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INTEGRATION OF SMALL-SCALE PHOTOVOLTAIC SYSTEMS INTO SECONDARY DISTRIBUTION GRIDS USING PHASE-LOCKED LOOP METHOD TO IMPROVE STABILITY

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***ABSTRACT*:**

With the increasing share of renewable energies in the global energy mix, solar photovoltaic systems, especially small-scale and rooftop systems, have grown significantly. However, the increasing penetration of these systems into secondary distribution grids has created new challenges in the areas of dynamic stability, power quality, and grid synchronization. This paper examines all the mentioned aspects of a specific 10 kW integrated PV system connected to the secondary of the secondary distribution network, including various standards such as grid, operation under severe faults, and control methods related to small-scale photovoltaic power plants. The main innovation of this research is the use of the SOGI-PLL (based on the second-order generalized integrator) structure as a synchronization method in the secondary distribution network, simultaneously considering the weak network conditions, the presence of harmonics, and the requirements of the low-voltage transient (LVRT). Unlike traditional methods such as Delay-PLL, which have poor performance in polluted and weak network conditions, the proposed method, using the SOGI filter and frequency feedback loop, is able to accurately extract the fundamental frequency component from the polluted voltage and maintains its stability in networks with low short-circuit ratio (SCR=5). In this paper, we conclude that the phase-locked loop method is suitable for integrating small-scale grid-connected photovoltaic systems to achieve better stability in the distribution network.

Keywords*: Renewable energies. SOGI-PLL structure. , Photovoltaic systems. To improve stability*

INTRODUCTION

The relative share of renewable energy, especially photovoltaic (PV), in the world's electric power sector is increasing exponentially. This is a collective result of the reduction in the cost of solar panels, and the improvement in panel efficiency, which is associated with the advancement in power electronics. Meanwhile, various types of small-scale photovoltaic power plants are growing rapidly due to the direct user benefits and government incentives. Naturally, there are different standards regarding grid integration and photovoltaic systems and other distributed generation (DG). Today, in addition to concerns related to environmental issues and the depletion of fossil energy resources, the economic growth and reduction in the cost of installing photovoltaic systems are factors in the development of photovoltaic systems for energy supply in many countries around the world (Naghviha and Parastgari, 2016). With the increasing penetration of photovoltaic (PV) sources in active distribution networks, the issue of voltage fluctuations and maintaining operational stability has become one of the main challenges for network operators. The intermittent nature of PV generation, especially due to phenomena such as cloud movement, causes local overvoltages and an increase in the frequency of operation of mechanical equipment such as on-load tap changers (OLTC), which traditional voltage and reactive power control methods alone cannot effectively manage. In this regard, the IEEE1547-2018 standard has defined a new role for smart inverters in voltage control by introducing network support functions such as Volt-Var and Volt-Watt; However, the uncoordinated exploitation of these capabilities can lead to control interference and increase network losses (Borazan and Salimifard, 1404).

Small-scale energy is provided by distributed energy generation sources. Renewable energies are of great importance compared to conventional ones because they are considered part of clean energies. For the safe operation of grid-connected and islanded modes, protective coordination intervals are properly designed. When the number of PV-based DNERs increases, the amount of fault current decreases. If the amount of fault current exceeds the loading limits, it creates a greater challenge for power system engineers (Pourvaez Esfahani and Khalili, 1401). Like other generators and power plants, photovoltaic systems can be installed and operated at any capacity. Even its limitation is much less than others and it can be built as generators with a power of milliwatts to several megawatts. However, due to the low energy conversion efficiency of this system and the high price of its equipment, the electricity produced from this system is somewhat more expensive. To design a photovoltaic system, it is necessary to consider and examine various factors, some of which are effective in calculating the capacity and output of the system, or estimating the electricity that is produced, and others play a role in selecting the type of equipment and their design. Given the reduction of fossil fuel resources and the increasing need for electrical energy in modern life today, the use of renewable sources in electricity generation is a suitable alternative to fossil fuels. Among these renewable sources, the use of solar energy is very significant due to its availability and high potential in producing clean energy. Urban and high-rise construction has reduced the efficiency of buildings based on integrated photovoltaic technology. The need for accurate architectural design in accordance with the amount of sunlight has led to the emergence of a new generation of clean energy buildings. Photovoltaic systems, originally developed and perfected for space applications, convert light energy directly into electrical energy (Aurei, 1401).

The growth of the use of power electronic devices in most renewable energy sources, in distribution networks, in voltage and current disturbances, is a major challenge. It will lead to power quality problems in the distribution system. With the growth of photovoltaic systems' connection density to the distribution grids more than expected, environmental factors, especially fluctuations in solar radiation, can affect undesirable changes in the quality of the supplied electricity. Power quality depends on factors such as the topology of the distribution system, the type of joint, the electronic equipment in use, the geographical area, and the length of the power lines of the distribution grid. Load behavior and weather changes will also affect power quality. One of the power quality problems is harmonics. Nonlinear network behaviors and the presence of sensitive loads can produce current harmonics. The network impedance will also combine with current harmonics to produce voltage distortion at the joint connection point. Harmonics will cause problems such as reduced life of transformers and induction motors, degradation of the voltage waveform, and malfunction of the protection system (Sadraei and Taghipour, 2015).

