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# Smart Grid Tied Solar Inverter Technology for Smart Grid

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**Summary:**

Grid tied solar inverter is one of the main component in the solar photovoltaic (PV) system and is used invariably in solar PV plants to convert the variable direct current (DC) output of solar PV system into alternating current (AC). Currently, majority of inverters that are used to connect the PV to the electric power grid are traditionally programmed to operate at unity power factor which means that all these solar inverters will feed as much active power into the point of common coupling (PCC) of the grid as is available from solar array which is dependent on solar irradiance. These traditionally programmed solar inverters do not have feature of reactive power generation. With the increase in number of renewable based DERs which are connected to the main grid, reactive power drawn from the grid as compared to active power has increased considerably as these solar inverters can inject only active power into the grid whereas reactive power required for operation of equipment is taken from grid. This affects the power quality of the grid as the power factor of the grid (supplied by the PV system that uses inverters injecting only active power) will go to a lowest value. Moreover, in order to supply the reactive power required for connected loads, utilities need to install capacitor banks and various types of FACTS devices which adds to operational complexity and additional cost to the system. In addition to above listed points, the solar inverter does not get utilized upto its rated capacity as the output of the solar inverter varies in direct proportion to the solar irradiance which varies invariably throughout the day and does not remain constant. This lead to underutilization of solar inverter when the irradiance is low. Additionally, the Indian government's National Smart Grid Mission aims to significantly enhance the nation's power infrastructure by addressing key smart grid challenges. A crucial aspect of this initiative involves integrating Distributed Generators to ensure grid voltage stability and reactive power support.

Above listed demerits of conventional solar inverter can be addressed by making the solar inverter “smart” - an inverter which not only performs standard functions of conventional solar inverter but also has the capability of addressing the issues discussed above by communicating with the electrical grid and generating reactive power of both lag and lead type as per the requirement of grid. This solar inverter can operate in various modes of reactive power compensation such as fixed reactive power, fixed power factor and volt-var mode and thus improves the capacity utilization of solar inverter.

This paper discusses various modes of reactive power compensation along with their operational line / window. A prototype of solar inverter module was developed in the laboratory and programming to carry out the various reactive power compensation modes was carried out in digital signal processor. Control / programming logic for generation of reactive power command for various reactive power generation modes are also discussed in detail. Experimental results, data and captured waveforms for various experiments carried out on developed solar inverter module prototype for various modes of reactive power compensation (for varying solar irradiance, varying grid voltage) are also explained and discussed in detail.

**Keywords:**
Smart solar inverter, grid tied solar inverter, reactive power compensation

## 1. Introduction

A smart grid is an advanced electricity network equipped with automation, communication, and IT systems that can monitor the flow of electricity from the generation point to the consumption point. It can adjust power flow or reduce load to match generation in real-time, while maintaining power quality. One significant advantage of the smart grid is its ability to integrate variable renewable energy sources more efficiently. Solar inverters, which are essential in solar photovoltaic (PV) plants, convert the variable direct current (DC) output from solar panels into alternating current (AC). Traditionally, solar inverters are designed to operate at a unity power factor, meaning they feed only active power into the grid, as available from the solar array. These traditional inverters do not have the capability to generate reactive power.

With the growing number of renewable-based distributed energy resources (DERs) connected to the grid, the amount of reactive power drawn from the grid has increased. This is because traditional solar inverters can only inject active power, while the reactive power needed for grid operation must be drawn from the grid itself. This imbalance can lead to power quality issues, such as a lower power factor at the point of common coupling (PCC) and voltage fluctuations beyond permissible limits.

These power quality challenges can be mitigated by upgrading solar inverters to "smart" inverters, which include reactive power compensation capabilities. A smart inverter not only performs the standard function of converting DC to AC but also addresses grid integration issues by offering reactive power support through sophisticated monitoring and communication of grid conditions. Smart inverters can generate reactive power (inductive or capacitive) under different operational modes, thereby improving the power factor and stabilizing voltage at the PCC.

