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An Overview on Current Control Techniques for Grid Connected Renewable Energy Systems

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Abstract. Most type of renewable energy systems works in conjunction with the existing electrical grids. Also, inverter technology has an important role to have a safe and reliable grid interconnection operation of renewable energy systems. It is also necessary to generate a high quality power to the grid with reasonable cost. They also must be capable of provide high efficiency conversion with high power factor and low harmonic distortion. For this reason, the control policy must be considered. Therefore, the most important current control techniques are investigated in this paper. The ability of them to eliminate the steady state error, fast transient response and the possibility of compensation for low order harmonics is also discussed and compared to each other.

Keywords: Current Control Techniques, Grid Connected Inverter, Renewable Energy System, Harmonic Distortion.

1. Introduction

Energy demand increasing makes important problems such as grid instability or even outage. Therefore, more energy must be generated at the grid. However, energy generation by big plant is not economically. Moreover, implementation of distributed generation is rapidly increased. Because of increasing global warming, limitation and high cost of fossil fuel sources, governments tend to increase use and implementation of renewable energy sources. The main difference between renewable energy and fossil fuels systems is up front cost versus lifelong energy cost. Currently, in most development countries, governments as well as utilities provide a variety of incentives, to help the renewable energy industry reach to a higher economic scale. However, renewable energy sources are not perfect, but they could be a good choice to replace with fossil fuels. Figure 1 shows the annual growth rates of renewable energies in the world between 2005 and 2010[1]. Solar/photovoltaic, wind, hydro, geothermal, tidal, wave and bio energy are examples of renewable energy sources which the solar/photovoltaic and wind are most popular among them. Figure 2 indicates the increasing of the sun and the wind energy capacity in the world, between 1996 and 2010 [1].

However, environmental friendly is the principal advantages of renewable energies, high up front cost and uncontrollability are the main disadvantages of it. Renewable energy sources can be used as an off grid or on grid systems. Most type of renewable energy systems works in conjunction with the existing electrical grids. The heart of the grid-direct system is a DC to AC inverter which adapts to the power grid voltage and frequency. Inverter technology has an important role to have safe and reliable grid interconnection operation of renewable energy systems. It is also necessary to generate a high quality power to the grid with reasonable

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cost. For this reason, up to date technologies of power electronics are applied for renewable energy inverters. They must be capable of provide high efficiency conversion with high power factor and low harmonic distortion. Based on control policy, line-commutated or self-commutated inverter can be selected. A line communicated inverter is tied to a power grid or line. The commutation of power (conversion from DC to AC) is controlled by the power line, so that, if there is a failure in the power grid, the photovoltaic system cannot feed power into the line. Self-commutated inverter is also divided to voltage source and current source inverter types. Voltage control scheme inverter, control the grid voltage. The current control scheme inverter controls the grid current. Compare to the current control scheme inverter, fault short circuit current for voltage current scheme is high.

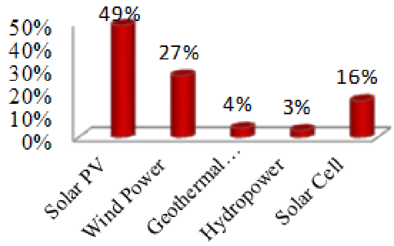


Fig.1: World Average Annual Growth Rates of Renewable Energy Capacity Between 2005-2010

