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An Advanced Hysteresis Controller to Improve Voltage Profile of Power System with PV Units: A Smart Grid Power Exchange Framework

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Abstract

Unlike traditional power grids, smart grids have the advantage of bidirectional power flow and having distributed generations. Distributed generation systems are usually supplied by renewable sources which can cause unpredicted voltage fluctuations as a result of being intermittent. While traditional compensating devices deal with the problem of voltage fluctuation and reduced power quality with a long response time, inverter based photovoltaic systems can supply the required reactive power for the system to remain stable having a short response time and less thermal losses than typical compensators. When the insolation is weak or at nights, the reactive power capability of voltage source inverters can be used to improve the system efficiency. The challenge here is to keep the inverter DC link input voltage within an acceptable bandwidth for the inverter to be able to continue its operation when there is no active power provided by the PV cells. This paper proposes a controlling system to completely use the nominal apparent power capacity of the PV inverter that is to use the inverter capacity to provide reactive power when the active power is not nominally supplied by the PV system. Simulation studies are carried out in MATLAB/SIMULINK to verify the effectiveness of the proposed method.

Keywords: Smart Grid; Power Quality; Voltage Profile; Reactive Power Compensation; Photovoltaic; Renewable Energy; Inverter Control; Switching

1. Introduction

Being environmentally friendly, the photovoltaic (PV) power generation systems have become an attraction in the last few years. The installed solar capacity all over the world has increased by 57% annually in the last ten years [1].PV systems are usually installed close to consumption points which can relieve generation, transmission, and distribution in power systems. This will also reduce the need for new investments and improves the load curve and the feeder voltage profile. Moreover, it will reduce the level of transformer loadings and electrical losses, as well as bringing environmental benefits by avoiding emission of pollutants [2,3].

Since the energy produced by PV systems is DC, in order to connect them to the grid it is needed to use DC-AC inverters in the grid interface. It has to be mentioned that currently used inverters are mostly current source inverters (CSI) operating in a unity power factor which will result in a system only capable of providing active power to the power system [4]. As a result, the locally needed reactive power has to be provided by means of capacitor banks placed near consumption points in the distribution system [5]. When the insolation is weak or at nights with the PV inverters working in a unity power factor, photovoltaic systems will lose their power generating capacities and become useless; all loads must be fed directly by the electrical grid and slow compensating infrastructures.

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There are various structures for PV inverters connected to the smart electrical grid [6]. However, using voltage source inverters (VSI) instead of current source inverters (CSI) makes the system able to have bidirectional reactive power flow within the system besides active power. When the PV system is not producing its nominal active power, the controller sets the inverter in order to compensate the reactive power. Moreover, keeping the input DC link voltage of the inverter in the desired range is the other duty of the control system. Also, the active and reactive powers passing through the inverter are limited by the nominal apparent power of the inverter. There has been some works trying to control the reactive power by PV systems [11, 15, 17]. However, none has been able to meet the apparent power constraints in the inverter; besides, the process of keeping the inverter DC link input voltage has not been presented in any of them. This paper, proposes a control system to let the PV system compensate the reactive power according to the system needs and the grid-tied inverter's left capacity after delivering all the produced solar active power to the smart grid. The smart grid provides communication infrastructures for the control system to keep the voltage of the system stable [7].

After reviewing reactive dispatch approaches in section II, we focus in section III on PV system structures in smart grids. Section IV analyses different operational modes of the PV inverters followed by the control and power circuit in section V. Section VI, verifies the proposed method via simulations and the paper is concluded in section VII eventually.

2. Options for reactive power compensation

In traditional power systems, power generated at large power plants is delivered to consumers through the vertically designed system of transmission and distribution grids. In distribution systems, the voltage is typically controlled at the entry point, and then it sags down the distribution lines, mainly because of consumption of reactive power by end consumers and the impedance of the distribution lines. A number of technologies are employed in the modern power systems for reactive power compensation, improving the power quality in the system. These technologies compensate for the fluctuations of voltage using controlled injections of reactive power at a few locations. Synchronous generators, capacitor banks, and end-user reactive compensators are the most common technologies used to compensate the flux of reactive power.