PV systems can be divided into two types: PV systems with and without storage. In the case of a stand-alone PV system with storage, the generated power charges a battery and is used to power the load. However, when a PV system is used without storage, the harvested power must be fully used by the load to maintain power balance. In other words, the power generation must be exactly equal to the load demand. Therefore, if the load does not match the maximum power output from the PV source, maximum power generation is not possible.

To avoid the need for bulky, short-lived, and expensive batteries, photovoltaic systems are preferably operated in grid-connected mode. One of the main objectives associated with all solar power plants is to generate the maximum power available from the solar panel. However, depending on the load demand, solar power plants can also operate outside the (MPP). Therefore, MPP is a desirable condition but not a necessary condition.

The entire power system grid can be broadly divided into three parts. Typically, electricity is generated in various power plants with a voltage level varying between 10.5 and 25 kV. This voltage is stepped up and the power is transmitted through the transmission network. The voltage level of the transmission network is between 220 and 765 kV. This power is transmitted through the sub-transmission network (66 or 132 kV) and finally to the distribution system. The distribution network is classified into two types: primary/medium voltage (MV) distribution network and secondary/low voltage (LV) distribution network. Industrial and residential loads are connected to the MV and LV distribution networks, respectively. All back-up photovoltaic systems are connected to the secondary distribution network. Since this paper mainly focuses on grid integration with rooftop photovoltaic systems, all the discussion is limited to the secondary distribution network only.

Grid-connected PV systems can be classified into three types based on installed capacity:
1) Power plant scale (1 to 10 MW)
2) Medium scale (10 to 1000 kW)
(3Small scale (10 kW)

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For example, small-scale rooftop PV systems cover approximately 12% (1247 MW) of the total PV system capacity in India. An additional 40 GW of rooftop PV is expected to be installed in India by 2022. Although the relative amount of rooftop PV is lower compared to large-scale PV, the number of installations is significantly higher. Power is transferred from the PV panel to the grid through a power converter. The associated control controls both the quality and quantity of the power transfer. The power stage and the control stage must adhere to specific rules and regulations, known as standards, while feeding power into the grid. Various international and national standards have been developed regarding PV integration in various industries. These standards specify basic operating principles, power quality recommendations, safety measures, and PV response to abnormal grid conditions, etc., to ensure proper grid integration. Power electronics are used to convert effective power from one form to another, as a power interface, between the DC output of the PV panel and the ac grid. For this purpose, it is connected to the utility grid. Most grid integration standards recommend that the PV current generated by the PV system should be in phase (amplitude, angle, frequency) with the distribution grid voltage. This requires coordination between the grid and the PV system. Among these methods, phase-locked loop (PLL)-based methods are the most popular. The aim of control related to PV systems is twofold. 1) to ensure maximum power extraction, and 2) to properly prepare the injected current to achieve the specified requirements, for which several control architectures and algorithms have been proposed. On-grid PV integration directly connects many active resources to the distribution grid. This extensive active distribution grid is not always equivalent to a microgrid because of the following:

1) there is no connection point.
2) there is no controllable switch to connect and disconnect it from the main grid.
3) The installed generation capacity can be much less than the critical peak load.

Therefore, the active distribution network cannot always be considered as a microgrid.

IMPORTANCE AND NECESSITY OF RESEARCH

In today's world, due to the depletion of traditional and non-renewable energy sources such as oil and various fossil fuels and the consequent increase in the price and scarcity of these types of energy sources, governments have started thinking about using alternative energy sources for non-renewable energy sources. The most important factor in choosing alternative energy sources for fossil fuels is the renewability of new resources and also the environmental friendliness of these types of resources. For this purpose, the use of energies derived from nature such as: solar energy, wind energy, energy from water flows, etc. has been globally popular. The use of distributed generation energy sources in the distribution network in order to increase the level of service to subscribers and improve the level of social welfare is of great importance for times when the network experiences problems such as outages and breakdowns, etc. (Dhoon and Gholitabar, 2017). The use of renewable energies and photovoltaic lighting systems is one of the effective ways to reduce environmental pollution caused by the consumption of fossil fuels by power generation plants. Considering the two percent share of street lighting in total energy consumption and the thirty percent share of lighting in the average electricity consumed in the household sector, the use of renewable energies in this sector will lead to a reduction in environmental pollution (Yaqub Vand, 2010). Basically, today, energy is the main and fundamental source of human life. Considering the depletion of fossil fuels, their destructive environmental effects and subsequent air pollution, as well as the increase in energy consumption, we can no longer rely on the energy source we use today; Therefore, we must look for a suitable alternative for them. Those energy sources that are constantly being reproduced in nature are called renewable energy. Researchers have introduced it as a suitable alternative to fossil fuels by examining renewable energies, especially solar energy; therefore, it can be said that the use of solar systems, especially photovoltaic solar systems, as the best energy sources that do not have any environmental harm is important. Renewable energies, especially photovoltaic solar energy systems, are the most effective solution for achieving economic benefits, increasing energy security, and reducing environmental pollution. Photovoltaic technology is a safe source of energy production and does not contain any environmental pollution; therefore, it is known as the healthiest type of energy. Among the environmental and economic benefits of photovoltaic systems are the sale of energy in a centralized and decentralized manner, increased energy security, provision of significant job opportunities, prevention of toxic gas emissions and reduction of greenhouse gas emissions (Majidi Majd and Shahabinia, 1403).