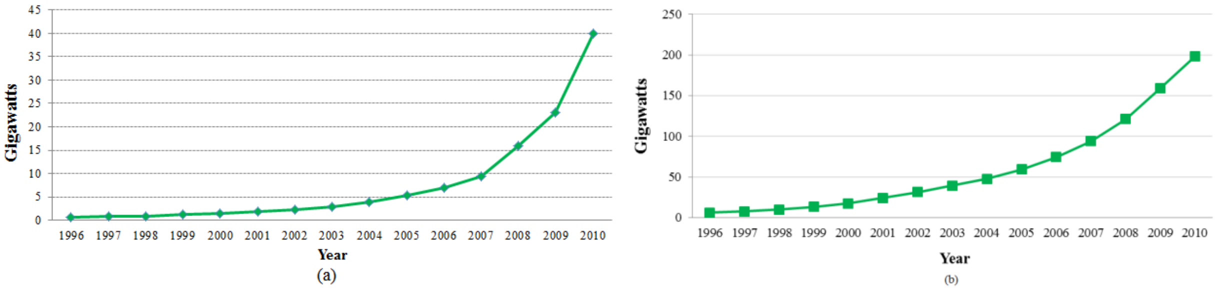


Fig.2: World Capacity (a) Solar/ PV (b) Wind

It is important that any inverter system connected to the grid does not in any significant way degrade the quality of supply at the point of connection. It is also important to consider the effects of a poor quality of supply on an inverter added to the system. Unbalanced input supply voltages and impedances make odd harmonics in ac current [2]. The harmonic content of the most modern pulse width modulated sine wave inverters is typically less than 3% THD. According to the IEEE standards [3] and IEC [4], the total harmonic distortion (THD) of the current injected to the grid should be lower than 5%. Then, different current control methods are proposed to obtain lower harmonic distortion. IEC harmonic distortion limits details for distributed generation system is presented in Table 1. The important aim of this paper is to give a comprehensive description of current control techniques for grid connected converters and comparison them according to their performance like steady state error, transient response and harmonic compensation. This paper is organized as follows. Current control techniques introduced in Section II, performance overview of current control techniques in Section III and finally, some conclusions are given in section IV.

Table.1: IEC Distortion Limits for Distributed Generation Systems [9].

Current Harmonic Number	Limit based on % of fundamental
3-9	< 4%
11-15	< 2%
17-21	< 1.5%
23-33	< 0.6%
>33	< 0.3%
Event Harmonics	< 25% of equivalent odd harmonics
Total Harmonic Distortion (T.H.D)	< 5%

2. Current Control Techniques

A General block diagram of grid connected renewable energy system is presented in Figure 3. Control of this system can be applying in input-side or grid-side. The main task of the input controller is to extract the maximum power from the renewable energy sources and protect the input side converter while, the grid side controller must check the active and reactive power which is transferred from renewable energy systems to the grid. Grid synchronization and controlling the power quality of power injected into the grid are another duty of the grid side controller.

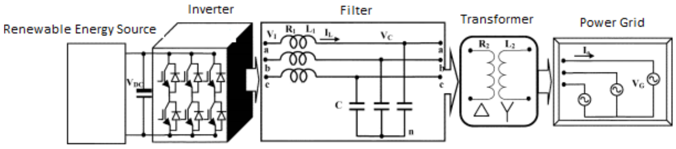


Fig.3: Grid Connected Renewable Energy Sources Block Diagram

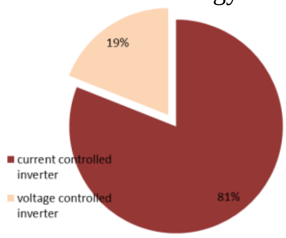


Fig.4: Current and Voltage Control Scheme Inverter Ratio

Based on the literature review, the self-commutated voltage type inverter is employed in all inverters, with a capacity of 1 kW or under, and up to 100 kW. By using a simple control circuit, current control scheme inverter can be achieved a high power factor. Therefore, the current control type inverters are more popular (Figure 4). In the current control scheme inverter, performing as an isolated power source is difficult, but there are no problems with grid interconnection operation [5]. The operations of the current controlled type inverters are depended on use of the current control technique types. Current control techniques can be classified into two main groups of the linear and nonlinear techniques. The most famous linear current control techniques (part 2.1) are proportional integral (PI)[6–10], Proportional Resonant (PR) and Repetitive Controller (RC). Predictive [11-12], dead beat and hysteresis [13] are the nonlinear controller which is discussed and investigated in part 2.2 of this section.