Large synchronous generators are able to control their output voltage within the prescribed bounds by manipulating reactive power [8]. However, the application of these system is geographically limited to the entry point to the power distribution system. Shunt capacitor banks are installed and operated in the distribution networks. From the viewpoint of the grid the shunt capacitors act like a source of reactive power. Optimal operation of capacitor banks tries to achieve a balance between the power quality, thermal loss, and the system capacity [9]. There are also some drawbacks in the integration of capacitors in the distribution network. High-frequency harmonics and switching transients which propagate through the network may cause resonances in some frequencies and significant damages to the equipment, respectively.

Another challenge in using capacitor banks is whether or not the capacitor bank installations can deal with the destabilizing effects of intermittent renewable generations penetrating into the distribution grid. Networks highly integrated with distributed renewable may require faster and more flexible control systems than capacitor banks can achieve.

Not extensively deployed, inverter-based technologies are an emerging class of end-user reactive dispatch technologies which have become highly promising according to several reasons as follows.

- Efficiency. With the reactive compensation being close to the reactive load, the average magnitude of the current flowing through the lines decreases resulting in a reduction in thermal power loss.
- Reliability. Not being dependent to large compensating units makes the system less susceptible to equipment failure. Moreover, a distributed control system is technically more resilient to cyber-attacks in comparison to centralized control systems.
- Flexibility. Individual compensators distributed in different parts of the system can combine their reactive injections in different ways, allowing the system to attain optimal operations.

Considering these advantages, this paper uses inverter-based technologies to compensate the reactive power in photovoltaic systems connected to smart grids.

3. Inverter based PV systems connected to smart grids

Smart grids are able to provide real-time information on the exchanged energy amounts and consumers' load patterns by means of bidirectional control systems and special protocols. This leads the system toward higher penetration levels of renewable resources and electric vehicles. Also, demand side

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management programs are made easier in smart grids, leading to an increased system efficiency as well as mitigating the intermittency impacts of renewable energy sources [16].

A. Connecting Renewable Energy Resources to smart grids

As utilizing the natural energy of the renewable improves the sustainability of energy production and benefits the environment, their integration is the driver for smart grid which has the following features:

- Smart grid technologies reduce the constraints in the integration of renewable sources and enable the grids to support greater percentage of intermittent renewable resources more effectively and at lower costs.
- Smart grid technologies such as demand response, advanced sensing, control software, and information infrastructures increase the system ability to balance supply and demand.
- Smart grid technologies bring about more efficient control systems responding to grid conditions, this will reduce the renewable energies integration costs in the system.
- Advanced and automated inverter and converter systems with communication software interfaces enable distributed management and applications for renewable generation.

With the increasing awareness of these features, smart grid research activities have been in the center of attention worldwide to develop the right tools and technologies, particularly in the field of photovoltaic systems.

B. Different PV Designs for Smart Grid Integration

Solar systems integrated in smart grids are required to have bidirectional flow of power and communication for seamless grid-tied PV interconnections. Inverters are the main operational parts of these intelligent systems which can have three different designs connecting the solar system to the grid; namely, central, string, and micro inverters.

Central inverters, used in conventional PV installations, carry out the DC voltage through a single central array to the grid. This may have significant fire and safety hazards, leading to higher installation and maintenance costs. To deal with individual panel effects, power conversion can be moved to each individual string providing DC-DC conversion to enhance the power delivered to the central inverter by each string. Besides string converters, string inverters can also improve the overall array efficiency reducing the impact of a single poorly-performing panel to its string rather than the entire array. Eliminating the central inverter as a potential single point of failure, these installations still need to deal with the costs associated with DC voltage transmission.

Taking the concept of string inverters to the next level, micro inverters are the most recent technology in which DC-AC conversion is provided from each individual panel rather than an entire string [10].

This paper proposes a smart grid based PV system which calls for real-time execution of a number of precise algorithms for efficient DC-AC conversion, PV panel power optimization through maximum power point tacking (MPPT), and voltage control through reactive power flow compensation. This concept is shown in Fig. 1. The processor and the control unit is used to control the active and reactive power flows. It also executes the MPPT algorithm and digital communication routines. It has to be mentioned that the proposed method can be implemented on any of the three inverter designs. However, a central inverter structure has been utilized in order to simplify the simulation analysis.