The voltage amplitude (V), frequency (f), and phase of the PV photovoltaic system must be matched to the grid before they are connected. These quantities are also used to continuously monitor grid conditions. Therefore, accurate and rapid determination of the phase amplitude and frequency of the grid voltage is essential. For this purpose, various power electronics converters and topologies have been proposed that generally convert the available DC power to AC power and feed it into the grid. Most grid integration standards recommend It is known that the PV plant should feed the phase current with the grid voltage. This requires coordination between the grid and the PV plant.

RESEARCH OBJECTIVES

The main objective of grid integration methods is to strike a balance between grid synchronization accuracy and circuit complexity. For integration with the secondary distribution grid, grid synchronization methods should be tested for weak and disturbed voltage conditions. Research on synchronization methods should also focus on eliminating the need for grid voltage sensors.

The scientific objectives of this research are:
1) Efforts to combine different technical requirements for rooftop PV integration into the existing distribution grid using small-scale single-phase inverters.
2) Consideration of various aspects of microgrid research, which can be directly used in grid feeding from PV plants to bridge the gap between microgrid research and PV injection into the existing distribution grid.
3) It summarizes the various standards, power interface architectures, grid synchronization techniques, and control methods related to small-scale grid-connected, low-voltage PV power plants.
4) It discusses the response of the PV system under normal and abnormal operating conditions.

RESEARCH HYPOTHESES

The phase-locked loop method is suitable for integrating small-scale grid-connected photovoltaic systems to achieve better stability in the distribution network.

3-2-3- Measurement Points and Control Signals

To implement the system controllers, the following signals need to be measured, which are shown in Figure 1 with specific symbols:
- Panel voltage (Vpv) and panel current (Ipv): These signals are measured at the input of the Boost converter and are used to implement the MPPT algorithm.
- DC link voltage (Vdc): This signal is measured across the DC link capacitor and applied to the DC voltage controller.
- Inverter output current (ig): This signal is measured at the filter output (transformer input) and applied to the current controller at the rotating reference (dq).
- Common point voltage (Vpcc): This signal is measured at the point of connection of the system to the grid (transformer secondary side) and applied to the synchronization system (PLL).
All measured analog signals, after passing through low-pass filters (to remove high frequency noise), are sampled by analog-to-digital converters (ADC) and transmitted to the digital controller (DSP or microcontroller).

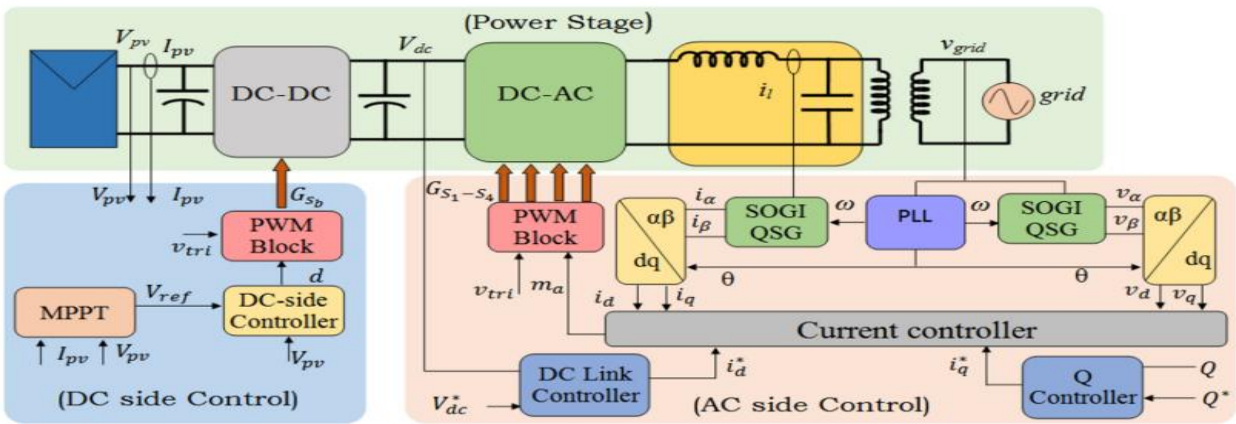

Figure 1. Complete block diagram of a 10 kW photovoltaic system connected to a secondary distribution network (Panigrahi et al. 2020)

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3-3- Mathematical modeling of system components

In this paper, the differential equations and relationships governing each of the system components are extracted. Mathematical modeling is the basis for the design of controllers and system stability analysis. All models are extracted based on the physical laws governing electrical circuits (Kirchhoff's voltage and current laws) and the characteristics of power electronic elements (inductor, capacitor, diode, and switch).

