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Direct maximum power injection control of grid-connected PV micro-inverter systems connected to the grid

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Abstract

The increasing use of fossil fuels such as gas and oil has caused many environmental problems, including air pollution, depletion of underground resources, the destructive phenomenon of global warming, destruction of the ozone layer, and many other problems for the environment. Photovoltaic systems are one of the most promising solutions to overcome these problems. Due to the low voltage of solar panels and the higher controllability of photovoltaic systems against changes in sunlight intensity during the day, DC-DC power converters are required. In this project, the aim is to design and build a DC-DC converter with the ability to provide high voltage gain at a suitable efficiency for a 1-string photovoltaic system with the ability to track the maximum power point 2. The designed converter is designed and analyzed with the ability to provide a voltage gain of 5/6 at the critical operating point, a minimum efficiency of 94%, and a power of 500 watts. This converter uses classical soft switching, so the switching losses are reduced, which in turn increases the efficiency of the converter. This converter has a lower voltage stress on the switch (4/0) than the existing techniques. On the other hand, while new converters use a large number of switches and magnetic cores in the cell to provide high gain, this converter uses the least number of switches and magnetic cores to achieve high gain. Also, the passive elements of this converter, such as inductor and capacitor, are in the order of a few microhenries and farads, and therefore the size of these components is also reduced. In addition, due to the high gain provided in lower duty cycles, the efficiency of the switch is increased, and therefore cheaper switches can be used. Also, due to the reduction in the size of passive elements, the size of the magnetic core is also reduced, which in turn optimizes the converter economically.

Keywords: Photovoltaic (PV); Step Up Inverter; Direct Power Control; System Impedance Matching

1. Introduction

With the depletion of fossil fuel resources and the increase in environmental pollution caused by them, the attention of the engineering community has been drawn to investment and development of renewable energy resources. There are various types of renewable energy such as solar, wind, geothermal, biomass, etc., among which solar energy has been widely considered by governments. Photovoltaic (PV) systems are one of the applications of solar energy. In these systems, sunlight is directly converted into electricity. In addition, features such as abundance, ease of operation, long life, and easy and quick installation and commissioning have led to solar energy and photovoltaic systems being considered as a suitable alternative to non-renewable energy sources such as fossil fuels. In addition, according to the available data, the amount of energy received by the Earth's surface from the sun is higher than other forms of energy, including non-renewable resources, nuclear energy, etc [1].

Currently, according to the research done, although the electricity generated by photovoltaic systems is more expensive than some common methods of electricity generation [2] but in the next few years, due to the existence of

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various scientific and technical advances such as the construction of energy conversion materials Light to electricity with high efficiency, optimization of the structure and performance of energy conversion process elements in photovoltaic systems, will lead to improvement of the situation and gradual reduction of investment costs in this sector. Therefore, today the issue of reducing the cost of electricity generated by PV systems has occupied a wide range of research by researchers. In solar power generation systems, a power inverter is used to convert direct current to alternating current and ultimately connect the photovoltaic source to the power grid. One of the most important parts of grid-connected PV systems is the control method used to control the solar inverter as the power transmission section in these systems. Therefore, before examining different configurations, it is necessary to know the characteristics required for a desirable controller in photovoltaic systems [3]. Many factors affect the efficiency of the power inverter control approach to ensure the most effective energy transfer. Low total harmonic distortion (THD) in the AC output current injected into the grid and obtaining the maximum power from the solar source by maximum power point tracking (MPPT) are among these factors. In addition, the controller must have fast dynamics and response to be able to adapt to rapid changes in environmental conditions and solar radiation. Also, due to the presence of unwanted harmonics in the current and voltage output of the inverter, it is necessary to use appropriate filters to eliminate these harmonics and improve the quality of the power injected into the grid. Maximum power point tracking (MPPT) is one of the most important and critical aspects that must always be considered in the control of grid-connected photovoltaic systems. Therefore, the structure of the power inverter must be such that it meets the mentioned objectives. [4,5]

2. Material and methods

2.1. Central Inverter

The structure of central inverters is often used in large-scale photovoltaic systems with three phases. These inverters connect a large number of solar modules to the grid. PV modules are connected in series or strings, and then to achieve high output power levels, each of these series connections is paralleled with diodes. Each of these strings generates a high and sufficient voltage level without the need for voltage amplification stages. Each string of PV modules has similar currents, and the voltage of each string is equal due to their parallel connection. Changes in irradiance among the modules in each string may result in differences in the maximum power point of each string, leading to central power point mismatch. Additionally, power losses due to string diodes, high voltage DC cables between solar modules, mismatch losses due to parallel string connections, and suboptimal utilization of irradiance, as well as inflexible design, which prevents achieving the benefits of mass production, are some of the limitations in this structure.

2.1.1. String Inverter

String inverters are a reduced version of central inverters, where only one string of solar modules is connected to the inverter. The input voltage may be sufficiently high and not require amplification. Unlike central inverters, there are no power losses due to string diodes in this configuration, and maximum power point tracking (MPPT) for each string can be achieved separately, preventing power loss due to string mismatches. However, since each string consists of a series connection of numerous solar modules, it may lead to disturbances in the MPPT process for each string.

2.2. Multistring Inverter

The configuration of these inverters is an advanced form of string inverters. A multistring inverter has multiple strings, each of which, to increase PV voltage, is connected to a common DC/DC converter and then to a common DC/AC inverter. Therefore, separate MPPT tracking is possible for each of these strings. One of the advantages of this topology over centralized inverter structures is the ability to control each string separately. Furthermore, the possibility of different solar module characteristics for each string and the expandability of the system by adding a new string with an additional DC/DC booster are among the advantages of this configuration.

2.2.1. Microinverters

Microinverters or AC modules are one of the most common structures in photovoltaic systems. AC modules are a combination of power inverters and solar cells in one electrical piece, providing integrated and modular structures. Maximum power point tracking is performed individually in microinverter-based photovoltaic systems, potentially extracting more solar energy compared to other structures. Fault detection in microinverters is straightforward due to each module being independently connected to the network. Other advantages of this topology over other structures include reducing the risk of electric arcs and fires (due to the absence of high DC voltages in the system), ease of operation, and reduction in installation and startup costs [6].

