Frequency Adaptive Repetitive Control of Grid Connected Inverter for Wind Turbine Applications

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Abstract—This paper is concerned with the current control of grid connected inverters based on a simple frequency adaptive repetitive controller. A grid-tie inverter is desired to behave as a robust current source inverter with the high gain in order to improve both the reference current tracking and disturbance rejection capabilities. The variations of grid impedance and frequency in distribution networks are some important challenges in the design of grid interfaced converters. In this research, the performance of a frequency adaptive repetitive controller (RC), which is based on the internal model principle (IMP), is investigated for a single-phase grid connected inverter.

I. INTRODUCTION

Nowadays, distributed power generation systems (DPGSs) based on renewable energy sources (RES), such as wind and solar energy are gaining more and more attention worldwide. With the exponentially increasing penetration of wind and solar electrical energy into the grid systems, utility converters should be compliant to more stringent standards and regulations than before. Not only should grid converters synchronize and transfer the variable produced power over to the grid, but also be able to exhibit advanced functions and ancillary services such as dynamic control of active and reactive power, stationary operation within a range of voltage and frequency variations, low voltage ride-through capability, etc. [1]. Being compliant to power quality international recommendations and standards such as IEEE 519-1992, IEC 61747, IEEE-1547, etc., requires an advanced current control strategy which is faced to some unavoidable disturbances and uncertainties. The variations of grid frequency and impedance at the point of common coupling (PCC) can directly affect the performance and stability of the converters [2]. Additionally, due to the proliferation of nonlinear loads, the grid voltage at the PCC is more likely to be distorted particularly in weak grid systems with long radial distribution feeders. The grid voltage distortion or unbalances can induce highly distorted low-order harmonic currents in the output of voltage sourced inverters. With a proper use of a low-pass filter such as L or LCL, it is possible to attenuate the high-frequency components of the injected current, but unfortunately, it is very difficult to filter the low frequency components induced by the grid voltage. The idea of applying a grid voltage feed-forward can suppress such induced current distortion, but the result is not satisfactory due to the presence of some delays and noise amplification, especially when the order of the harmonics is high. There have been some improvements and modifications to grid voltage full feed-forward techniques as expressed in [3, 4]. Another solution is to increase the current loop gain of the converter at some frequencies of interest by adopting properly designed harmonic compensators (HC) in the controller.

As shown in Fig. 1, the control strategy applied to the grid-tie inverter consists mainly of two cascaded loops. Usually there is a fast internal current loop which regulates the grid current and an external voltage loop which controls the dc-link voltage. The inner loop is designed with high bandwidth characteristics aiming to ensure accurate current tracking with fast dynamic response. In other words the VSI is forced to equivalently act as a current source amplifier with high disturbance rejection against grid voltage distortion. The dc-link voltage controller is designed for balancing the power flow in the system.

In the following a brief review on some important current control strategies is given and the main properties of each structure are highlighted.
A. Proportional-Integral Controller

Proportional-Integral (PI) controller is widely used in industry and power electronic converters. Due to the infinite DC gain characteristic, PI controller is the best candidate for regulating DC values with zero steady state error, but in the case of tracking (rejecting) sinusoidal signals (disturbances) the performance degrades significantly. By adopting the Park transformation AC values can be converted to DC quantities. In order to compensate for grid induced low order harmonics, multiple synchronous reference frames strategy (MSRF) can be used [1]. However, high computational efforts, large amount of data memory and strong dependency to the phase-locked-loop (PLL) operation are some limiting factors for using voltage oriented control (VOC) method with MSRFs. Also it is of more complexity to implement the voltage oriented control strategy for single phase systems.

B. Proportional Resonant Controller

Recently Proportional Resonant (PR) controller attracted an increased interest due to its superior performance over the PI controller when regulating sinusoidal signals. Basically, the functionality of the PR controller is to introduce an infinite gain at a selected resonant frequency for eliminating the steady state error at that frequency and is therefore conceptually similar to an integrator whose infinite DC gain forces the DC steady-state error to zero. The resonant portion of PR controller can be therefore viewed as a generalized AC integrator (GI), as proven in [6]. A PR controller is used to control the fundamental current. But generally several GIs that resonate for each harmonic frequency of interest (3rd, 5th and 7th) are used in parallel as harmonic compensators in order to reduce the current THD for compliance with standards, as shown in Fig. 2. Harmonic compensators do not affect the stability of the system unless they are tuned at the proximity of the cross over frequency. This structure is a successful solution in applications with distributed generation systems, where harmonics compensation, especially for low order harmonics, is required.