1-3-3- Solar panel model and electrical characteristics

A solar panel is a nonlinear element whose output current depends on its voltage across it, solar radiation intensity, and ambient temperature. In this study, a single-diode model is used to model the solar panel. The equation governing the panel output current is as follows:

$$I_{pv} = I_{ph} - I_s\left[\exp\left(\frac{V_{pv}+R_s I_{pv}}{nV_t}\right)-1\right]-\frac{V_{pv}+R_s I_{pv}}{R_{sh}} \quad .١$$

Where, Ipv is the panel output current (amperes), Vpv is the panel output voltage (volts), Iph is the photogenerated current (proportional to solar radiation), Is is the diode reverse saturation current, n is the diode ideality factor (usually between 1 and 2), Vt is the thermal voltage, Rs is the panel series resistance, and Rsh is the panel shunt (parallel) resistance.
The photogenerated current (Iph) depends on the radiation intensity and temperature and is calculated from the following equation:

$$I_{ph} = \left(I_{ph\_ref} + K_i\left(T - T_{ref}\right)\right)\times\frac{G}{G_{ref}} \quad .٢$$

Where, Iph_ref is the photogenerated current under reference conditions (irradiance 1000 W/m2 and temperature 25°C), Ki is the temperature coefficient of the current (in amperes/degree Celsius), T is the ambient temperature (in Kelvin), Tref is the reference temperature (298 Kelvin), G is the instantaneous irradiance intensity (W/m2), and Gref is the reference irradiance intensity (1000 W/m2).

Open circuit voltage (Voc) and short circuit current (Isc) are two key panel parameters that can be extracted from the I-V characteristic. In open circuit conditions (0Ipv=), the output voltage is equal to Voc. In short circuit conditions (0Vpv=), the output current is equal to Isc.

To reduce the high frequency harmonics produced by the inverter, a low pass filter L is used at the output, which consists of an inductor with inductance Lf and series resistance Rf. The differential equation governing the inverter output current is obtained by applying Kirchhoff's Voltage Law (KVL)

$$L_f\frac{di_g}{dt} = V_{inv} - V_g - R_f i_g \quad ٣$$

By rearranging the equation:

$$\frac{di_g}{dt} = \frac{1}{L_f}V_{inv} - \frac{1}{L_f}V_g - \frac{R_f}{L_f}i_g \quad ۴$$

Where, ig is the inverter output current (the same current injected into the grid), Vinv is the inverter output voltage (filter input), and Vg is the grid voltage (filter output).

Filter transform function L:
By applying the Laplace transform to equation 3-14, the filter transform function is obtained as follows:

$$G_{filter}(s) = \frac{i_g(s)}{V_{inv}(s) - V_g(s)} \quad ۵$$

This conversion function will be the basis for the design of the current controller.

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2-3-3- **Boost Converter Model**
The Boost converter is a boost DC-DC converter consisting of an inductor (Lb), a power switch (MOSFET), a diode, and an output capacitor (Cdc). This converter controls the output voltage by changing the duty cycle (D) of the switch. Using the State-Space method, the differential equations governing the Boost converter in the two states of switch conduction and diode conduction are extracted as follows:

State 1: Switch on (0 t ≤ DT ≤)
In this state, the switch conducts and the diode is off. The inductor stores energy and the capacitor supplies the load. State 2: Switch off (DT ≤ t ≤ T)
In this state, the switch is off and the diode is on. The inductor discharges its stored energy to the capacitor and load.

Average Model:
For the design of controllers, the average model of the converter is used, which is obtained by averaging the state equations over a switching period:

$$6\ \frac{di_L}{dt} = \frac{1}{L_b}V_{pv} - \frac{1}{L_b}(1-D)V_{dc}$$

$$7\ \frac{dV_{dc}}{dt} = \frac{1}{C_{dc}}(1-D)i_L - \frac{1}{C_{dc}}I_o$$

The relationship between output and input voltage in steady state:

$$8\ \frac{V_{dc}}{V_{pv}} = \frac{1}{1-D} \quad \Rightarrow \quad V_{pv} = V_{dc}(1-D)$$

This relationship shows that as the duty cycle D increases, the output voltage increases and vice versa. Therefore, by changing D, the input voltage (panel voltage) can be controlled and set at the maximum power point.

Boost Converter Inductor Value: For operation in Continuous Conduction Mode (CCM), the inductor value must be greater than the following relationship:

$$9\ L_b > \frac{D(1-D)^2 R}{2f_{sw}}$$

Where R is the equivalent load resistance and fsw is the switching frequency.