2.2.2. Microinverter Classification

The recent years have seen a significant increase in the use of microinverters for solar power generation due to their relative advantages over other configurations, as briefly mentioned in the previous section. In this regard, the classification of microinverters and other mentioned structures is based on certain features such as (a) the type of power circuit used and how the single-phase network is separated from the solar module, (b) the number of power processing stages, (c) how the power circuit connects to the network, and (d) whether a transformer is used in the circuit. Although transformers provide circuit isolation, they are rarely used by designers due to their high losses and heavy weight. Thus, microinverters are generally classified into single-stage and two-stage categories.

Efficiency and cost-effectiveness should always be considered as paramount factors in choosing the type of grid-connected inverter in photovoltaic systems. Two-stage configurations consist of a DC/DC boost to enhance voltage and control MPPT of solar modules and then a DC/AC inverter for controlling the injected power and current into the network. On the other hand, in single-stage structures, all these functionalities are achieved in a single stage. In recent years, the use of single-stage microinverters connected to the grid in photovoltaic systems has been emphasized to reduce the number of power conversion stages, thereby increasing overall system efficiency, enhancing reliability, and reducing associated costs. The use of more powerful electronic components, smaller hardware dimensions, increased efficiency, cost reduction, and increased reliability are among the advantages of single-stage structures compared to two-stage ones. In this thesis, a single-stage grid-connected microinverter without a transformer will be used. The circuit used will be introduced and elaborated on in the following chapter [7].

3. Review of Photovoltaic System Control Methods

The integration of a photovoltaic (PV) system with a utility grid has been studied by many researchers, which proves the grid-connected inverter mentioned above could be an ideal choice to raise the voltage level of PV systems. [8,9]. Various control methods have been proposed for managing power electronic converters used in photovoltaic (PV) systems [10,11] Among the most important and common of these methods are hysteretic control, linear control, sliding mode control, predictive control, and intelligent control. Hysteretic control utilizes the non-linear nature of power converters to determine the switching state of power switches by comparing measured variables with their reference values and considering a given hysteresis band for error. This analog controller relies on pulse width modulation (PWM) for implementation and requires a high sampling frequency in a digital platform.

One of the most common linear control methods is the use of proportional-integral (PI) controllers. However, these controllers suffer from issues such as steady-state error and ineffective disturbance rejection [12]. To address this, proportional-resonant (PR) controllers reduce steady-state error using infinite gain at the resonant frequency [13]. However, applying this infinite gain poses a challenge for these controllers. Additionally, due to the sinusoidal and periodic nature of output current in grid-connected inverters, repetitive control is another method proposed for PV system control [14]. Tracking a periodic reference signal with any waveform is an advantage of repetitive control over PR controllers, which are only used for sinusoidal reference tracking. However, the instability of this controller under certain conditions is a drawback. Linear and nonlinear feedback control methods have been proposed to ensure controller stability [15,16].

Furthermore, newer control methods using more powerful microprocessors have been introduced for designing controllers for PV systems. Among these, intelligent control methods such as fuzzy controllers, neural networks, and other controllers like sliding mode control and predictive control are notable. Fuzzy logic and neural networks are often used when system control and some of its parameters are unknown. Sliding mode control is a variable structure controller that designs the controller for grid-connected inverters using the switching nature of converters [17]. By defining a variable sliding surface, the desired sinusoidal reference is tracked. This method is robust against uncertainties but requires complex computations. A predictive controller model has been proposed for grid-connected single-phase inverters [18]. The drawbacks of this control method include complexity and the need for a modulator for its implementation.

3.1. Voltage Source Inverters

Considering that in voltage source inverters, the average output voltage magnitude is usually higher than the input DC voltage [19], if an output voltage with larger magnitudes than the input voltage is required, a DC/DC booster converter must be used between the DC source and the inverter [20]. Therefore, as mentioned in the previous chapter, in dual-stage configurations, depending on the voltage level and required power, the use of two converters can lead to increased complexity, weight, cost, and overall efficiency reduction of the system [21]. This is while a single-stage structure can increase the input voltage level and control the output current and power in just one power processing stage. Thus, using fewer power electronic components, reducing or compacting the hardware dimensions of the system, increasing system efficiency, reducing costs, and increasing reliability are among the major advantages of single-stage structures over dual-stage ones. Figure 1 illustrates the general structure of a grid-connected microinverter with single-stage topology.

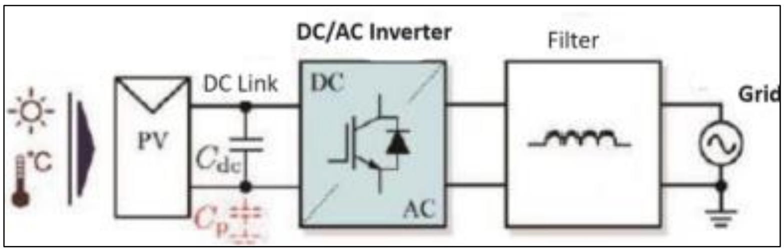

Figure 1 Configuring a single-stage micro-inverter

As depicted in this figure1 ,the PV module is connected to the DC link capacitor (Cdc) in parallel, which is then connected to the DC/AC inverter. In a single-stage topology, power is transferred between the photovoltaic source and the grid through the Cdc capacitor. The Cp capacitor serves as a protective capacitor. The input voltage of the inverter undergoes power conversion in a single stage, and the output of the inverter is connected to the grid via an appropriate filter. By applying necessary controls, a specific output power is injected into the grid. The focus of this thesis is on the control of grid-connected single-stage inverters. Subsequent sections will discuss the system analysis and behavior of the single-stage inverter circuit in grid-tied and islanded modes [22-23].