Some performance degradations can be observed due to the round-off errors when implementing resonant controller on a fixed-point DSP. Round-off errors cause the voltage or current wave shape to change slightly from cycle to cycle resulting in significant fluctuations in its RMS value [7]. Although the above mentioned problem could be resolved by using delta operator [8, 9], the performance of the PR controller degrades significantly in the case of grid frequency variations. With the addition of damping factor to resonant filters coefficients, the quasi-resonant controllers with wider bandwidth and the sacrificed lower gain are produced. Another solution is to make the resonant filter coefficients adaptive with respect to the grid frequency variations [10]. In this method the high gain of the ideal filter is preserved but in the case of implementing multiple harmonic compensators, each filter must be retuned separately leading to the increase of computational burden and errors. In this paper a kind of adaptive repetitive controller (RC) is introduced which can easily tune all resonant frequencies simultaneously by adapting the RC time delay parameter.

C. Deadbeat Controller

It has been shown recently that deadbeat current control is well suited for grid-connection application if adequate robust control performance is provided to mitigate the sensitivity of deadbeat controllers to system parameter variation and disturbances. Disturbance observers such as Luenberger observer, reduced-order observers, and time delay estimators are proposed to enhance the robustness of the conventional deadbeat controllers [11]. However, the nature of these observers as low-pass filters reduces the robustness of control performance, particularly against relatively high frequency grid harmonics and disturbances.

D. Other Controllers

The details for using other controllers based on Hysteresis Band (HB), robust, sliding mode and ANN-based control can be addressed in [12-15] respectively.

II. ANALYSIS OF REPEATED CONTROLLER

As discussed in the last section, repetitive controller which is based on the internal model principle [16] can be used for control of utility converters with periodic reference signals or disturbances. The internal model principle states that a controlled output can track a class of reference commands without any steady state error if the generator (or the model) of the reference is included in the stable closed-loop system. Therefore, it can be used to provide exact asymptotic tracking (rejecting) of periodic reference signals (disturbances). It is well known that the generator of a sinusoidal signal that contains only one harmonic component is a harmonic oscillator, in other words, a resonant filter. Thus, following this idea, if a periodic signal has an infinite Fourier series of harmonic components, then an infinite number of harmonic oscillators are required to track or reject such a periodic signal. Fortunately as shown in Fig. 3, in the repetitive control approach, a simple time delay in a proper feedback array can be used to produce an infinite number of poles, thereby simulating a bank of an infinite number of harmonic oscillators, which leads to a system dynamics of infinite dimension.

![Figure 2. PR controller with harmonic compensators [1].](image)

![Figure 3. Repetitive controller structure.](image)
Assuming $T$ is the time delay period, the RC transfer function can be written as (1):

$$G_{RC}(s) = \frac{e^{-sT}}{1-e^{-sT}} = \frac{1}{1/2 + 1/2(1+e^{-sT})}. \quad (1)$$

Using (2), the transfer function can be expressed as (3):

$$\mathcal{R} \frac{e^{sT} + e^{-sT}}{e^{sT} - e^{-sT}} = \mathcal{R} \sum_{k=-\infty}^{\infty} \frac{1}{x^2 + k^2} = \frac{1}{x} \sum_{k=-\infty}^{\infty} \frac{1}{x^2 + k^2} = \frac{1}{x} \sum_{k=-\infty}^{\infty} \frac{2x}{x^2 + (2\omega)^2} \quad (2)$$

$$G_{RC}(s) = k_R \left[ -\frac{1}{2} + \frac{1}{T} \left[ s + \frac{2s}{s^2 + \omega^2} + \frac{2s}{s^2 + (2\omega)^2} + \ldots \right] \right]. \quad (3)$$

Comparing (3) and Fig. 2, it is easily concluded that RC is equivalent to a parallel combination of an integral, proportional and many resonant controllers which can be tuned simultaneously by the RC time delay parameter. It should be noted that due to the infinite dimension characteristics of the RC, it is very probable to have an unstable system. This is why RC controllers must be implemented with a proper low-pass filter in cascade in order to preserve the system phase and gain margins within the acceptable range [17]. As indicated in Fig. 4, RC is added to a primary controller of $G_{c}(z)$ in a plug-in structure aiming to improve the system steady state performance. In this figure $K_R$ and $Q(z)$ are the RC gain and the low-pass filter respectively [18]. A compensating filter of $G_{p}(z)$ is used in order to cancel the phase lag of the primary closed loop system which results in a higher bandwidth for harmonic compensation. In Fig. 4, $N$ is the number of samples per period and $G_{p}(z)$ is the plant model. It is assumed that the closed loop transfer function of the system without RC, $H(z)$, is stable and is calculated as (4). Consequently the transfer function of the error signal can be calculated as (5):

$$H(z) = \frac{G_{c}(z)G_{p}(z)}{1 + G_{c}(z)G_{p}(z)}. \quad (4)$$

$$E(z) = \frac{R(z)}{1 - Q(z)z^{-N}} \left[ \frac{1}{1 + G_{c}(z)G_{p}(z)} \right] \left[ \frac{1}{1 - Q(z)z^{-N}(1-k_RG_{c}(z)H(z))} \right]. \quad (5)$$