Smart solar inverters do not interfere with the normal operation of the solar inverter, while also ensuring better utilization of the inverter's capacity—something traditional inverters without reactive power compensation cannot achieve.

A prototype of a smart solar inverter was developed to demonstrate and experiment with various reactive power compensation modes. This inverter is capable of operating in modes such as: i) fixed reactive power, ii) fixed power factor, and iii) volt-var mode.

Laboratory experiments were conducted on a single-phase, dual-stage grid-connected solar inverter controlled by the digital signal processor 'TMS320F28335'.

The remainder of the paper is organized as follows: Section 2 discusses the control scheme for the smart inverter with reactive power compensation. Section 3 outlines the different reactive power compensation control modes. Section 4 presents the experimental results, and Section 5 provides the conclusion.

## 2. Control scheme of Smart Solar Inverter

Three approaches can be used for achieving reactive power compensation using smart solar inverter. First is by using the solar inverter with higher kVA rating based on the planned maximum amount of reactive power injection. Second is by compromising on the amount of active power injected into the grid whenever the apparent power rating exceeds the rated value of the solar inverter. Third is by providing preference to the active power generation and injecting reactive power in a fashion that the apparent power does not exceed the rating of solar inverter. First approach will impact the economics of the PV system because of cost involved with the higher rating solar inverter. Second approach will result into decreased efficiency of the solar PV system as the solar inverter is required to operate outside the maximum power point (MPP) leading to generation of lesser active power. Looking into the compromise associated with first two approaches, in this paper it is proposed to operate the solar inverter using third approach.

In the third approach, the Maximum Power Point Tracking (MPPT) is given the priority which means that for abundant availability of solar irradiance, the smart inverter will inject active power into the grid as per the relation of active power generation with solar irradiance. However, if the cloud blocks the sun and causes the PV array's maximum power to drop below a set value, say 90%, then any of the reactive power compensation mode can be switched ON. This will enable the system to utilize the unused capacity of the solar inverter which otherwise would not be used when the solar inverter is programmed to operate in conventional mode (unity power factor operation) without compromising on cost and efficiency.

Figure 1 presents the control scheme for reactive power compensation in smart solar inverter. For traditional operation of solar inverter in which only active power is injected in the grid by the solar inverter, the active component (id* or i_d-reference) of the reference current is controlled and the reactive component (iq* or i_q-reference) is set as zero. For reactive power compensation mode of solar inverter, the reactive component (iq*) of the reference current is used as an additional control variable to the control system.

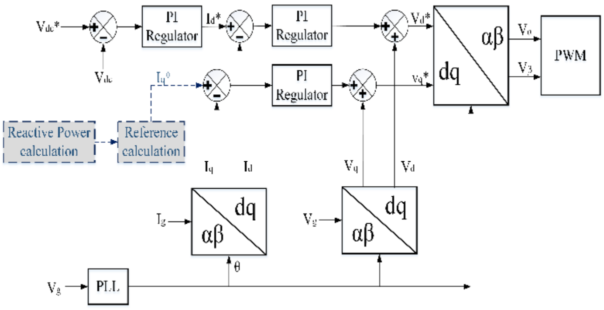

Figure 1: Control scheme of smart solar inverter

Both the active and reactive components of the injected current are controlled separately to control the active and reactive power. The reactive component of the reference current can be used to vary the reactive power by using either an external reference signal or by using additional measurement block as mentioned in the figure 1.

## 3. Reactive Power Compensation Control Modes

This section discusses the various control modes of reactive power compensation using grid tied solar inverter. Different control strategies for reactive power compensation are (i) fixed reactive power (fixed Q), (ii) fixed power factor (fixed cos φ) (iii) volt-VAR {Q(V)} and (iv) power – power factor mode. When programmed to operate in any of the above listed mode, the solar inverter will inject reactive power (either lagging or leading) in addition to active power. Such type of operation is termed as partial reactive power compensation.