2.1 Linear Current Control Techniques

2.1.1 Proportional Integral (PI)

Proportional (P) controllers were used as former grid connected controller. However this kind of controllers has an inherent steady-state error [14]. The P controller's steady state error was eliminated by adding integral component to the transfer function [15]. Therefore, the average value of current error reduced to the value of zero by changing the integral components. Even so, the current errors can appear in transient conditions. Transient response of the proportional integral (PI) controller is limited by the proportional gain. Then the gain must be set at a value that the slope of the error is less than the slope of the carrier saw tooth waveform required for generating the firing pulses of the inverter. Most of the PI controller's applications are in dq control, since they have an acceptable performance while regulating the dc variable. A PI controller gain is determined via (1):

$$G_{PI}(s) = K_P + \frac{K_i}{s} \tag{1}$$

Where K_P and K_i are the proportional and the integral gain of the PI controller. The controlled current has to be in phase with the grid voltage. Therefore, the phase angle used by the $abc \rightarrow dq$ transformation module has to be extracted from grid voltages. However, PI controller is mostly used in dq control, but it could be used in abc frame as well. The related matrix transfer is presented in [16]. To overcome on transient respond to the problem of the PI controller, an average current mode control (ACMC) was introduced. Since the additional derivative component which was used in ACMC not only the steady state error removed, but again the fast transient response achieved. Consequently, the regulator gain improves at the switching frequency. However, this method has the problem of high frequency sub-harmonic oscillations with the current mode control and its instability is reported under a certain conditions, too. A PI controller compensation operates as low and high pass filters [17]. Under unbalanced conditions, harmonic compensators for both positive and negative sequences of each harmonic order are required. For instance, four compensators are needed for the fifth and seventh harmonics compensation. Hence, their control algorithms become complicated.

2.1.2 Proportional Resonant (PR)

The ideal proportional resonant controllers (PR) [18–21] widely used in abc directly when the control variables are sinusoidal. PR controllers present a high gain around the natural resonant frequency of ω, which is presented by (2).

$$G(s) = K_p + \frac{K_i s}{s^2 + \omega^2} \tag{2}$$

Where ω, K_p and K_i represent the resonance frequency, proportional and the integral gain of the PR controller. This controller achieves a very high gain about the resonance frequency. Therefore it can omit the steady state error between the reference and the controlled signal. The width of the frequency band about the resonance point, depends on the integral time constant of K_i. A low K_i can cause a narrow band, while a high K_i causes a wider band. The high dynamic performances of a PR controller have been described in different papers such as [22]. The PR controller harmonic compensation can be achieved by cascading several generalized integrators, which are tuned to resonate at the specified frequency. Therefore, selective harmonic compensation at different frequencies can be achieved. A typical harmonic compensator (HC) has been introduced for compensation of the third, fifth, and seventh harmonics [23]. The transfer function of the HC is shown in (3):

$$G_h(s) = \sum_{h=3,5,7} K_{ih} \frac{s}{s^2 + (h.\omega)^2} \tag{3}$$

Where ω is the natural resonance frequency, h is the harmonic's number and K_{ih} is the integral gain of the related harmonic. Then it is simple enhance to the abilities of the scheme, by adding harmonic compensation properties with more resonant controllers in parallel to the main controller. In this case, the harmonic compensator works on both positive and negative sequences of the selected harmonic. Therefore, only one HC is needed for one harmonic order. Moreover, another advantage of the HC is that it does not affect the dynamics of the PR controller, and it just has an effect on the frequencies that very close to the resonance frequency. However, since the distorted currents usually contain more than one order harmonics, it would be preferable to use many resonant compensators, which are tuned at different harmonic frequencies, and cascaded together or nested in different rotating reference frames to achieve the multiple harmonics compensation.