3-3-3- **DC Link Capacitor Model**
The DC link capacitor (Cdc) is a key element in the system that is responsible for energy storage, oscillatory power compensation, and dynamic isolation between the Boost converter and the inverter. The differential equation governing the DC link capacitor voltage is obtained from the balance of input and output currents:

$$10\ C_{dc}\frac{dV_{dc}}{dt} = I_{dc\_boost} - I_{dc\_inv}$$

Where, the output current of the Boost converter is calculated from Equation 11. The input current to the inverter is calculated from Equation 12.
The output current of the Boost converter, assuming 100% efficiency and using power balance, is calculated as follows:

$$11\ I_{dc\_boost} = \frac{V_{pv} \times I_{pv}}{V_{dc}} = I_{pv}(1-D)$$

The input current to the inverter is also obtained from the balance of AC and DC power, assuming 100% efficiency:

$$12\ I_{dc\_inv} = \frac{V_{inv} \times I_g}{V_{dc}}$$

Where Vinv is the inverter output voltage and Ig is the grid injection current.

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DC link voltage ripple considering instantaneous power fluctuation (
$V_{dc} I_{dc\_ripple} P_{ripple} =$ ،(The DC link voltage ripple amplitude is calculated from Equation 13:

$$13\ \Delta V_{dc} = \frac{P_{pv}}{2\omega_g C_{dc} V_{dc}}$$

where is the angular frequency of the grid. This relationship is the basis for calculating DC link capacitor capacity.

4-3-3- single-phase voltage source inverter model and output filter
The single-phase voltage source inverter (VSI) is a full-bridge type with four power switches (S1, S2, S3, S4). This inverter is controlled using pulse width modulation (PWM) and with high switching frequency (fsw).
Inverter output voltage relationships:

The inverter output voltage (Vinv) is produced as a pulse wave with Vdc amplitude and using PWM modulation. In the average model, this voltage is expressed as follows:

$$14 V_{inv}(t) = V_{dc} \times m_a \times \sin(\omega t + \phi)$$

where ma is the amplitude modulation index (ratio of the reference signal amplitude to the carrier signal amplitude), ω is the grid angular frequency, and ϕ is the phase angle of the output voltage relative to the grid voltage.

3-3-5- Secondary Distribution Network Model
The secondary distribution network is a network with an effective voltage of 220 V and a frequency of 50 Hz to which residential and small commercial consumers are connected. In this study, the network is modeled as an ideal sinusoidal voltage source with a series impedance (Thönen equivalent):

$$15 V_{pcc} = V_g - Z_g \times I_g$$

Where, Vpcc is the point of common connection (PCC) voltage, Vg is the grid voltage (ideal source with amplitude of 311 V and frequency of 50 Hz), Zg is the series impedance of the grid and Ig is the current injected into the grid.

The series impedance of the grid is considered in two different cases:
1. **Strong grid case:**
In this case, the series impedance of the grid is very small and negligible ( ). As a result, the PCC voltage will be equal to the ideal grid voltage ( ). This case simulates the conditions of distribution networks close to superdistribution substations.

٢**. Weak Network Case:**
In this case, which is one of the key scenarios of this research, the series impedance of the network is modeled as a series resistance and inductance with specific values. The short circuit ratio (SCR) is defined as:

$$16\ SCR = \frac{S_{sc}}{P_{pv}}$$

where, Ssc is the short circuit power at the PCC point and Ppv is the rated power of the system. In weak networks, SCR<10 and usually SCR<3 is considered for very weak networks. The network impedance is calculated from the following equation:

$$17\ Z_g = \frac{V_g^2}{S_{sc}}$$

And assuming a certain X/R ratio (usually between 5 and 10 in distribution networks), the series resistance and inductance are separated as follows:

$$18\ R_g = \frac{Z_g}{\sqrt{1+(X/R)^2}}$$

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19 $L_g = \frac{X_g}{\omega_g} = \frac{(X/R)\times R_g}{\omega_g}$

As Zg increases (SCR decreases), the voltage drop across the grid impedance increases and the PCC voltage (Vpcc) moves away from the ideal grid voltage (Vg). This condition affects the performance of the PLL and current controllers and can lead to dynamic instability, which is discussed in detail in the Results section.

4-3- **System Controller Design**

In this section, the design of all controllers required for the correct operation of the grid-connected photovoltaic system is presented. According to the article (Panigrahi et al., 2020), the system control is divided into two main parts:
(1) DC side control (related to the panel and Boost converter)
(2) AC side control (related to the inverter and the grid).
DC side control includes the Maximum Power Point Tracking (MPPT) algorithm, which is responsible for extracting the maximum power from the solar panel. The AC side control consists of three main parts: the DC link voltage controller (outer loop), the current controller in the dq rotating reference (inner loop), and the grid synchronization system (PLL), which is the core of this research. In the following, each of these controllers is designed in detail.