The structure of a single-stage resistive load boost inverter is illustrated. - Figure 2

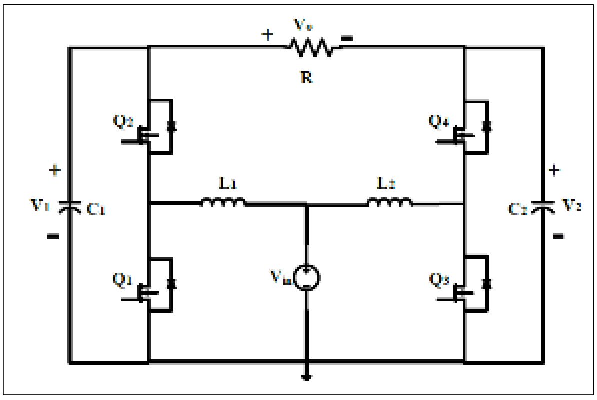

Figure 2 Ideal step-up inverter with resistive load

3.2. Grid-connected modes

In this paper, the grid is considered as an approximation of a real network and is modeled as a pure sinusoidal voltage source with a constant magnitude, i.e., Vg=Vmsin (ωt). However, connecting energy generation sources to the grid always poses challenges. One of the most recognized detrimental phenomena in source-grid connections is harmonics. Harmonics can be the cause of equipment damage. A common method to eliminate harmonics is to use a low-pass filter between the inverter and the grid. There are various filters for this purpose. L, LC, and LCL filters are the most common.

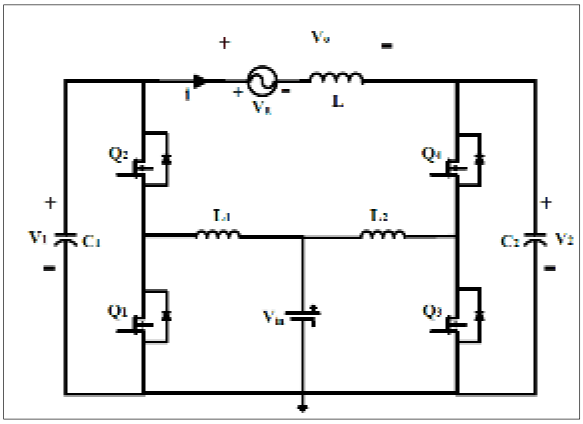

Figure 3 Grid-connected boost inverter

Among the introduced filters for harmonic elimination, LCL filters perform better, but their use comes with challenges such as more complex control, increased system order, and harder controller design. This is while L and LC filters have simpler design and control processes. In this research, an L filter is used to connect the boost inverter to the grid. The operation and switching model of the circuit in this case are similar to the grid-connected boost inverter with a resistive load, as explained in previous subsections. Therefore, the nonlinear dynamic equation and indeed the average model of the grid-connected step-up inverter according to Figure 3, with state variables i_1, V_1, i_2, V_2, and i, are obtained as follows:

$$L_1\frac{di_1}{dt} = v_{in} - Dv_1$$

$$C_1\frac{dv_1}{dt} = Di_1 - i$$

$$L_2\frac{di_2}{dt} = v_{in} - D'v_2$$

$$C_2\frac{dv_2}{dt} = D'i_2 + i$$

$$L\frac{di}{dt} = v_1 - v_2 - v_g \qquad \text{Eq (1)}$$

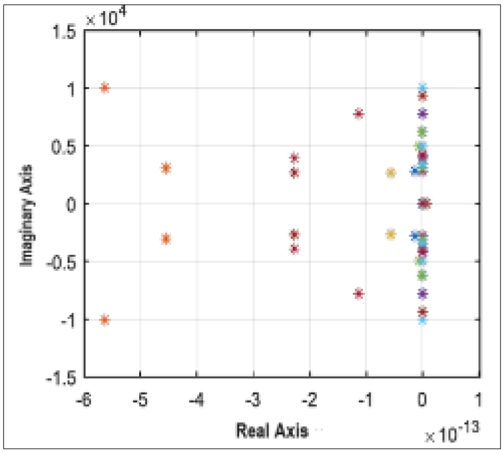

Figure 4 The pole locations of the system's open-loop in the grid-connected mode at different operating points and for simultaneous changes in D and D' within the range [0, 1].

In this case, the desired system is of fifth order, and d and d' are considered as input, and ov as the system output. By considering equations D and D' based on equation (1) and using the linearized equation of the grid-connected boost inverter, the pole locations of the system's open loop, for different operating points and for simultaneous changes in D and D' in the range [0, 1], are shown in Figure 4.

3.3. Proposed Control System Structure

Considering Figure 5, in this case as well, the system's open-loop exhibits marginally unstable behavior, and in fact, the grid-connected boost inverter demonstrates undesirable behavior in the open-loop mode.