2.1.3 Repetitive Controller (RC)

Another kind of the grid connected controllers is repetitive controller (RC) which can omit the steady-state error by periodic controlling of the components. The RC controllers achieve a large gain at the integral multiples of fundamental frequency. The RC controllers like sliding mode [24-27], odd-harmonic repetitive controller [28] and dual-mode repetitive controller [29] are introduced to obtain the dynamic response. These repetitive controllers are implemented as harmonic compensator and current controller, to track the fundamental reference current. However, RC controllers can cause a slow dynamic response and they are applied only in the static mode.

2.2 Nonlinear Current Control Techniques

2.2.1 Predictive Control

Current controller based on prediction is one of the nonlinear grid connected controllers. The predictive control strategy is based on the fact that only a finite number of possible switching states can be generated by a static power converter, and that models of the system can be used to predict the behavior of the variables for each switching state. To select the appropriate switching state to be applied, a selection principle must be defined. This selection principle is expressed as a quality function that will be evaluated for the predicted values of variables to be controlled. Prediction of the future value of these variables is calculated for each possible switching state. The switching state that minimizes the quality function is also selected.

A predictive current control block which is shown in Figure 5, is applied to predict the next value of the output current by using the existing output current. Then, the quality function determines the error between the predicted output current and the reference current. Finally, the voltage which minimizes the current error is selected and applied to the output current. This kind of controller is well known for their possibility to include nonlinearities of the system in the predictive model. Predictive controllers give a better performance while the mathematical model is accurate, linear and time invariant. Because of complicated computationally of the predictive controller, it needs a large control loop time period.

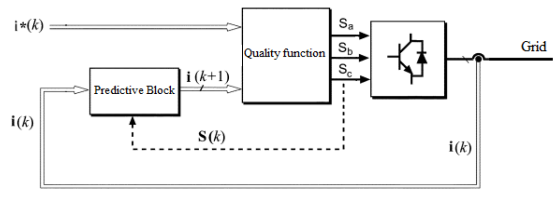


Fig.5: Predictive Current Control Block Diagram

2.2.2 Dead-Beat Control

When the choice of the voltage vector is ordered to a null error with a one sample delay, the predictive controller called dead beat controller. In this case, among the additional information given to the controllers, non-available state variables like flux and speed can be included. Therefore, observer or other control blocks are needed to determine these variables which often may be shared in the control of the complete scheme. The gain of this controller is achieved by the bellow's formula:

$$G_{DB} = \frac{1 - az^{-1}}{b(1 - z^{-1})} \tag{4}$$

Where a represents by (5) and b is given by (6):

$$a = e^{-\frac{R_T}{L_T}Ts} \tag{5}$$

$$b = -\frac{1}{R_T}(e^{-\frac{R_T}{L_T}TS} - 1) \tag{6}$$

Where R_T and L_T are the equivalent interfacing resistance and inductance seen by the inverter, respectively. Dead beat controller has a sample time delay, since it regulates the current when it achieves its reference at the end of the next switching period. Then, the controller indicates one sample time delay. In some cases like [30] an observer can be used by controller to complicate this time delay which is shows in Figure 6. The transfer function of this observer can be obtained by (7):

$$F_{DB} = \frac{1}{1 - Z^{-1}} \tag{7}$$

Then, the new current reference is:

$$i^{*'} = F_{DB}(i^* - i) \tag{8}$$

This kind of controller is fast, simple and it is suitable for microprocessor-based application [31].

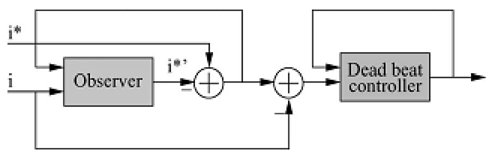
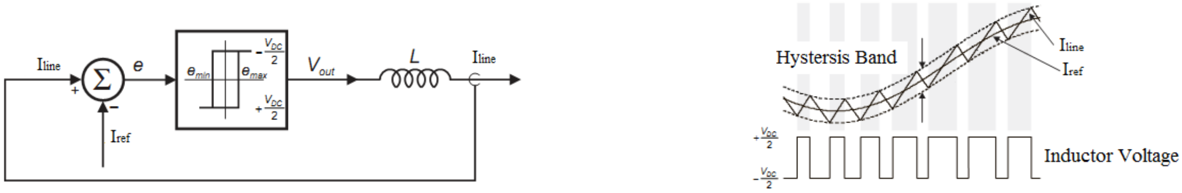