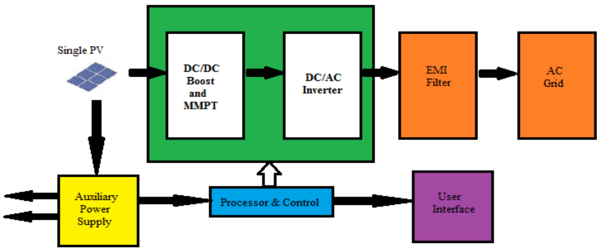

Fig. 1. Intelligent PV system interface concept

4. Smart PV Inverters Operation

Fig. 2 presents the overview of a single phase grid connected inverter. To connect an inverter to the electrical grid, it is needed to utilize a control system along with numerical data of the voltages, angles, active power, and reactive power. Hence, the active power P and the reactive power Q exchanged between the grid and the inverter can be calculated through equations (1) and (2).

$$P = \frac{V_i V_s}{2\pi f L_C} \sin \delta = P_{MAX} \sin \delta \tag{1}$$

$$Q = \frac{V_i^2}{2\pi f L_C} - \frac{V_i V_s}{2\pi f L_C} \cos \delta \tag{2}$$

Where V_i = voltage on the terminals of the inverters, V_s=voltage of the electrical grid, L_c = inductance of the coupling inductor, δ = phase difference between voltages V_i and V_s, and f=frequency of the system.

In order to reach reactive power transfer between the inverter and the grid, it is needed to provide an amplitude difference between their voltages. When the inverter terminal voltage is greater than the grid voltage, but they are in the same phase, the inverter will provide only reactive power to the grid (capacitive mode). Conversely, with the inverter terminal voltage being less than the grid voltage, it will absorb reactive power from the grid (inductive mode).

The inverter will be able to exchange active power with the grid in case the system has energy storage devices (e.g. battery, fuel cell, PV) on the DC side. Active power flow can be controlled through controlling the phase of the inverter terminal voltage. In case of absorbing active power from the grid, the output voltage is generated with a delay and with the same magnitude as the grid voltage. The inverter can also provide active power to the grid when generating an output voltage having the same magnitude as the grid voltage but advanced in phase.

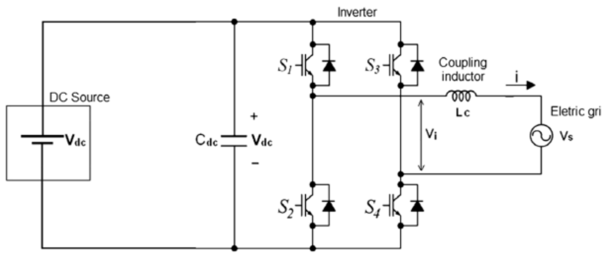

Fig. 2. General single-phase inverter system connected to the electrical power grid

All the functions described previously, absorption or generation of active and reactive power, have the ability to be controlled independently. The active power of the inverter depends on the amount of the power supplied by the PV system and is determined by the performance of the inverter. At a specific value of active power, the exchanged reactive power is controlled by the internal switching characteristics of the inverter. Also, the reactive power supplied or absorbed by the inverter is limited by the nominal apparent power S, which is normally determined by the maximum active power that the PV system can supply [11].

Inverters are the heart of intelligent grid-tied renewable systems and future smart grids. These inverters convert the absorbed energy so that it will be compatible with the grid quality. However, they are applicable as long as the renewable source, e.g. solar, is producing energy; otherwise, they will be idle and the system loses its efficiency. One way to overcome the system idleness during the times when there is no sunlight or at nights is to use the inverters as reactive power compensators. This application will help the system voltage to remain stable without using expensive capacitor banks.

Employing inverters to provide active power and compensate for reactive power is not a new concept [12, 13]. Nevertheless, these special designed active filter inverters are not suitable for grid-tied applications. It will be interesting to enable the existing inverters to operate in reactive power compensation mode when the active power is not nominally supplied by the PV cells. However, when active power is not available, the challenge is how to pre-charge the DC bus and keep it regulated within limits to be able to inject or absorb the desired level of reactive power. The controller used in this paper provides a strategy that enables PV inverters to absorb little active power from the grid when the renewable source is not available to regulate the DC bus voltage to keep it within limits.

Simultaneous Injection of Active and Reactive Power during Normal Operation

When the PV system is providing active power, the amount of reactive power is determined by the system power exchange capacity and the needs of the grid. In normal conditions, it is prior to provide all the produced active power to the grid. Since the produced solar energy is usually less than the nominal apparent power of the inverter, the rest of its capacity is dedicated to the reactive power flow according to the equation $|Q| = \sqrt{S^2 - P^2}$[14].