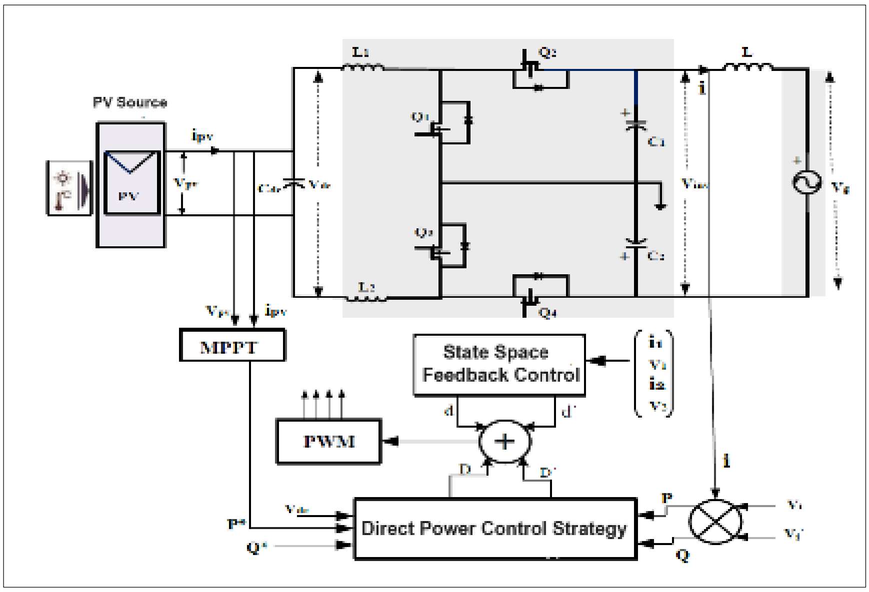

Figure 5 Designing the controller for the grid-connected boost inverter

In fact, this structure is hierarchical and consists of two sequential stages, where the first stage is for tracking the maximum power point, and the second stage is for power control. The first stage determines the reference current and power required for the next stage by using a Maximum Power Point Tracking (MPPT) algorithm. Proper tracking of this reference power is achieved through the direct power control method in the second control stage. Our focus is on controlling the injected power into the grid. Due to the distinct operation of these two stages, initially, an appropriate operating point is extracted from the photovoltaic source to determine the maximum power using an MPPT algorithm. Then, based on the determined operating point, the second stage is responsible for controlling and injecting the maximum power determined into the grid, effectively generating a sinusoidal output current with quality and phase matching the grid voltage. In this thesis, we implement the Perturb and Observe (P&O) method for MPPT, and subsequently design a controller using the direct power control strategy to inject maximum power for the grid-connected boost inverter [24].

3.4. Control of the grid-connected boost inverter

So far, the operation of the MPPT algorithm and its consideration as the required maximum power reference for designing the maximum power injection controller in the grid-connected boost inverter has been discussed. Furthermore, by placing a capacitor in parallel with the photovoltaic module, which serves as the input power source for the grid-connected boost inverter, the oscillations present in the photovoltaic module voltage are significantly reduced. Therefore, it can be assumed that there is a voltage source at the input connected to the desired boost inverter. Subsequently, the process of identification, modeling, and analysis of the behavior of the grid-connected boost inverter system, as well as the controller design process, are based on this assumption. Now, before discussing recent developments, a review of boost inverter controllers will be provided.

Various methods have been proposed for controlling the nonlinear system of the boost inverter. Designing a controller using feedback linearization control method for the grid-connected mode with the aim of injecting high-quality active and reactive power, regulating the DC link voltage, and regulating the reactive power to the desired value in the presence of system uncertainties and disturbances has been considered. In this method, the voltage loop and the reactive power loop are completely decoupled. Another method involves designing two back-to-back control loops for regulating the output voltage and coil current in each of the inverter modules of the grid-connected boost inverter. In this approach, one of the inverter modules is controlled as the current source and the other as the voltage source. However, this control method, in addition to requiring a current control loop, cannot completely guarantee the stability of the system under possible practical conditions. The mode of grid connection for the boost inverter has also been presented in references. However, the reference values required for the back-to-back control approach are obtained from an external control loop based on active and reactive power control. Nonlinear control through coil current based on the sliding mode dynamics method is also one of the nonlinear control methods introduced for controlling the boost inverter. One of the disadvantages of this controller is the steady-state error due to the use of a proportional-integral (PI) controller and the presence of oscillations in the system response. In addition, controller design based on hybrid control approach and also designing a controller based solely on output current control using a closed-loop control loop are other methods proposed for controlling the boost inverter in photovoltaic systems.

In general, the conventional control method used in grid-connected microinverters in photovoltaic systems is to use current control method, whose output is modulated for inverter switching, so that the required active and reactive power reference values are obtained from the active and reactive power values, the reference current value is obtained by using the active and reactive power values. In this approach, the injected power also changes with the grid voltage variation, and it cannot inject the required power stably. In contrast, in the mentioned reference, with active power control, active and reactive power reference values are directly injected into the grid through a full bridge inverter with a constant DC input source. Based on this, unlike conventional current control methods, even with changes in voltage in the grid, the desired power can be independently controlled and injected into the grid. Therefore, in this thesis, by employing the direct power control strategy, which has a simple concept and structure and is also capable of desirable performance in power electronic systems, a controller is designed to inject maximum power generated from the photovoltaic source into the grid through the boost inverter.

3.5. Improving System Behavior Using State Feedback Control

As mentioned, the grid-connected boost inverter exhibits inappropriate circuit behavior in the open-loop state. Therefore, the goal of controller design in this section is to increase stability and stabilize the closed-loop system, essentially improving system behavior. Thus, designing an internal feedback controller using the state feedback method to enhance and improve the behavior of the grid-connected boost inverter system is addressed.

To design an internal feedback controller based on the state feedback method to significantly improve the oscillatory behavior of the system, the controllable subsystem section (Ac', Bc') is utilized. Considering the number of dynamics in the controllable subsystem section and having 2 inputs, the control gain matrix for the state feedback controller is considered as follows:

$$U(t) = -KX(t) \;\longrightarrow\; U(t) = \begin{bmatrix} d(t) \\ d'(t) \end{bmatrix} = -\begin{bmatrix} k_{11} & k_{12} & k_{13} & k_{14} \\ k_{21} & k_{22} & k_{23} & k_{24} \end{bmatrix} \begin{bmatrix} i_1 \\ v_1 \\ i_2 \\ v_2 \end{bmatrix}$$

Eq (2)

By substituting it into the state equations, the following equation is obtained:

$$\begin{cases} \dot{X}(t) = (A - BK)X(t) \\ y(t) = CX(t) \end{cases}$$

Eq (3)

The roots of the controlled system are obtained by the characteristic equation det[sI-(A-BK)]=0. By comparing the expressions of this equation with the desired characteristic equation, the values of the state feedback gain matrix K are calculated, placing the eigenvalues of the closed-loop system at the desired locations. Considering the desired pole locations as slightly over-damped at -499±9902i and -3110±104i, the state feedback vector is obtained as follows:

$$K = \begin{bmatrix} -0.001 & 0.0003 & 0 & 0 \\ 0 & 0 & -0.001 & 0.0003 \end{bmatrix}$$

Eq (4)

By applying the designed state feedback controller to the nonlinear system of the grid-connected boost inverter, the pole locations of the closed-loop system for different operating points and simultaneous changes in D and D' in the interval [0 1] are presented in Figure 6.