In order to have the asymptotic stability condition (6) must be satisfied.

$$\left| Q(z)(1-k_RG_{c}(z)H(z)) \right| \leq 1 \quad (6)$$

According to (6), the best stability performance of RC occurs when $K_RG_{c}(z)H(z) = 1$. However, due to some modeling errors, it is impossible to compensate the plant model completely. The phase of the vector $1-K_RG_{c}(z)H(e^{j\omega})$ could exceed (-90,90) in high frequencies. Therefore, it is possible that the trace of $1-K_RG_{c}(z)H(e^{j\omega})$ gets out of the unit circle. Thus a modified repetitive control is adopted in the system which makes $Q(z) < 1$ at high frequencies, as shown in Fig. 5. It is noteworthy to mention that there is always a trade-off between the stability margin (the circle radius) and the error convergence rate which is proportional to $K_R$. In this paper a zero-phase low-pass filter of $Q(z) = 0.25z^{-1} + 0.5 + 0.25z$ is used as proposed in [19].

In the case of frequency variation, the RC performance degrades significantly leading to the injection of highly distorted currents exceeding the THD threshold of 5%. This condition is more likely to happen in weak grid systems connected to wind farms. Normally the demands for wind turbine (WT) systems are more severe compared to those applying to photovoltaic (PV) systems. In fact, both voltage and frequency ranges of operation are larger, thus WT systems should have a fast control strategy that allows them to ride-through when grid voltage and frequency variations occur.

III. FREQUENCY ADAPTIVE RC

In the repetitive control technique, the ratio of the sampling frequency to the grid frequency is an integer.
However, this ratio cannot maintain an integer in the case of frequency variations. In 2002, a kind of adaptive RC with the fictitious sampling points was proposed [20]. However, the fictitious sampling points are calculated from practical sampling points by linear calculation and there are errors between them. The repetitive control method proposed in [13] uses a variable first-order low-pass filter for the frequency adaptation. Though its resonant point for the fundamental frequency can be perfectly matched, the rest resonant points still deviate from the harmonics. This will decrease the harmonics compensation performance. Another idea is to design a proper low-pass finite impulse response (FIR) filter of \( Q(z) \) with adjustable linear characteristics, which means that its delay time is linear to the frequency [21]. In this paper an efficient, still simple method of frequency adaptation which was used in dynamic voltage restore (DVR) [22], is presented. As shown in Fig. 6, the time delay compensator of \( L(z) \) is added to the previously designed low-pass filter aiming to force the RC time delay parameter to be equal to the error signal time period \( T \). For digital implementation of this idea the error signal time period can be separated into two terms of integer and fractional non-integer multiple of the sampling time period. The fractional part can be digitized to \( L(z) \) using the Pade’s approximation and Tustin’s discretization method as in (9):

\[
T = NT_s + lTs, 0 < l_s < 1 \rightarrow G_{RC}(s) = \frac{e^{-NT_s}e^{-lTs}}{1-e^{-NT_s}e^{-lTs}} \tag{7}
\]

\[
e^{-lTs} = \frac{1-\frac{lTs}{2}}{1+\frac{lTs}{2}} \tag{8}
\]

\[
s = \frac{2z-1}{T_s z+1} \Rightarrow L(z) = \frac{(1-l_s)+(1+l_s)z^{-1}}{(1+l_s)+(1-l_s)z^{-1}} \tag{9}
\]

Note that the Pade’s approximation holds true since the fractional part of the time delay is less than the sampling time period which is very small compared to the error signal time period. Another thing to mention is that \( L(z) \) has a unit magnitude which does not affect the stability condition of the system. In this approach the coefficients of \( L(z) \) can be updated continuously with regard to the grid frequency variations.

### IV. SYSTEM DESCRIPTION

To evaluate the performance of Adaptive RC a single phase grid connected inverter with an LCL filter is designed. The resonance frequency of the filter is designed to be at least 3.69 kHz for the worst case grid inductance of 200uH which can provide the high band-width for harmonic compensation up to more than the 19th order. Adopting the unipolar switching pattern, the filter attenuation factor is designed to be -90dB at 40 kHz which satisfies the IEEE 1547 standard. Detailed parameters of the system are tabulated in TABLE I. Fig. 7 shows the inverter model and the primary current control loop. For the sake of simplicity \( G_s(z) \) is chosen to be a proportional constant of \( K_p \). In this topology the capacitor current is fed-back to the controller as a kind of active damping signal. The current loop control parameters are designed for the damping ratio of \( \zeta = 0.7 \) and the gain and phase margin of 10.6dB and 57.7 degrees respectively. The open loop frequency response of the current loop with the added RC is shown in Fig. 8. Other controllers such as PI or deadbeat [23] can be utilized instead of \( K_p \) as to improve the converter transient response in case of non-periodic disturbances or rapid changes. It is noteworthy to mention that in case of needing faster error convergence time, the dynamical response of the repetitive controller can be enhanced by using Dual Mode or Odd-Harmonic Repetitive Controllers (DMRC or OHRC) [24].