1-4-3- **Maximum Power Point Tracking (MPPT) Algorithm by Perturb & Observe (P&O) Method**

In this section, the P&O algorithm is introduced and implemented as one of the most common maximum power tracking methods. The operating principles of this method are based on creating a disturbance in the panel voltage and observing the changes in the output power. If the power increases with increasing voltage, it means that the direction of the disturbance is correct and should be continued. Otherwise, the direction of the disturbance is reversed. The decision criterion in this algorithm is based on voltage changes (ΔVpv) and power changes (ΔPpv), which are expressed as follows:

20 $\Delta P_{pv} = P_{pv}(k) - P_{pv}(k-1)$

21 $\Delta V_{pv} = V_{pv}(k) - V_{pv}(k-1)$

If ΔPpv >0 and ΔVpv >0, the reference voltage increases. If ΔPpv>0 and ΔVpv<0, the reference voltage decreases. If ΔPpv<0 and ΔVpv>0, the reference voltage decreases, and if ΔPpv<00 and ΔVpv<0, the reference voltage increases. The disturbance step (ΔVref) determines the tracking speed and accuracy and should be selected according to the performance criteria. The reference voltage generated by the MPPT is applied to the panel voltage controller (implemented in the Boost converter).

2-4-3- **DC Link Voltage Controller (Outer Loop)**

The DC Link Voltage Controller is a proportional-integral (PI) controller that is responsible for maintaining the DC link capacitor voltage at its reference value (400 V). This controller calculates the error by comparing the measured voltage (Vdc) with the reference value (Vdc_ref) and, after applying the coefficients Kp_dc and Ki_dc, generates the reference current along the d-axis (id_ref). The output of this controller is used as the input of the current controller in the inner loop. The equation of this controller is as follows:

22 $i_{d\_ref}(t) = K_{p\_dc}(V_{dc\_ref} - V_{dc}(t)) + K_{i\_dc}\int (V_{dc\_ref} - V_{dc}(t))dt$

The design of Kp_dc and Ki_dc coefficients is based on the pole placement method and considering the desired dynamic response (settling time of about 50 milliseconds and overshoot less than 5%). Also, to prevent saturation of the integrator, an anti-saturation mechanism is used.

3-4-3- **Rotating Reference Flow Controller (SRF): Inner Loop**

The rotating reference flow controller (SRF) is the specialized heart of the AC side control that is responsible for controlling the injected current to the grid. In this method, the time-varying sinusoidal currents in the static reference (αβ) are converted to DC quantities in the rotating reference (dq) using the Park transform. This conversion is performed using the angle estimated by the PLL (θ). The Park transform is defined as follows:

23 $\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$

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where iαig is the measured current and iβ is the orthogonal signal generated by the orthogonal signal generator (OSG). In the dq reference, the id component is equivalent to the effective current in line with the grid voltage (active power) and the iq component is equivalent to the current perpendicular to the grid voltage (reactive power). The flow controller uses two separate PI controllers for the d and q axes. The reference current in the d-axis is generated by the DC voltage controller, and the reference current in the q-axis is assumed to be zero to achieve unity power factor.

4-4-3 **Network synchronization system (SOGI-PLL): proposed method**
Network synchronization system is responsible for accurate and fast estimation of phase angle, frequency and range of network voltage. In this research, the structure of SOGI-PLL (based on generalized second-order integrator) (Panigrahi et al., 2020) is used as the proposed method. Due to its high resistance to harmonics and frequency changes, this method is very suitable for use in the secondary distribution network (which is often polluted and weak).

SOGI-PLL structure consists of three main parts:
(a) SOGI-based orthogonal signal generator (SOGI-OSG):
This section produces the orthogonal signal ( ) from the input signal ( ). The differential equations governing SOGI are as follows:

24 $$\frac{dx_1}{dt} = \omega`(x_2 + k(\upsilon_\alpha - x_1))$$

25 $$\frac{dx_2}{dt} = -\omega` x_1$$

where is the estimated in-phase signal, is the estimated orthogonal signal, is the estimated angular frequency, and k is the SOGI gain (usually for optimal response).

The estimated voltage amplitude is also calculated from the following equation:

26 $$V`_{amp} = \sqrt{(\upsilon`_\alpha)^2 + (\upsilon`_\beta)^2}$$

(b) Phase detector:
This section calculates the phase error between the grid voltage and the estimated voltage. In the reference dq which rotates by the estimated angle ( ), the q component of the voltage is equivalent to the phase error. Using the Park transform on the SOGI outputs, the phase error is calculated as follows:

27 $$\upsilon_q = -\upsilon`_\alpha \sin(\theta`) + \upsilon`_\beta \cos(\theta`)$$

In the locked condition, and the estimated angle is equal to the grid angle. In the fault condition, it is equivalent to the phase error and is used as the input to the PI loop.

(c) Loop filter and voltage controlled oscillator (VCO):
The loop filter is a PI controller that receives the phase error ( ) and produces the estimated angular frequency ( ). The equation of this controller is as follows:

28 $$\omega`(t) = K_{p\_pll} \times \upsilon_q(t) + K_{i\_pll} \int \upsilon_q(t)dt + \omega_{grid}$$

where is the nominal angular frequency of the network (radians per second) and and are the PI controller coefficients of the PLL loop.

The estimated frequency is limited to the range to avoid unstable operation under severe fault conditions. The voltage controlled oscillator (VCO) also produces the estimated phase angle ( ) by integrating the estimated frequency:

29 $$\theta`(t) = \int \omega`(t)dt$$

In this research, to improve the performance of SOGI-PLL in secondary distribution network (which has multiple harmonics and noise), an adaptive method for adjusting SOGI gain (k) and PI coefficients based on voltage quality index (such as THD) is proposed, which increases stability and reduces phase error in different conditions. Also, using a modified structure to generate orthogonal signal ( ) with the ability to remove low-order harmonics is another innovation of this research.