### 3.1 Fixed Reactive Power Mode

When the inverter is operated in fixed reactive power (Q) mode, then the solar inverter will inject reactive power based on the reference command of reactive power injection (i_q-reference). Generally, most of the time, the active power generated by solar inverter is less than 90% of its rated capacity. The remaining 10% capacity of the solar inverter can be utilized to provide reactive power. The inverter may inject inductive (lagging) reactive power or capacitive (leading) reactive power based on the polarity of reference command of reactive power injection (i_q-reference). In figure 2, the inverter may operate on any of the operational line based on the input command wherein the line named as operational line in figure 3 indicates operation of solar inverter at fixed reactive power. The value of i_q-reference can be varied from +1 to -1 per unit value.

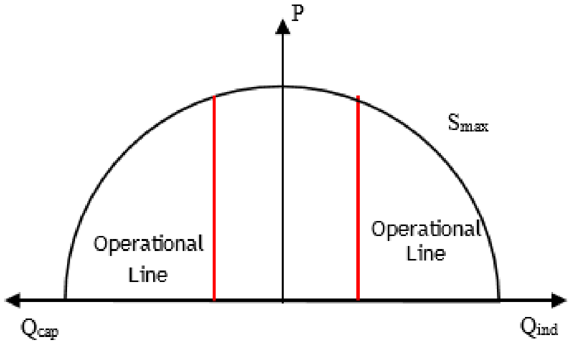

Figure 2: Operational window for fixed reactive power control mode

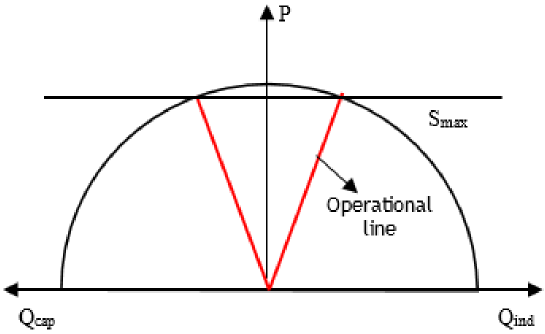

Figure 3: Operational window for fixed power factor control mode

### 3.2 Fixed Power Factor Mode

When the inverter is operated in fixed power factor mode, the inverter varies its reactive power output in proportion to the active power injected in the grid so as to maintain fixed power factor. However it is to be noted that as per the third approach (discussed in section 2), the MPPT is given priority so when the irradiance is sufficiently available and the inverter is injecting active power into the grid in such a way that the rated power operation of the inverter is met, the reactive power control mode will be suppressed. The inverter programmed to operate in fixed power factor mode, will operate on any of the operational line as set by the user / programmer, wherein the line named as operational line in figure 3 indicates operation of solar inverter at a set power factor.

### 3.3 Volt VAR Mode

When the inverter is operated in volt var mode, the inverter will inject reactive power based upon the value of voltage at the PCC. A typical characteristic curve that may be set in the inverter program for volt var mode operation is depicted in figure 4. From this figure, it can be seen that the inverter will not inject any reactive power when the per unit voltage at the PCC is in the range of 0.95 to 1.05. However for per unit voltages in the range of 0.9 to 0.95 and 1.05 to 1.1, the inverter will inject leading and lagging reactive power respectively based on the equations of these lines so as to bring the voltage at the PCC within limits of normal operation range. Injecting capacitive (leading) reactive power when the voltage at the PCC goes below set range will help in increasing the voltage. Same type of explanation can be applied to inductive reactive power. The inverter will inject only capacitive or inductive reactive power when the per unit voltage at the PCC are less than 0.9 or greater than 1.1 value respectively.