<table>
<thead>
<tr>
<th>TABLE I. PARAMETER VALUES OF THE SYSTEM.</th>
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<tbody>
<tr>
<td>Utility Voltage, ( (v_g) )</td>
</tr>
<tr>
<td>Grid Inductance, ( (uH) )</td>
</tr>
<tr>
<td>Inverter-Side Inductance, ( L_1 ) ( (mH) )</td>
</tr>
<tr>
<td>Grid-Side Inductance, ( L_2 ) ( (mH) )</td>
</tr>
<tr>
<td>Filter Capacitance, ( C ) ( (uF) )</td>
</tr>
<tr>
<td>Switching Frequency ( (kHz) )</td>
</tr>
<tr>
<td>Sampling Frequency ( (kHz) )</td>
</tr>
</tbody>
</table>

![Figure 6. Frequency adaptive repetitive controller.](image)

![Figure 7. Model of grid connected inverter with active damping](image)
V. SIMULATION RESULTS

The simulations have been carried out using Matlab/Simulink. The grid is concerned to have a THD of 6.57% with the harmonic components tabulated in TABLE II. As shown in Fig. 9, the performance of the proportional controller is very poor. The injected current has a large steady state error with the THD of 19.14%. With the addition of RC to the proportional controller in a plug-in structure, it is possible to reach to the THD of less than 2% with zero steady state error which is compliant to IEEE 1547 standard (Fig10.A). But with the slight variation of grid frequency the performance of P+RC controller degrades (Fig 10.B).

TABLE II. THE UTILITY VOLTAGE HARMONICS AT THE PCC

<table>
<thead>
<tr>
<th>h</th>
<th>3</th>
<th>5</th>
<th>7</th>
<th>9</th>
<th>11</th>
<th>13</th>
<th>15</th>
<th>17</th>
<th>19</th>
</tr>
</thead>
<tbody>
<tr>
<td>X%</td>
<td>4.4</td>
<td>3.2</td>
<td>2.8</td>
<td>1.5</td>
<td>1.2</td>
<td>1</td>
<td>0.6</td>
<td>0.5</td>
<td>0.4</td>
</tr>
</tbody>
</table>

In order to evaluate the performance of the frequency adaptive P+RC, the grid frequency is changed in two steps of 50 to 49 and 49 to 51 hertz. Fig. 11 shows the dynamical responses of SOGI-FLL and the injected current in the case of frequency variation. As shown in Fig. 11, there are some current spikes at the instant of frequency abrupt changes which may damage the semiconductor switches. But normally the grid frequency changes very slowly thus the spikes would not occur in practice. As compared in TABLE III, the THD values for the adaptive system are satisfactory. The system performance for handling non-periodic disturbances such as abrupt changes in the reference current or voltage sag is shown in Fig. 12 and Fig. 13 respectively. It is evident that the injected current tracks the reference signal rapidly thus it is possible to inject the desired active or reactive power in the case of DG power variations or grid faults. It is assumed that the inverter input power is kept constant during the voltage sag occurring at the instant of 0.58 seconds.

TABLE III. THD VALUES FOR P+RC AND ADAPTIVE P+RC.

<table>
<thead>
<tr>
<th>Frequency(Hz)</th>
<th>P+RC</th>
<th>Adaptive P+RC</th>
</tr>
</thead>
<tbody>
<tr>
<td>49</td>
<td>7.2%</td>
<td>1.98%</td>
</tr>
<tr>
<td>50</td>
<td>1.94%</td>
<td>1.94%</td>
</tr>
<tr>
<td>51</td>
<td>7.9%</td>
<td>2.17%</td>
</tr>
</tbody>
</table>
VI. CONCLUSION

In this paper a brief survey on different control strategies for grid connected inverters was given. As discussed repetitive controller, which is based on the internal model principle, equivalently acts as a combination of PR controller and infinite number of ideal resonant filters (harmonic compensators) with infinite gains. The salient feature of the controller is the simple implementation and the ability to tune all the resonant frequencies simultaneously via the adaptation of the RC time delay parameter. As it was shown in the simulations the performance of repetitive controller can degrade significantly in the case of grid frequency variations while in the frequency adaptive scheme the high performance of the current controller is still preserved. Finally it was shown in the simulations that the system dynamical responses for some step changes in the reference current and the voltage sag are sufficiently fast.

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REFERENCES