VAR Mode at Night

Typically, grid-tied inverters are preceded by a DC-DC converter stage regulating the DC bus voltage of the inverter. However, These DC-DC converters become idle when there is no active power production. (Fig. 3).

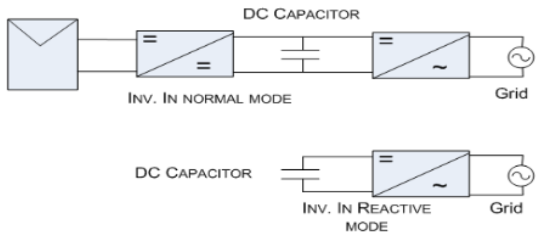

Fig. 3. Inverter switching to reactive mode

The operation of the inverter in VAR mode requires two steps:

The DC bus capacitor pre charging.

Keeping the DC bus voltage within limits, while regulating the injected reactive power.

In order to compensate for the reactive power when there is no active power, the DC link capacitor has to be charged in advance. Hence, the inverter will utilize its inverse diodes to act as a rectifier.

To regulate the voltage of the DC link capacitor, a hysteresis control loop is utilized which has two operation modes, as shown in Fig. 4.

Mode 1 (charging mode): If the DC bus voltage drops below V_{DC_Lo} active power needs to be absorbed from the grid to charge the DC bus

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capacitor. The active power drawn is a function of the estimated losses, $K * P_{loss}$.

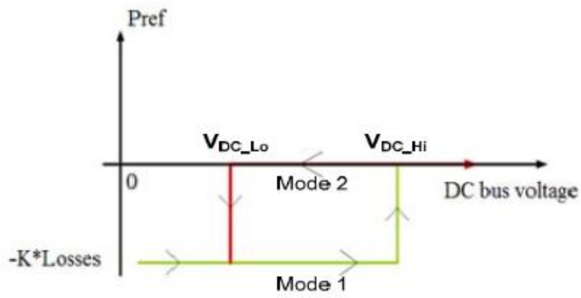

Fig. 4. Hysteresis controller operation

Mode 2 (discharge mode): With the DC bus voltage reaching the upper limit, V_{DC_Hi}, the active power absorption is set to zero and the DC bus voltage will start decreasing gradually, due to the inverter internal losses. As soon as the capacitor voltage reaches the lower limit, the controller will be switched to mode 1.

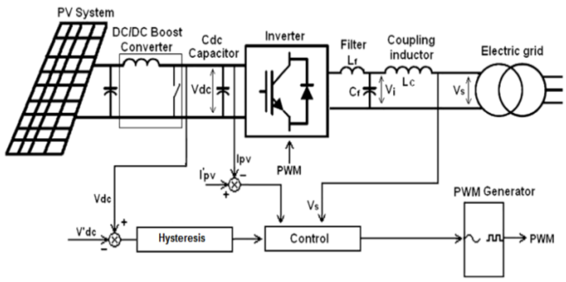

Fig. 5. Power system and control of the grid connected PV system

5. Control Technique and Power Circuit

The basic idea of the control technique is to use a pulse width modulation (PWM) pattern to control the inverter with the main objective of setting the power angle in accordance with the energy supplied by the photovoltaic system. Furthermore, this system has the objective of changing the voltage magnitude at the inverter terminals for the inverter to be able to generate or absorb reactive power to or from the grid. This aim can be achieved by working on the active and reactive components of the current vector I_p and I_q, respectively. Such components can be altered by working properly with the inverter.

The full system structure, shown in Fig. 5, consists of the PV, a DC-DC boost converter, a capacitor on the DC side, an inverter with PWM control switching frequency of f_s , a filter, a coupling inductor on the DC side, voltage and current sensors, and the control system.

As it was mentioned, it is necessary to maintain the DC bus voltage V_{dc} constant. The hysteresis controller is added here to regulate the error between the measured and the desired DC link voltage. When the measured DC link voltage value is higher than the reference DC value, the error is positive, the inverter will increase the amount of active power production. With the error being negative, the inverter's delivery of active power will decrease or stop [15].