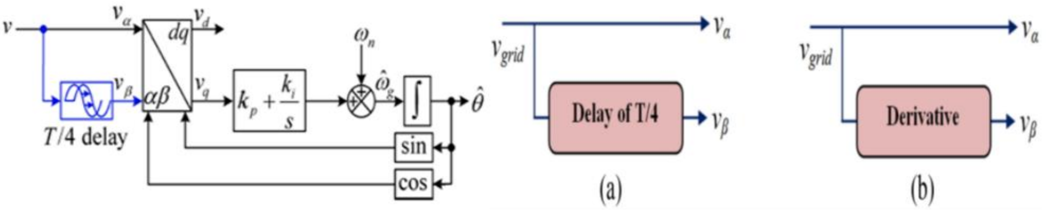

Figure 2: pPLL (Product-type PLL) structure

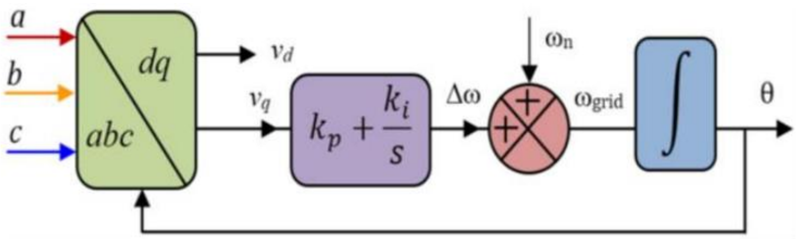

Figure 3: Park-PLL structure

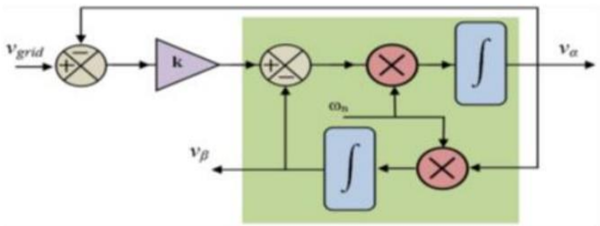

Figure 4: Structure of QSG (Quadrangular Signal Generator)

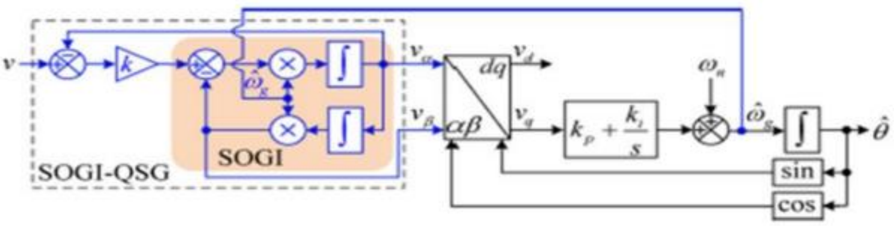

Figure 5: SOGI-PLL structure

Compliance with IEEE 1547 and IEC 61727 standards
In this research, all control designs and parameter selections have been carried out based on the requirements of IEEE 1547 and IEC 61727 standards. Table 1 shows a summary of the most important requirements of these standards and how they are met in the proposed system.

Table 1: Compliance of the proposed system with IEEE 1547 and IEC 61727 standards

Implementation method in this research	Standard requirement	Parameter
PI controller with Anti-Windup	±5% of nominal value	DC Link Voltage
L filter + resonant controller	< 5%	Current THD
Resonant controller at h=3,5,7,9	<4%	Odd Harmonics (3-9)
Isolation transformer	< 0.5% of nominal current	DC Injection
Iq_ref=0 control in normal mode	> 0.9	Power Factor
Reactive power injection strategy	According to Table IV	LVRT Cut-off Time
Frequency detector with ROCOF	According to Table V	Frequency Cut-off Time
ROCOF method + active method (if necessary(	2 >seconds	Island detection

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Simulation Parameter Settings

The main simulation parameters are summarized in Table 2. These parameters are selected based on the characteristics of the 10 kW system and the secondary distribution network and are constant in all test scenarios except those that are explicitly changed.

Table 2: Main System and Simulation Parameters

Unit	Amount	Parameter
Kilowatt	١٠	System Rated Power (Ppv)
Volt effective	٢٢٠	Grid Voltage (Vg)
Hertz	٥٠	Grid Frequency (fg)
Volt	۴٠٠	DC Link Voltage (Vdc)
Microfarad	٢٢٠٠	DC Link Capacitor (Cdc)
Millihenry	۵	Filter Inductance (Lf)
Ohm	٠,١	Filter Resistance (Rf)
Kilohertz	١٠	Inverter Switching Frequency (fsw)
Second	١e-۵	Simulation Time Step (Ts)
Second	٢	Total Simulation Time (Tsim)
-	Runge-Kutta 4 (ODE4)	Numerical Solution Method

- Test and Evaluation Scenarios

For a comprehensive evaluation of the system performance, five main scenarios have been defined, each testing specific aspects of the system performance. These scenarios have been selected based on international standards and real challenges of active distribution networks.