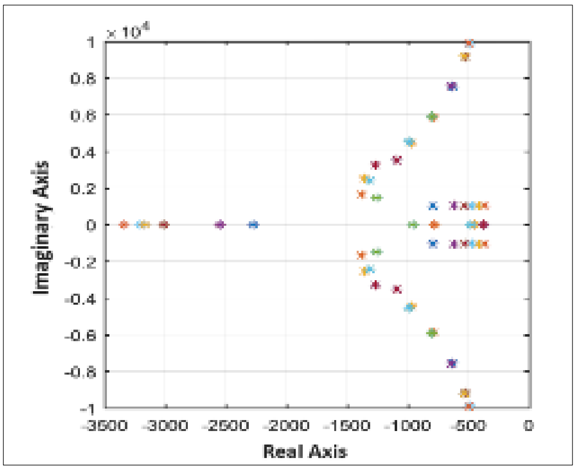

Figure 6 Position of the poles of the system / closed-loop inverter with a load reactor at various operating points and for simultaneous changes in D and D' within the interval [0, 1].

As depicted in Figure 6, the pole locations of the closed-loop system have shifted towards the left of the imaginary axis with the application of the designed state feedback controller, resulting in the system reaching the desired stable state. The simulation results presented in Figure 6 indicate an improvement in system behavior due to the implementation of the proposed controller.

3.6. Power Injection Using Direct Power Control

In this section, the objective is to control and inject the maximum specified power into the grid. Typically, current control methods are used for power injection control, whereas in this case, active and reactive power are directly used as reference signals. Thus, the subsequent discussion focuses on designing a controller for power injection into the grid using direct power control.

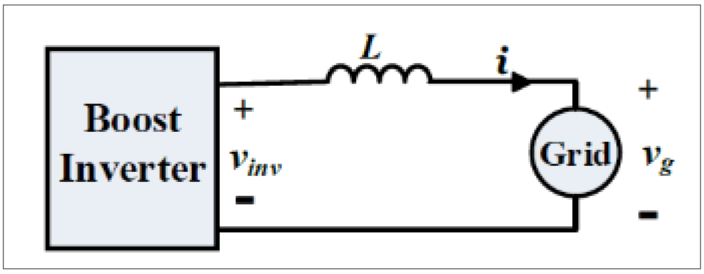

Figure 7 The equivalent circuit of the grid-connected booster inverter

The relationship between grid voltage, inverter output voltage, and current passing through the inductor filter, as shown in Figure 7, can be expressed as follows:

$$v_o(t) = v_{inv}(t) = L\frac{di(t)}{dt} + v_g(t)$$

Eq (5)

The inverter output voltage is defined as follows:

$$v_o(t) = v_{inv}(t) = L\frac{di(t)}{dt} + v_g(t)$$

Eq (6)

Considering equation (6), it is a real positive value, and R and $vi(t)$ represent a shunt resistance placed in series with the inductor filter. The purpose of considering a shunt resistance in R is to stabilize the control system and prevent an increase in losses, thereby increasing the efficiency of the photovoltaic system.

The proposed control system for power injection is depicted in the diagram shown in Figure 8, where the inverter output voltage (V_{inv}) is considered according to equation 7 as follows:

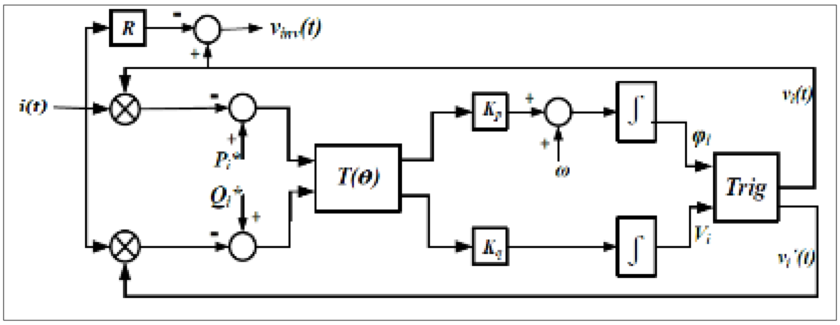

Figure 8 Proposed control system for power injection

In equation 8, $\varphi i(t) = \omega t + \delta(t)$, where ω represents the system frequency, δ represents the phase, and Vi represents the amplitude of the inverter voltage. The active (iP) and reactive (iQ) powers are calculated as follows, where θ and Z represent the phase and impedance magnitude of the supply line, respectively.

$$v_{inv}(t) = v_i(t) - Ri(t) = V_i(t)\cos\big(\emptyset_i(t)\big) - Ri(t)$$

Eq (7)

The decoupling of active and reactive powers for independent control is performed using the transformation matrix $T(\theta)$. Therefore, after applying the transformation matrix $T(\theta)$ to equations 8 and 9 the following relationships are obtained:

$$P_i = \frac{V_i}{2Z}[V_i\, cos\theta - V_g\cos(\delta + \theta)]$$

$$Q_i = \frac{V_i}{2Z}[V_i\, sin\theta - V_g\sin(\delta + \theta)]$$

$$\vec{Z} = R + jX = R + jL\omega = Ze^{j\theta}$$

Eq (8)

The equations for the blocks T(θ) and Trig are as follows:

$$T(\theta) = \begin{pmatrix} sin\theta & -cos\theta \\ cos\theta & sin\theta \end{pmatrix}$$

$$\begin{pmatrix} v_i(t) \\ v_i'(t) \end{pmatrix} = \begin{pmatrix} V_i\cos(\emptyset_i) \\ V_i\sin(\emptyset_i) \end{pmatrix}$$

Eq (9)

Therefore, considering equation 10, it can be said that active power is primarily controlled by δ, and reactive power is controlled through Vi.

$$\begin{pmatrix} P_i' \\ Q_i' \end{pmatrix} = T(\theta)\begin{pmatrix} P_i \\ Q_i \end{pmatrix} = \frac{V_i V_g}{2Z}\begin{pmatrix} \sin\delta \\ \dfrac{V_i - V_g\cos\delta}{V_g} \end{pmatrix}$$ Eq (10)

Equation (4 - 27) serves as the foundation for the method of active power control in the grid-connected operational mode. It should be noted that the parameters *p_k* and *q_k* are positive real constants, which will be further addressed in the design process.

$$\frac{d}{dt}\begin{pmatrix} \delta(t) \\ V_i(t) \end{pmatrix} = \begin{pmatrix} k_p & 0 \\ 0 & k_q \end{pmatrix} T(\theta)\begin{pmatrix} P_i^* - p_i(t) \\ Q_i^* - q_i(t) \end{pmatrix}$$ Eq (11)

Figure 9 illustrates the block diagram of the LTI model of the desired power injection controller to the network.