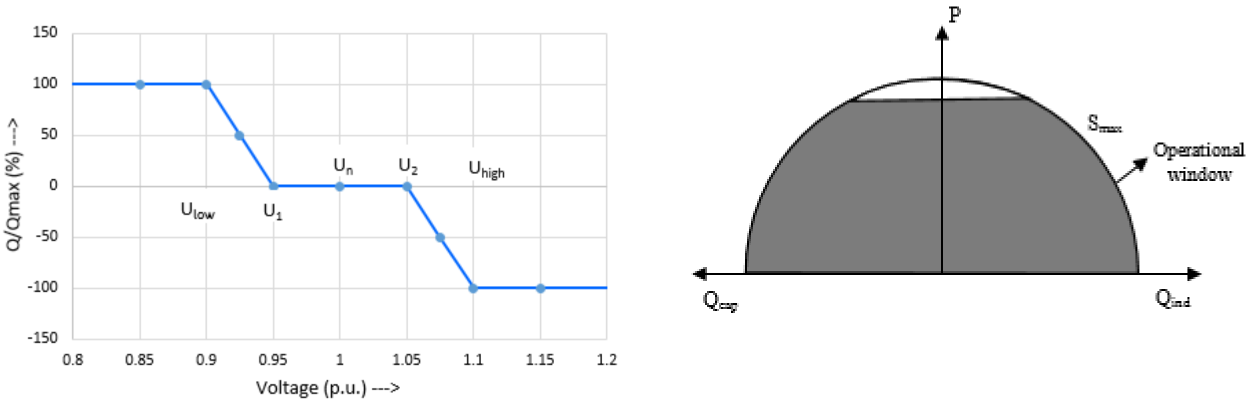

Figure 4: Characteristic curve and operational window for volt var control mode

### 3.4 Power – Power factor mode

When the inverter is operated in this mode, the inverter varies its power factor according to the characteristic curve. The typical curve can be given by the plant operator. In this mode, the power factor is varied when the active power output reaches a pre-defined value say 50% of the rated output of inverter. Figure 5 shows the operational window for this mode.

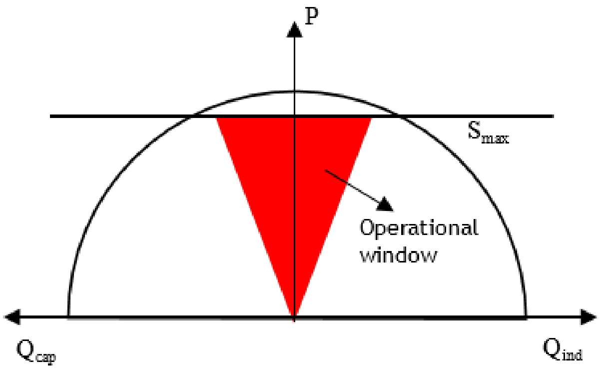

Figure 5: Operational window for power – power factor mode

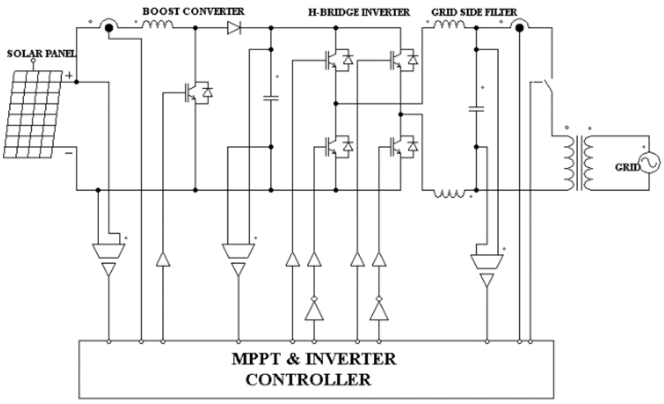

Figure 6: Topology of grid tied solar inverter

## 4. Hardware Results

This section presents various experimental results carried out on a developed grid tied solar inverter and discusses the results in detail. A prototype of solar inverter with dual stage, single phase topology of 5 kVA rating is developed for experimentation. Schematic diagram of the developed inverter is shown in figure 6. PV simulator is used to simulate solar PV panels of 5.04 kW.

### 4.1 Experiment 1: Fixed Reactive Power Mode

To demonstrate the increase in utilization of the solar inverter when operating in fixed reactive power mode, the solar irradiance and ambient temperature value is kept as 500 W/m2 and 250C respectively for the entire experiment duration. The inverter is programmed to provide the reactive power compensation in accordance with the reactive power command (i_q-reference). Figure 7 shows the i_q-reference command given to the solar inverter and Table I summarizes the various timelines for injection of reactive power command.

