An Adaptive Frequency PLL Approach for Grid Connected Multifunctional Inverter for Residential Applications

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Abstract. This paper presents an adaptive frequency Phase locked loop (PLL) based approach for grid connected multifunctional inverter is presented for residential applications. The proposed control structure deals with non-linear loads and also non ideal grid voltages like magnitude variation, frequency variation, unbalance harmonics, etc. and can effectively address the DC offset in a voltage signal which in turn improves the power quality. A third order generalized integrator based PLL with adaptive frequency and DC offset elimination blocks will effectively deal with the power grid voltage fluctuations, frequency variations and eliminate the phase difference between PLL output. This approach is implemented as control algorithm for single-stage single-phase grid connected multifunctional inverter topology for PV applications which feeds energy to the grid. The Maximum Power Point Tracking is obtained by Perturb & Observe method for extracting maximum power from a Photovoltaic system. A detailed analysis with the proposed control technique is presented in this paper. Experimental tests are conducted at various operating conditions to describe and verify the performance of the proposed control using MATLAB / Simulink.

1. Introduction

Energy demand across the world is constantly rising due to increase in population, advances in technology and industrialization. Due to wide increase in energy demand across the world, the non-renewable energy sources which are in limited quantity are exhausting rapidly. Therefore, there is a necessity to shift to alternative and clean sources of energy generation as it not only meets the global energy demand, but also reduces environmental pollution, global warming and depletion of ozone layer. Among all renewable energy sources, solar photovoltaic energy is more adopted as it the most readily available source of energy which is also cost-effective and maintenance free. The application of solar PV systems is divided into two main areas in power systems: standalone or off-grid and on grid or grid connected. Standalone PV systems generate electricity for remote loads while grid connected applications are used to supply power for local loads and utility grids. The on-grid solar PV systems can supply the excess energy to the grid during low peak demands. The Grid interfaced PV systems are more commonly opted than standalone systems for as they do not require a battery which reduces the cost and maintenance. Moreover, in the grid connected PV system, the transmission and distribution losses are less as the power is generated and consumed close to the load demand. For on-grid PV systems the installation cost is high but the maintenance cost is low. There are two types of power generation in SPV systems which is either single-stage or two-stage in the distribution system.

Single-phase single-stage SPV-based inverters are proposed by some researchers for active power injection into the line as they are compact, reduced weight, easier integration and highly efficient compared with two stage topologies [1]. Two-stage multifunctional inverters also work well for active power injection in addition to power quality improvement [2], but they require an additional switch with
additional control that increases the complexity, reduces the reliability and increases the cost. Due to this, single-stage multi-functional inverters which use only one power circuit are becoming more popular these days for residential applications [3]. Inverter is the most significant unit of the grid connected photovoltaic systems as it converts DC power produced by the PV module into AC power to integrate with either the grid or the load. There are three types of multilevel inverter topologies which namely neutral point clamped (NPC), flying capacitor and cascaded H-bridge. A cascaded multilevel voltage source converter is robust, efficient and reliable and plays vital role in the grid integration of SPV system and is also a key element in Active power filters but it is increasing the capital cost because of additional switches and also increasing the computational burden due to a greater number of switches. Multifunctional inverters have many advantages like lower harmonic distortion, voltage stability, reactive power compensation and improved power quality. Grid synchronization is one of the most important aspect in distribution systems connected to grid as it plays a vital role concerning the interconnection of energy resources to the grid and a two-level inverter with multifunctional support will satisfy residential consumers. Furthermore, grid synchronization of SPV systems faces lot of challenges as it must ensure maximum power injection to the grid, provide good active power injection and reactive power compensation, reduce harmonic in turn keeping track of maximum power point of PV array. Hence, for the inverter to operate efficiently, it is required that the control algorithm operates efficiently especially when the grid voltage has abnormalities and irrespective of the behavior of the load. For this, a good phase locked loop technique is required that detects rapid changes in grid voltage, phase angle, frequency and generates accurate reference signals despite any disturbances in the signal.

Figure 1. Single-Stage PV Grid Connected System.