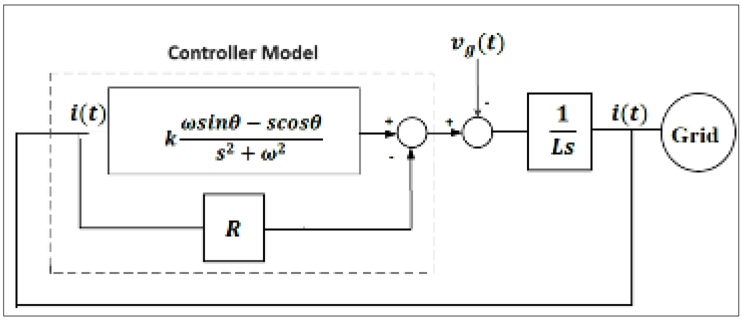

Figure 9 The model of an LTI (Linear Time-Invariant) power injection controller to the grid.

Considering equation (4 - 28), the control system without the presence of R will always be unstable. Whereas, taking the effect of the series resistance R into account in the control system, the characteristic equation is obtained as follows:

$$\Delta(s) = 1 + k\frac{s\cos\theta - \omega\sin\theta}{(Ls+R)(s^2+\omega^2)} = 0$$ Eq (12)

Based on equation (4 - 29), the maximum value of k for the stability of the power injection control system to the network is obtained as a result of equation (4 - 30):

$$k_{max} = \frac{R\omega}{\sin\theta} = R\omega\sqrt{1 + (\frac{R}{L\omega})^2}$$ Eq (13)

Thus, by applying the proposed controller to the inverter connected to the network, after improving and modifying the system behavior, the desired active and reactive powers will be controlled and injected into the network accordingly.

4. Results and discussion

The system, including the parameters of the photovoltaic source, the booster inverter, the filter, and the network, is presented for simulation. The photovoltaic module model is SPR-305-WHT manufactured by SunPower, the specifications of which are shown in Table 1.

Furthermore, by placing a capacitor Cdc=2 mF at the output of the photovoltaic source, the output voltage of the photovoltaic source, and hence the input voltage of the booster inverter, are assumed to be approximately constant and equal to 100 volts. The frequency and peak voltage of the grid are also considered to be 50 hertz and 311 volts, respectively.

The performance of the proposed controller has been investigated through simulation using MATLAB/Simulink software environment.

Table 1 Parameters of the step-up inverter and the photovoltaic system

Parameter	Symbol	Value
Maximum Power	P_M	10.044 mm
Series Resistance	R_S	No space after paragraph
Parallel Resistance	R_P	No space after paragraph
Reverse Saturation Current	I_{sat}	No space after paragraph
Nominal Temperature	T_N	No space after paragraph
Radiation	G_n	No space after paragraph
Inductors	L_1, L_2	No space after paragraph
Capacitances	C_1 ,C_2	No space after paragraph
Filter Inductance	L	No space after paragraph

In this section, the simulation results of the booster inverter in three conditions: resistive load, inductive load, and connected to the network will be presented. It should be noted that in the connected to the network condition, since the goal is to control and inject the maximum power extracted from the photovoltaic source into the grid, only in this condition, the photovoltaic source will be considered as the input to the booster inverter.

The characteristic curves of the photovoltaic array and the maximum power points for different radiation levels are shown in Figure 10.

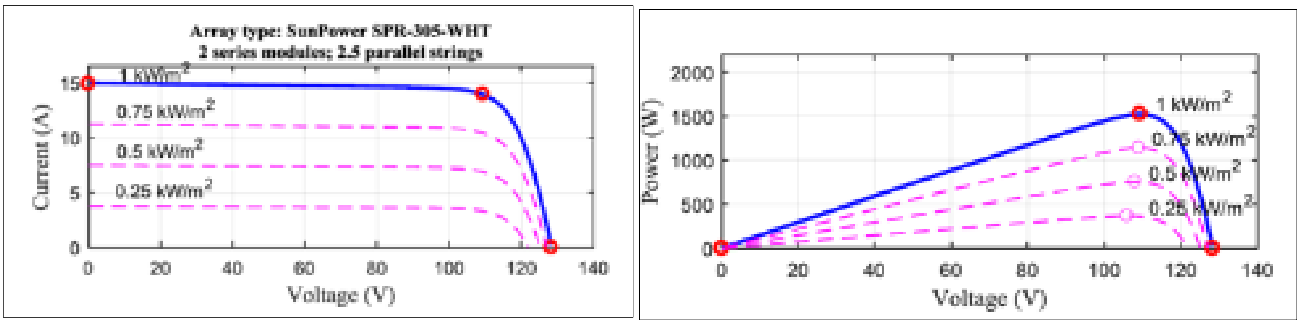

Figure 10 Characteristic curves of the photovoltaic array for different radiation levels

As seen in Figure 10, with an increase in radiation intensity, the output current and power of the photovoltaic module increase. Additionally, the sensitivity of the photovoltaic array voltage to its current varies for different radiation levels, meaning that with increasing radiation, the voltage changes of the PV source relative to its current changes are more pronounced. Moreover, changes in radiation have a greater impact on the output power of the solar source compared to changes in temperature, and this effect is more likely to occur in practical conditions. Therefore, to assess the performance of the controller in the grid-connected booster inverter mode, simulations are conducted under normal operating conditions of the photovoltaic source and at a constant ambient temperature of 25°C.

4.1. Step Up Inverter with Resistive Load

The designed controller for the booster inverter with a resistive load is aimed at improving the system's behavior and can maintain all its desirable features and performance for the booster inverter with an inductive load as well. In this case, all circuit components are similar to those of the booster inverter with a resistive load, except that at the output terminal of the booster inverter, an inductive load of L=8mH, R=100Ω is considered.