Figure 6 shows the grid voltage and injected current. As can be seen, the inverter output current reaches a steady sinusoidal state after a short transient (about 50 milliseconds) and is completely in phase with the grid voltage, indicating unity power factor (PF≈1). The steady-state current amplitude is about 32 A, which corresponds to a power of 10 kW and a voltage of 220 V. The current waveform is well sinusoidal and there is no noticeable distortion, indicating the correct operation of the current controller and output filter. The time for the current to reach 90% of its final value (response time) has been measured to be about 30 milliseconds, and its settling time (entering the range of 2% of the final value) has been measured to be about 50 milliseconds.

Comparison of performance of SOGI-PLL and Delay-PLL in presence of harmonics

To demonstrate the advantage of the proposed method, the performance of SOGI-PLL is compared with the simpler Delay-PLL method (in which the orthogonal signal is constructed with a quarter-cycle delay) in the presence of harmonics. Table 4-4 shows this comparison. As can be seen, Delay-PLL has a poor performance in the presence of harmonics, and its phase error and frequency oscillations increase sharply. In contrast, SOGI-PLL is able to extract the fundamental frequency component well and maintain its stable performance.

Table 3: Comparison of performance of SOGI-PLL and Delay-PLL in the presence of harmonics

Delay-PLL	SOGI-PLL	Indicator
١٢,۵	٢,٠	Permanent phase error (degrees)
٠,۴۵	٠,٠٢	Estimated Oscillation Frequency (Hz)
١٨٠	٧٠	Lock time (ms)
۶,٨	۴,١	THD injection current (%)

The main achievements of this research can be summarized as follows:

1. Providing a robust synchronization method: The proposed SOGI-PLL method with stable operation capability in harmonic-contaminated distribution networks and weak networks with low SCR was introduced as an effective solution for integrating photovoltaic systems into the secondary distribution network. This method

has significant advantages over traditional methods (such as Delay-PLL), including higher accuracy, shorter locking time, and greater resistance to grid disturbances.

2. Design and implementation of a comprehensive control system: A complete control system including MPPT, DC link voltage controller, dq reference current controller, and SOGI-PLL synchronization system was designed and implemented, which meets all the requirements of a grid-connected photovoltaic system.

3. Performance evaluation under different conditions: The system performance was evaluated in five different scenarios (normal, harmonic, weak grid, LVRT and radiation changes) and the stability and power quality of the system were confirmed under all conditions.

RESEARCH LIMITATIONS

Despite the successes achieved, this research has faced some limitations that will be useful for future research:

1. Using an average model instead of a switching model: In this research, average models have been used for power converters. Average models do not represent high-frequency dynamics (related to switching) and may not cover some phenomena related to high-order harmonics. Using more accurate switching models can bring the results closer to reality.

2. Failure to consider multi-inverter systems: In this research, a single-inverter system has been investigated. In real distribution networks, several inverters are usually connected to the grid in parallel, which may cause interference and new instabilities. Further research is needed to investigate the interaction between multiple inverters and its impact on grid stability.

SUGGESTIONS FOR FUTURE RESEARCH

Based on the results and limitations of this study, the following suggestions are made for future research:

1. Investigation of multi-inverter systems: Given the increasing number of rooftop photovoltaic systems, investigating the interaction between multiple inverters connected to a common point of connection (PCC) and its impact on grid stability is an important research topic. Designing coordination methods between inverters can help improve the overall grid stability.

2. Development of the proposed method for three-phase systems: The SOGI-PLL method in this study is designed for single-phase systems. Developing this method for three-phase systems (using SRF-PLL or DSOGI-PLL) and investigating its performance in three-phase distribution networks can expand the application of the research.

3. Investigating the performance in networks with very low SCR: In this research, a weak network with SCR=5 was investigated. Investigating the system performance in networks with SCR<3 (very weak networks) and providing appropriate control solutions for these conditions could be an interesting research topic.

FINAL CONCLUSION

In this thesis, a comprehensive method for integrating small-scale photovoltaic systems into the secondary distribution network using a phase-locked loop was presented. The proposed method based on SOGI-PLL, with high resistance to harmonics and weak network, showed stable and reliable performance under different conditions. The designed system is capable of being implemented in real distribution networks by complying with the requirements of IEEE 1547 and IEC 61727 standards. The simulation results in five different scenarios confirmed the system stability, desirable power quality, and successful operation under LVRT and radiation variations. According to the obtained results, it can be claimed that the use of phase-locked loop method (especially SOGI-PLL) in the integration of small-scale photovoltaic systems into the secondary distribution network significantly contributes to improving the network stability and provides an effective solution for increasing the penetration of renewable energies in active distribution networks. It is hoped that the results of this research can be used as a reference for engineers, researchers, and energy policymakers to develop and promote the use of solar energy in distribution networks.

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