The voltage and current magnitudes and also phase angle of the grid voltage signal is estimated by a good Phase Locked Loop. An accurate PLL performance is required for proper integration of the grid under non ideal grid conditions and also for the control of grid connected power electronic converters. In all power electronic converters like grid connected inverters and reactive compensators, the dc offset, harmonics and phase jumps in the measured signal will diminish the PLL performance. SRF-PLL is widely used due to its simple control mode and good response speed [4]. A modified SRF-PLL for single-phase systems has shown better performance but the complexity is increased when prone to unbalanced signals [5]. Furthermore, SRF-PLL will have a large error in phase if there is a voltage fluctuation and high order harmonics exists in the grid voltage signal [6]. A good phase lock is obtained by Decoupled Double Synchronous Reference Frame – PLL which can eliminate the double harmonics caused by negative sequence component but this method has a huge amount of computation and slow dynamic response [7] and also the performance deteriorates when the grid signals have abnormalities. The second-order generalized integrator SOGI-PLL is simple and an efficient grid synchronization technique. SOGI-PLL has superior performance compared to SRF, ANF- based PLL and GI- based PLL [8]. In addition, the SOGI- PLL keeps tracking the input signal even after the fault conditions like voltage sag or phase jump [9]. For a three-phase four-wire Shunt Active Power Filter, a new control scheme for extraction of reference current using single phase SOGI-PLL has also been studied [10]. However, the
performance of this method is not satisfactory when lower order harmonics and DC offset are present in the voltage signal.

A control algorithm which uses an Inverse Park Phase-Locked Loop method for Multifunctional Grid-Connected SPV System [11] performs effectively under change in irradiance, grid disturbances and also under load perturbations but it uses multiple transformations wherein the computational burden increases. But the estimated frequency contains low frequency oscillations when the grid voltage has a dc offset. A new Control Algorithm for UPQC under abnormal grid conditions using Dual Second-Order SOGI based PLL [12] is proposed. An Improved dual-SOGI control is also studied for a three-phase unified power quality conditioner [13]. Some of the researchers proposed Frequency-locked loop techniques where frequency can be obtained adaptively such as Modified Dual Second-order Generalized Integrator PLL for grid synchronization [14]. This method employs a third integrator to eliminate dc offset but has not shown superior performance than other PLL techniques. Enhanced-comb frequency locked loop-based control is proposed which can reduce the grid current harmonics under abnormal grid conditions but did not specify anything about dc offset [15]. Many PLL methods have been studied and extensive research is being carried out for grid connected inverter applications. The advantages and disadvantages of PLL’s are studied [16-18]. If DC offset is present in the signal, these PLL’s perform less efficiently as the DC offset will be difficult to block due to its low frequency [19]. If the voltage varies more than 0.88-1.1pu, the sag and swell appear which makes the converter lose its control and causes the grid to trip.

Keeping in view of these problems, a mixed second-order generalized integrator called as third order generalized integrator-based phase locked loop is proposed in this paper for grid integration of PV with power quality improvement features. Many research works have been carried out to optimize the performance and extract maximum power from the PV panels [20]. This paper proposes a simple and robust controller for grid connected PV system and a modified P&O Method for tracking of maximum power point with a good tracking precision and improved response time [21]. The algorithm of the proposed control is explained in flow chart and the MPPT characteristics are shown in Figure 2 and Figure 3 respectively.

This modified method is compared with traditional fixed step size P&O methods, where the step size is larger which in turn results in faster dynamic response but excessive steady state oscillations. This results in comparatively low efficiency. The proposed technique has a larger step size when far away from MPP to obtain fast response speed but it is small step size near the near the MPP to get better performance.
The modified variable step size P&O MPPT algorithm proposed in this paper improves both the dynamic and steady state performance of the system. The output power, voltage and current of the proposed method when the temperature changes and irradiance are studied and compared with the traditional P&O method. The proposed control algorithm will generate gating pulses to the multifunctional inverter in such a way to efficiently integrate PV with the grid in addition to real power injection and harmonic rejection with improved power factor. A high-performance P&O technique is reviewed to identify the best suitable MPPT technique for single-stage multifunctional inverter for PV applications [22]. The proposed method tracks the accurate magnitude, phase and frequency and analysis is carried out to test the controller efficacy during harmonic loading, voltage sag, and swell in the grid voltage signal and sudden increase in load when applied. The control approach proposed in this paper found effective and can effectively eliminate the zero drift or grid voltage DC offset caused by sampling process or A/D and D/A conversion process in addition to the phase and magnitude estimation. The performance of the proposed controller is tested in MATLAB / Simulink environment with simpower systems block set.