Table I. Timeline summary for various reactive power command to the solar inverter

| Time interval | i_q-reference | Remark |
|---|---|---|
| t1 < t < t2<br>t2 < t < t3 | 0.4<br>0.5 | Injecting inductive reactive power |
| t3 < t < t4 | 0 | No reactive power command |
| t4 < t < t5<br>t5 < t < t6 | -0.4<br>-0.5 | Injecting capacitive reactive power |

Various hardware results captured using power meter are as shown in figures 8 to 10. It can be seen from figure 8 that the solar inverter is injecting inductive and capacitive reactive power into the grid based on the polarity of the reactive power command as shown in figure 7. It can also be observed from figure 9 that the inverter is injecting active power throughout the experiment duration based on the set value of irradiance (which in this case is 500 W/m2), which shows that the active power injection does not get affected by the reactive power command. Injection of active power into the grid is based on the MPPT operation. Reactive power injection in addition to active power leads to increase in apparent power (figure 10). For the time period t1 < t < t3 and t4 < t < t6 where the reactive power command is issued, the apparent power is greater than rest of the timelines in the figure 10. This shows effective utilization of the solar inverter. The percentage increase in the utilization of the solar inverter is 40% approximately for i_q-reference = 0.5 and -0.5 and 20% for i_q-reference = 0.4 and -0.4 for this experimental setup.

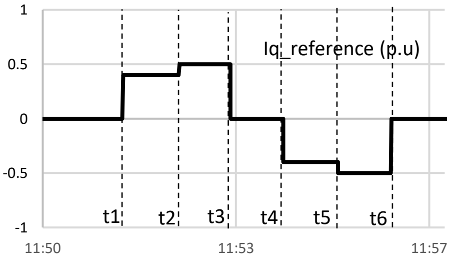

Figure 7: Reactive power command (Iq_reference)

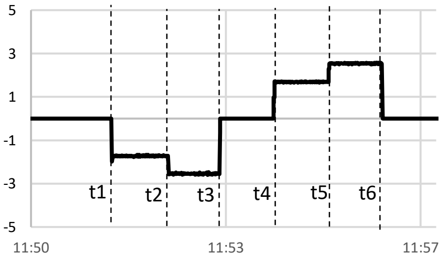

Figure 8: Reactive power from solar inverter (kVAR)

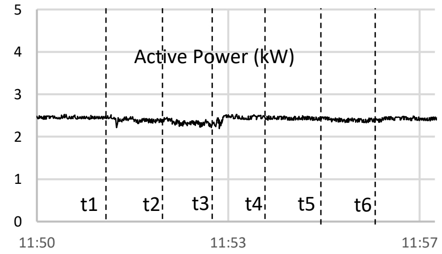

Figure 9: Active power from solar inverter (kW)

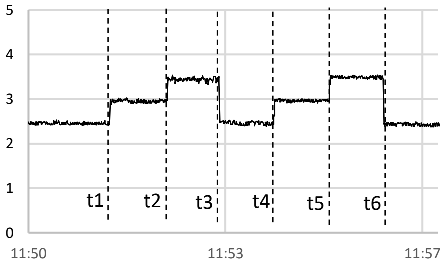

Figure 10: Apparent power from solar inverter (kVA)