The control should also set the inverter output voltage amplitude so as to be proportional to the PV current I_{pv} which changes according to the insolation level. The error between the reference current I'_{pv} and the measured current I_{pv} is determined and used to control the output reactive power of the inverter. The inverter will not exchange any reactive power when this error is zero, meaning that the PV panel is producing its nominal active power. When the measured I_{pv} is lower than I'_{pv}, the control system sets the inverter in order to absorb or supply reactive power from or to the grid. When the grid voltage is smaller than its nominal effective reference voltage, the inverter supplies reactive power to the grid; the inverter will absorb reactive power from the grid when its voltage is larger than its nominal reference. Pursuing the needs of the electrical grid, the inverter's reactive power will increase following the decrease or stop of the PV active power, avoiding inverter idleness. However, the nominal apparent power of the inverter limits the amount of reactive power allowed to be absorbed or supplied according to the active power generation.

Simulations and Results

Simulations for the proposed system are carried out in MATLAB/SIMULINK to determine the amounts of active, reactive, and apparent power in different scenarios. The DC link and the AC grid reference voltages are 390V and 220V respectively. Nominal features of the PV system are: output power 2000W, output DC voltage 390V, under conditions of maximum power, with an insolation level of $1000 W/m^2$ and at a temperature of 25 °C.

When the grid voltage is below its nominal effective reference value, the reactive power has to be supplied by the inverter. Conversely, the inverter has to absorb the reactive power from the grid when the grid voltage exceeds its reference. As a result, this system will help the grid voltage remain stable by means of exchanging reactive power.

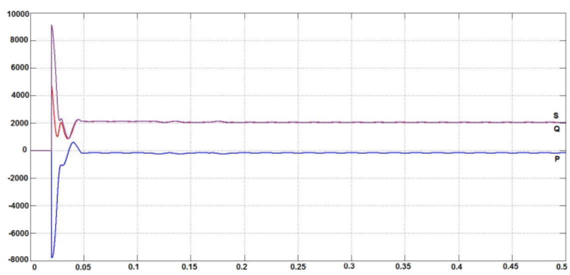

Fig. 6. Supplied P, Q, and S. PV generation is 0%.

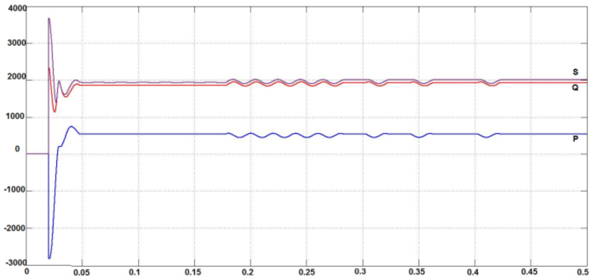

Fig. 7. Supplied P, Q, and S. PV generation is 25%.

Results obtained for the proposed system are shown in Fig.s 6-13. These results can be divided into two groups: results shown in Fig. s 6-9 are for the times when the grid voltage is below the reference voltage of 220V. As seen in these Fig. s, with the grid voltage being less than 220V, the inverter supplies reactive power to the distribution grid. Fig. s 10-13 are obtained in the grid over-voltage conditions which has caused the inverter to absorb reactive power from the network. It has to be noticed that the apparent power constraint has been met in all scenarios.

Fig. s 6-9 show the active, reactive, and apparent powers from the inverter to the grid for the case of a grid voltage drop. Four scenarios of different insolation levels for the grid reactive power deficit condition has been taken into account: Case 1- 0% insolation level (Fig. 6); Case 2- 25% (Fig. 7); Case 3- 75% (Fig. 8); Case 4- 100% (Fig. 9).

As illustrated in the results, the active power supplied by the inverter increases with the insolation level. Since the active and reactive powers reach to a stable condition after some transients, it can be said that the control system works properly. Also, the amount of the supplied reactive power decreases with the active power increasing; which is the result of active power provision being prior to reactive power exchange. Afterwards, results admit that the inverter does not remain idle even if the amount of active power generation drops as a result of insolation weakness.

The control system is designed in a way that it supplies or absorbs no reactive power when there is a maximum insolation level. On the other hand, when the insolation level is zero, almost all the apparent power capacity of the inverter will be dedicated to reactive power. However, the inverter will absorb a little amount of active power from the grid which counts for the power losses in the inverter components. That's the reason for the negative active power seen in case 1.

Fig.s 10-13 show the active, reactive, and apparent powers supplied by the inverter for the case of grid voltage rise. Like the previous case of grid reactive power deficit, there are four conditions of insolation levels: Case 1- 0% insolation level (Fig. 10); Case 2- 25% (Fig. 11); Case 3- 75% (Fig. 12); and Case 4- 100% (Fig. 13).