2. Proposed System Configuration and Control Algorithm based on TOGI

The proposed single-phase grid connected Solar Photovoltaic generating system consists of Solar PV string, single phase H-bridge Voltage Source Converter (VSC), an interfacing inductor, a ripple filter, a single-phase grid and non-linear/power electronic load as shown in Figure 1. The PV string is obtained by a series parallel combination of small rating pv modules which are connected across the DC link of the VSC. A single-phase H-bridge inverter is used to transfer PV power to the grid [23]. A ripple filter connected between the VSC and the grid can dampen out the ripples present in the output signal of the VSC. To absorb the instantaneous voltage difference between the PWM voltage of VSC and the grid voltage, interfacing inductor is used. The non-linear load connected across the grid is a diode bridge rectifier and a multifunctional inverter connected through the Point of Common Coupling (PCC). The proposed controller not only transfers real active power to the grid and load but also compensates the reactive power drawn by the loads. Furthermore, the proposed controller can effectively eliminate the zero drift or DC offset caused by sampling process. The controller estimates peak amplitude and phase angle of the grid voltage signal and evaluates reference current for generating of gate signals to the inverter. A detailed control technique is explained in further section. This method which uses TOGI based PLL and QSG not only used to detect both phase and magnitude and obtain synchronized output signal but also reject higher order harmonics in the signal. The parameters like solar irradiance, wind direction, temperature etc. may disturb the output of PV array. An efficient P&O technique is used to extract maximum power from solar panel under varying temperature conditions. TOGI based extraction is implemented which improves the power quality at the distribution mains under nonlinear load and abnormal grid conditions [24]. The TOGI PLL can achieve adaptive frequency tracking in case of any frequency fluctuation of the power grid voltage. The proposed control algorithm which uses TOGI structure has the following benefits:

1. The TOGI can estimate the amplitude and phase of a grid voltage even under the disturbances and uneven grid faults.
2. Can accurately lock the phase in case the grid voltage consists of higher order harmonics, sags, swells and DC offset etc. in the grid. This method is proved to provide accurate and faster response. This has a modified frequency tracking ability by which the tracking precision and adaptability is improved.

The TOGI design structure is implemented and experiments are carried out on the proposed control algorithm due to the above-mentioned advantages.

2.1 Third Order Generalized Integrator

The conventional SOGI-PLL cannot provide accurate information if grid voltage consists of DC voltage and higher order harmonics. To overcome this disadvantage, this paper proposes a new control strategy
by adding DC offset elimination unit and adaptive frequency estimation unit to the existing SOGI PLL. The block diagram of the proposed structure is shown in Figure 4. This novel technique has two blocks, which are DC offset elimination unit and a frequency estimation unit.

1. The presence of dc offset in the signal will create oscillations at the fundamental frequency. The DC offset in a voltage signal or zero offset in the sampling process is suppressed by the DC elimination unit when the signal is passed through the TOGI. The unit restricts dc component and makes sure only the AC signal passes to the TOGI which in turn makes the magnitude of orthogonal signals equal without the DC offset and phase of the signal with a phase difference of 90°.

2. The adaptive frequency estimation unit will track the frequency accurately during a disturbance in the power grid frequency. The grid voltage orthogonal signal is constructed in such a way that the resonant frequency of TOGI will change with the grid frequency instantaneously.

\[
\begin{align*}
H'(s) &= \frac{V_{vo}}{V_{in}} = \frac{k_{w} s^2}{s^2 + (K + k_{dc}) w^2 s^2 + w^2 s + k_{dc} w^2} \\
H'(s) &= \frac{V_{vo}}{V_{in}} = \frac{k_{w} s}{s^2 + (K + k_{dc}) w^2 s^2 + w^2 s + k_{dc} w^2} \\
H'(s) &= \frac{V_{vo}}{V_{in}} = \frac{k_{w} (s^2 + w^2)}{s^2 + (K + k_{dc}) w^2 s^2 + w^2 s + k_{dc} w^2}
\end{align*}
\]

The adaptive transfer function is expressed as:

\[
w' = k_{f} \in \frac{V_{d}}{s} + w
\]

The above equation (4) is the transfer function of adaptive frequency unit [25].

