Simulink. Instead of using z-function or s-function, this paper adopted a C-language mimicking Simulink environment based Matlab-script approach to implement control algorithm. Such an approach is closer to DSP or microcontroller implementation[11].

IV. CONCLUSION

This paper presents a detailed study on an inverter with series-connected resonant filter. The relationship between the THD and power injection from the inverter into the grid shows that in order to keep the THD under limit, there is a requirement on the minimum power injection
into the grid for a chosen inductance and capacitance in the filter. This paper also presents a technique to synchronize the inverter with the power grid at the point of common coupling. This synchronization algorithm is part of the control of the real power and reactive power injection into the grid. The computed numerical results justify the validity of the proposed topology and its power control algorithm.

REFERENCES


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