As evident from the following figures, due to the instability of the system in an open-loop configuration, the output voltage exhibits significant oscillations, and the system's response stability is poor. The following figures depicts the effect of the proposed controller on the output voltage of the booster inverter with an inductive load.

As will be observed in the results, the output voltage exhibits excellent quality similar as before, indicating that all the desirable characteristics resulting from the implementation of the designed controller, such as voltage output oscillation suppression, improved system response stability, and voltage output range control, are maintained, even with the presence of an inductive load. This can be considered as one of the advantages of the proposed controller.

4.2. Grid-Connected Booster Inverter

The goal of this section is to inject the maximum power harvested from the photovoltaic source into the grid using the designed controller discussed. Before evaluating the performance of the proposed controller for power injection into the grid, simulation results of applying the designed feedback controller to the grid-connected booster inverter, aimed at improving the system's behavior, are presented. Figure 11 shows the output voltage waveform of the grid-connected booster inverter in an open-loop configuration.

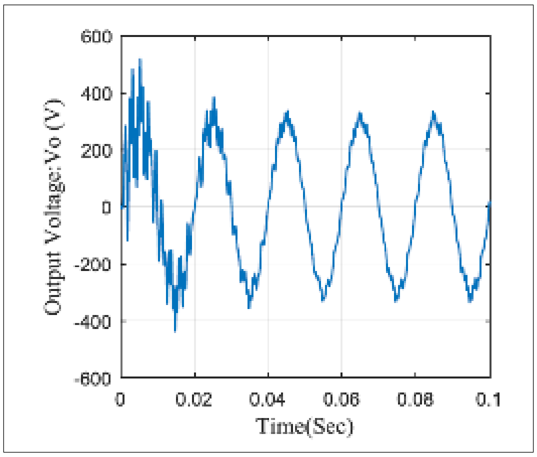

Figure 11 Output voltage of the booster inverter with a resistive load in open-loop operation without applying the controller

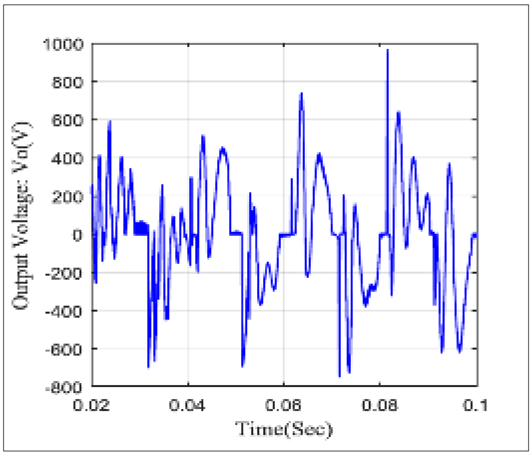

Figure 12 Output voltage of the system in open-loop operation of the grid-connected booster inverter without the controller applied

It can be observed from Figure 12 that due to the unstable boundary condition of the inverter system - as shown in Figure 12 - in an open-loop configuration, the output voltage exhibits severe oscillations.

With the application of the designed controller using the feedback state method, the output voltage stabilizes, as shown in Figure 13.

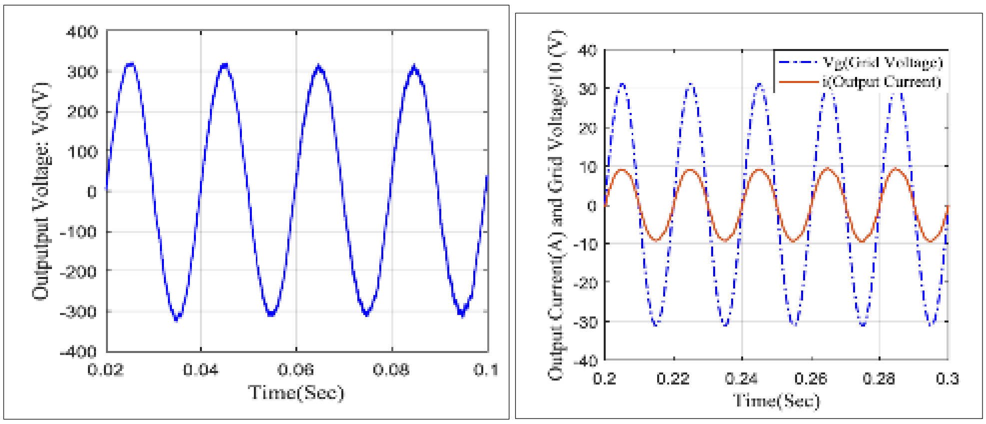

Figure 13 a) Output voltage of the system in closed-loop operation of the grid-connected booster inverter with the feedback control applied. b) Output current and grid voltage.

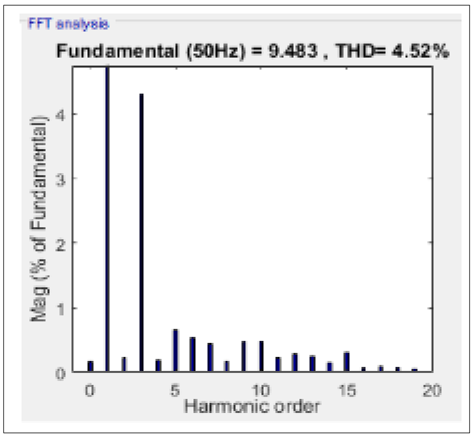

Figure 14 Total Harmonic Distortion (THD) of the output current.