Fig.6: Block Diagram of Dead-Beat Controller

2.2.3 Hysteresis Control

Hysteresis current control is a method for controlling a voltage source inverter to force the grid injected current follows a reference current. A block diagram of a hysteresis controller is shown in Figure 7(a). The line current and reference current are used to control the inverter switches. Lower and upper hysteresis band limitations are related to the minimum and maximum error directly $(e_{\min}, e_{\max})$. When the reference current is changed, line current has to stay within these limits. The range of the error signal $(e_{\max} - e_{\max})$ directly controls the amount of ripples in the output current from the inverter which is called the hysteresis band. The ramping of the current between the two limits is shown in Figure 7(b). These kinds of controllers not only are robustness and simple but also have a good transient response. Due to the interaction between the phases, the current error is not limited to the value of the hysteresis band. The switching frequency of this controller changes by load parameter's variations which is changed the bandwidth and it can cause resonance problems. Moreover, the switching losses resist the application of hysteresis control to lower power level. This problem can be solved by employing variable limitation as mentioned in [32-35]. However, it requires system parameter's details.



(a) (b)

Fig.7: (a) Hysteresis Current Controller Block Diagram (b) Hysteresis Current Controller Operational Waveform

3. Performance Overview of Current Control Techniques

Current control techniques help inverters to provide stability, low steady state error, fast transient response and low total harmonic distortion when renewable energy sources are connected to the grid. Among linear grid connected controllers, the PI controller has a large gain at low frequencies where the PR controller gives the highest gain about resonance frequency, and RC achieves its high gain at the integral multiples of the fundamental frequency. This group of controllers are well known to eliminate the error. However, their dynamic response is not enough good compared to nonlinear controllers. Among linear controller techniques RC has the lowest transient response, and PR is the fastest one. Because of the dq control structure of PI controllers, their ability to compensate the harmonics is based on using low pass and high pass filters. However, a harmonic compensator for each harmonic order is necessary. Then, the control algorithm is become complicated. In overall, PI controllers are poor in eliminating the current harmonics. PR controllers as PI controllers are unable to give a large loop gain at the multiple harmonic frequencies to provide a good compensation for a wide band of harmonics. In linear controller group, RC gives a simple and practical solution for multiple harmonics compensation. A summary of comparison between linear controller techniques is shown in table 2.

Table. 2: Linear Current Control Techniques Comparison

	PI	PR	RC
High Gain	at low frequencies	around resonance frequency	at the integral multiples of the fundamental frequency
Steady State Error Elimination	Very Good	Very Good	Very Good
Dynamic Response	Fast	Very Fast	Slow
Harmonic Compensation	Poor	Poor	Good

Nonlinear controllers are famous for their dynamic response. This group has a fast transient response. Then, they can eliminate the low order current harmonics. It must be considered that the current waveform will carry harmonics at switching and sampling frequency's order. In this case, fast sampling capability of the hardware used is necessary.

4. Conclusion

Pollution and climate change are powerful reasons to cut down our use of coal, oil and natural gas. However, the environment is not the only the reason to replace the fossil fuel sources with renewables. In fact, if fossil fuels are emitted no pollution whatsoever, they would still be causing big problems for modern society. Renewable energy is very flexible because of it can be used in small systems for distributed generation or in truly massive installations for centralized generation. Since most of renewable energy systems are connected to the grid, using controlled inverter is necessary to have a safe and reliable grid interconnection. In this way, the current control type inverter is more commonly used, then in this paper the structure of the important linear and nonlinear current control techniques like PI, PR, RC, hysteresis, predictive and dead beat control were described. Finally, their ability to provide a high power quality generation to the grid was explained.

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