### 4.2 Experiment 2: Fixed Power Factor Mode

In this experiment, the solar irradiance is varied from 400 W/m$^2$ to 1000 W/m$^2$ as shown in figure 11 and the ambient temperature is set as 25$^0$C. The inverter is programmed to operate at fixed power factor of value 0.85. Depending upon the value of set power factor, the controller calculates the value of i_q-reference, based on which the reactive power is injected into the grid. The inverter is programmed as per approach 3 described in section 2 according to which the MPPT operation is given priority over reactive power compensation. Hence when the irradiance reaches value of 900 W/m$^2$, the reactive power command is suppressed to zero value which means that the solar inverter will not inject reactive power into the grid beyond irradiance of 900 W/m$^2$ and will pump only active power into the grid. The value of i_q-reference achieved by the controller is shown in figure 11. The negative value of i_q-reference plotted in figure 11 for ease of representation. The reactive power injected by the inverter for various values of reactive power command is shown in figure 12. Active power injected by the solar inverter as obtained by the MPPT operation of the controller for various values of irradiance is shown in figure 13. In order to show the increase in utilization of the solar inverter when operated in fixed power factor mode, apparent power is plotted for two different cases in figure 14 – one with fixed power fed mode (plotted with black colour) and other with traditional operation of solar inverter in which inverter is operated at unity power factor (plotted with blue colour). It can be observed from plot of two apparent power plots of figure 14 that for the same value of irradiance, the apparent power of solar inverter is greater for the case of reactive power compensation mode (0.85 power factor) as compared with unity power factor mode. The two apparent power plots coincides only for irradiance value equal to 900 and 100 W/m$^2$, where the i_q-reference is programmed to settle to zero. Figure 15 shows the power factor of the grid tied solar inverter. It is set at 0.85 for the time till solar irradiance is 800 W/m$^2$, after which the power factor sets to unity value so that the apparent power by the solar inverter does not exceed the rated design value.

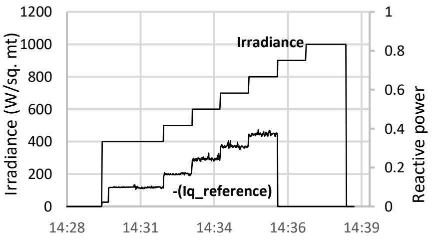

Figure 11: Irradiance and i_q-reference variation with respect to time

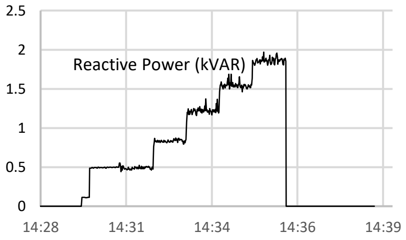

Figure 12: Reactive power from solar inverter (kVAR)

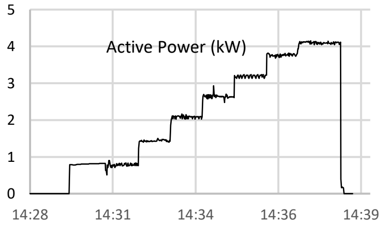

Figure 13: Active power from solar inverter (kW)

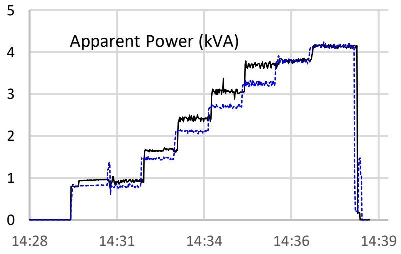

Figure 14: Apparent power from solar inverter (kVA)

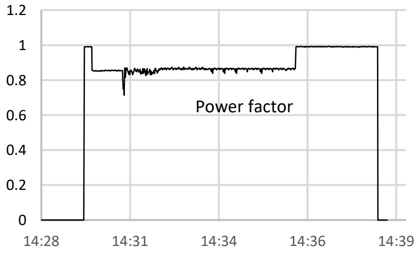

Figure 15: Power factor at the inverter output

## 5. Conclusion

This paper presents smart solar inverter which is having capability to inject lagging or leading reactive power into the grid. This inverter act smartly by communicating with the grid parameters and help in increase in utilization of solar inverter resource which otherwise not getting utilized in traditional solar inverter. The requirement of reactive power compensation in solar inverter has been discussed. Various modes of reactive power compensation along with their operational line / window are discussed. Hardware results for various experiments on developed prototype of solar inverter are presented in detail. Experimental results showed that the active power capability of solar inverter is not compromised while performing reactive power compensation. Moreover, reactive power compensation through solar inverter helps in enhancing the utilization of solar inverter and also provide support to the grid.

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