2.2 Estimation of Peak Grid Voltage and Current

The grid voltage \(V_{t}\) is sent to TOGI based PLL for estimation of phase \((\omega t)\) and peak magnitude \((V_{P})\). The orthogonal signals of voltage and current signals that are generated from the TOGI based QSG are
free from ripples. The magnitudes of voltage and current signals are obtained by supplying the angular frequency of PLL back to the QSG of voltage and load current to generate in-phase and quadrature signals as shown in Figure 5.

\[ V_p = \sqrt{V_{3a}^2 + V_{3b}^2} \]  
\[ I_p = \sqrt{I_{L3a}^2 + I_{L3b}^2} \]  

### 2.3 Generation of Reference Currents

The P&O based MPPT technique is used for estimating the reference DC Voltage \( V_p \) and peak value of power \( P_{pv} \) from the string. The peak grid current is directly proportional to the peak value of power and inversely proportional to grid voltage. \( I_{pv} \) is the peak value of grid current for a given solar power and grid voltage signal. The equation is given as:

\[ I_{pv} = \frac{2 \times P_{pv}}{V_p} \]  

The estimated peak current is then multiplied with synchronizing signal to get instantaneous grid current. The mathematical equation for calculation of injected current is given as:

\[ I_p = I_p + I_{loss} - I_{pv} \]  
\[ I_p = I_p \times U, \]  

The DC link voltage and reference voltage \( V_{dc}^{*} \) are compared and the error signal obtained is supplied to the PI controller. The output of PI controller calculates the loss component of current signal. The magnitude of reference current is obtained if the estimated current \( I_p \) is added with the loss component of current \( I_{loss} \) and subtracted with injected current \( I_{pv} \). Now the measured source current is compared with the estimated source current at the PCC and is supplied to a hysteresis current controller which generate gate signals for the multifunctional inverter connected to the grid as shown in Figure 6. The multifunctional inverter switched with these gating pulses will make grid current follow estimated reference current through which overall unity power factor is achieved.

![Figure 6. Control Algorithm](image)

### 3. Simulation Results and Discussion

In this section, MATLAB simulation is carried out to test the efficacy of the proposed control for a single-phase Multifunctional Inverter (MFI) interfaced with grid and non-linear loads. Adaptive frequency based PLL was proposed for the quadrature signals generation which in turn peak estimation of magnitude and phase angle of the grid voltage signal. Similarly peak of the load current signal is also estimated using TOGI based QSG. The performance of the system is tested using MATLAB / Simulink on a single-phase residential system. A single-phase 230V system with frequency 50 Hz, \( R_s=0.5 \), \( L_s=1.5\text{mH}, L_L=60\Omega, L_L=0.060, V_{dc}=400\text{V}, C_{dc}=3600\mu\text{F}, K_p=0.1, K_i=0.6 \) is chosen for simulation.
Initially, steady state conditions with a PV Temperature at 25°C and an irradiance of 1000w/m² are tested while interfacing to grid and non-linear load and the results are shown in Figure 7. In this condition, even when the load applied is non-linear, the source current is linear and sinusoidal and the THD is within the IEEE limits. In Figure 8, a voltage swell of 15% is applied to the grid voltage in order to create a voltage disturbance but, the controller acted accordingly and tracked the grid voltage magnitude and phase accurately which proves the effectiveness of the proposed controller. In order to test the dynamic changes in the load current, a sudden load is applied. The controller has shown fast response in tracking the changes in the load current and performed well while meeting with PV source and the grid as shown in Figure 9. PV is also tested along the change in irradiance where a clear reduction of PV current can be observed with the changes in irradiation from 1000 to 800 W/m², 800 to 600 W/m² and 600 to 1000 W/m² from Figure10 to 12. The PV Temperature is also changed from 25°C to 35°C and 35°C to 30°C as shown in Figure 13 & 14. From all these test cases it is determined that the proposed controller is tracking the grid voltage and current accurately during adverse grid and load conditions and the MPPT is tracking the change in temperature and irradiance properly within the shortest possible time.
4. Conclusion

A simple controller based on frequency adaptive approach for a single-phase single-stage grid connected multifunctional inverter is presented and experimentally tested using MATLAB / Simulink. The tracking ability of the grid voltage or load current signal under adverse grid conditions and sudden load changes has been experimentally proved. The solar PV system is integrated with the grid in such a way to feed the load and also to the grid during off load conditions. The controller is tested during change in temperatures and irradiance, voltage swell, non-linear load conditions and sudden changes in load. In all these conditions, the tracking of peak load current and voltage magnitude and phase are found to be satisfactory.

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