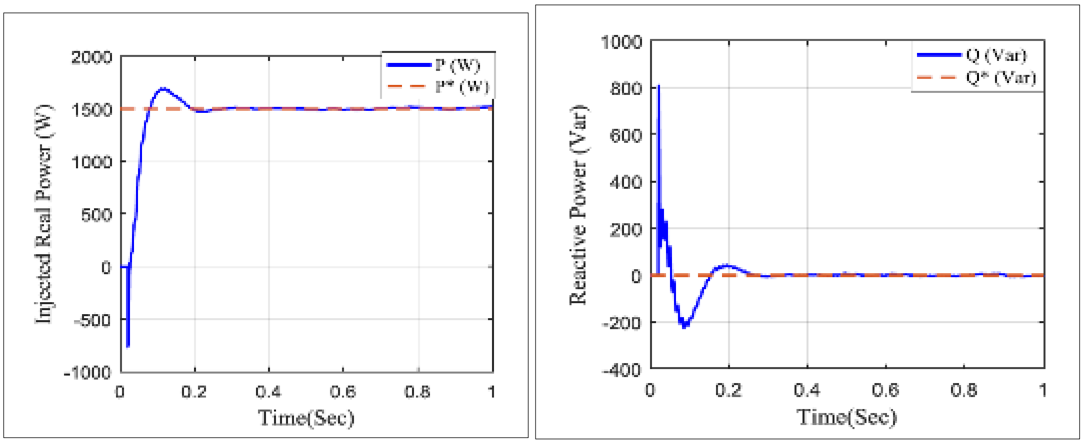

Figure 14 The injected power to the grid with the application of the proposed controller: a) Real (active) power. b) Reactive power

Now, after improving the behavior of the grid-connected booster inverter system, the performance of the proposed controller for injecting the maximum power obtained from the photovoltaic source into the grid is examined. As mentioned before, normal operating conditions for the photovoltaic source under radiation of 1000 W/m^2 are depicted to illustrates the voltage and power of the photovoltaic array, respectively.

It is noted that the output current is in phase with the grid voltage. Therefore, the output current exhibits very low total harmonic distortion (THD) - as shown in Figure 14, the average THD is 4.52%, indicating very high-quality and suitable waveform. Figure 15 depicts the controlled active and reactive powers injected into the grid.

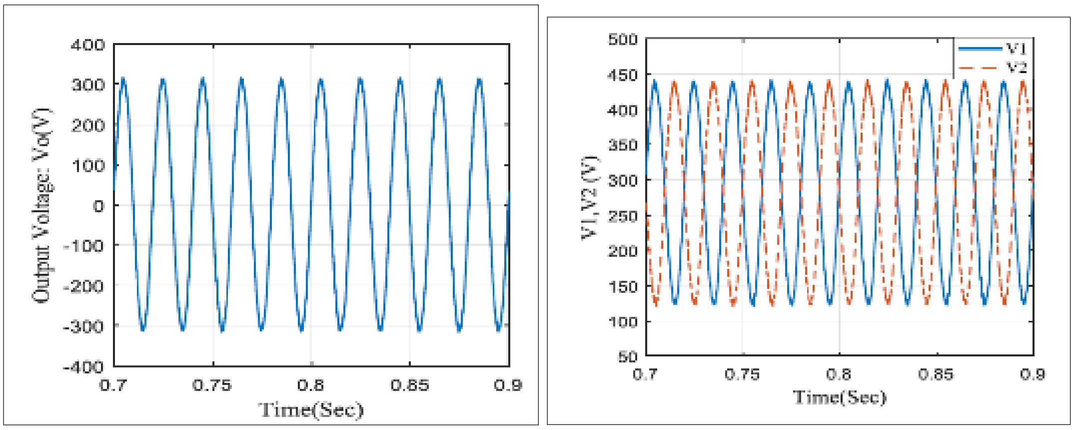

Figure 15 a) Output voltage of the circuit. (b) Output voltage of each of the converters on both sides of the circuit with the controller applied.

It is observed that the proposed controller has demonstrated satisfactory performance for controlling and injecting the maximum extracted power from the photovoltaic source to the grid via the booster inverter, as shown in Figure 16. In other words, the active and reactive powers have effectively tracked their desired reference values. The voltage output waveform of the grid-connected booster inverter and the voltage output waveform of each of the presented converters on both sides of the circuit for applying the proposed controller to the system are illustrated in Figure 15.

5. Conclusion

This thesis presents the analysis and design of control for single-stage single-phase booster inverters for two modes of grid connection, aiming to improve the system behavior and control the output voltage. Also, it aims to inject the maximum extracted power from the photovoltaic source to the grid through the booster inverter. Unlike typical voltage source inverters, the considered booster inverter, by reducing the power conversion stages, enhances reliability and overall efficiency of the systems. However, the studied booster inverter, due to its nonlinear nature and resonant structure, exhibits very weak stability and highly oscillatory behavior.

Therefore, initially, the booster inverter is considered with a purely resistive load connected to the grid, and in order to increase stability and achieve the desired sinusoidal output waveform with high quality, a feedback-based controller is designed. This controller is designed to effectively add real resistance to enhance the stability of the system. Using voltage feedback in each of the circuit's converters, the control and compensation of the output voltage range are addressed. The linearized model of the booster inverter is obtained using state-space equations to achieve this goal. The advantage of this method lies in its simplicity in both analysis and implementation.

Furthermore, the production of the output voltage with very low total harmonic distortion (THD) and high quality without the need for output filters is one of the notable features of the proposed control method. Additionally, the results indicate that the designed controller can maintain all its desirable features even when considering a resistive load at the output of the booster inverter, which is a valuable capability of the proposed control method.

Thus, before designing the power injection control controller for the grid-connected booster inverter, by employing the state feedback control method, stability enhancement and closed-loop system improvement are achieved. Then, the power control strategy is designed to track the maximum power point of the photovoltaic source using the Perturb and Observe (P&O) method to determine the maximum reference power. Subsequently, the active power control strategy is applied to the closed-loop system to inject the maximum power from the photovoltaic inverter into the grid. The results show that the reference values of active and reactive powers are accurately tracked, and the injected current into the grid also exhibits desirable and suitable quality.

Based on these results, the active power control method for power electronic power injection systems in photovoltaic applications is considered a suitable control solution. One of the advantages of the proposed controller is its use of reference values of active and reactive powers in the controller design process, unlike traditional current control methods in power injection systems. In this regard, even with voltage variations in the grid, the desired power can be independently injected into the grid. Considering this feature, the proposed controller has a straightforward concept and a simple structure in practical conditions.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare no conflict of interest.

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