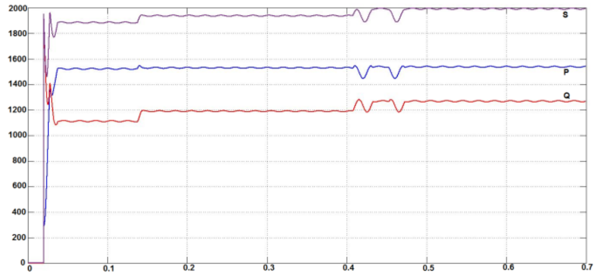

Fig. 8. Supplied P, Q, and S. PV generation is 75%.

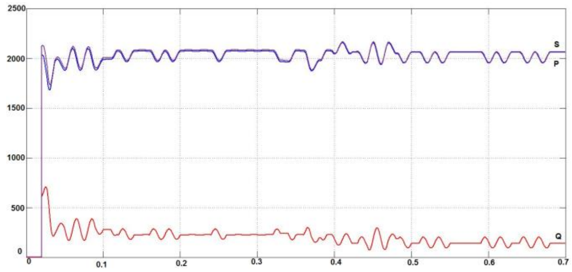

Fig. 9. Supplied P, Q, and S. PV generation is 100%.

In the case of grid reactive power excess, the inverter absorbs reactive power and Q has a negative amount, showing an inversion in the direction of reactive power flow. All these results are stabilized after some transients showing that the system works properly as predicted.

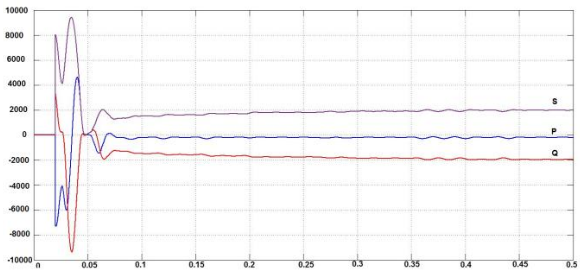

Fig. 10. Supplied P, Q, and S. PV generation is 0%.

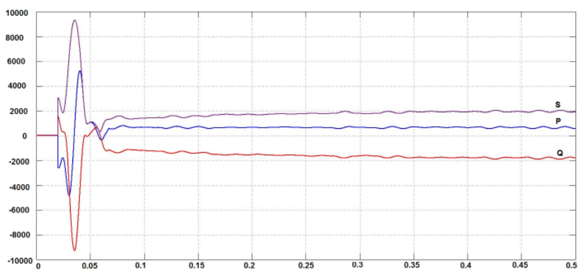

Fig. 11. Supplied P, Q, and S. PV generation is 25%.

6. Conclusions

This paper proposed a control approach to enable grid-tied inverters to compensate for the reactive power beyond the active power capability.

Using a single full bridge inverter, the DC bus voltage was regulated within limits, active power could be drawn from the grid in certain conditions, and the desired amount of reactive power could be exchanged, taking into account the apparent power limitation of the inverter. The power angle and the amplitude of the inverter output voltage were controlled correctly in order to control the active and reactive powers exchanged with the grid. Using reactive power capability of the PV inverters could help the grid power factor to be improved, support the local voltage, and decrease the losses. The simulation results confirmed that the control system performs well for the analyzed PV system.

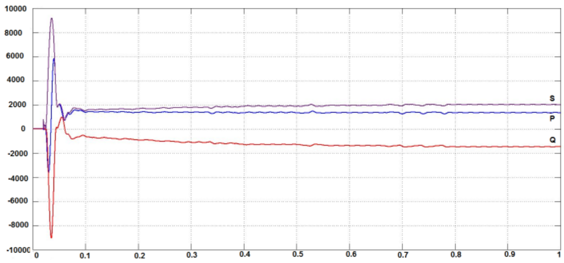

Fig. 12. Supplied P, Q, and S. PV generation is 75%.

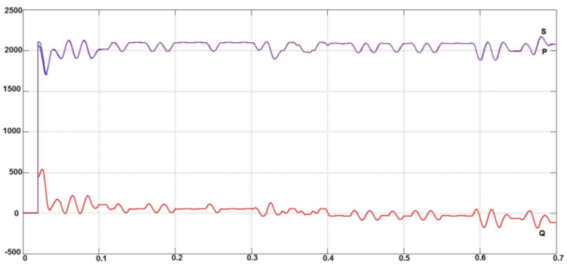

Fig. 13. Supplied P, Q, and S. PV generation is 100%.

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