Reactive power control of solar photovoltaic inverters for grid code compliance support

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ABSTRACT

The compensation of reactive power in smart inverters is one solution to address the issue of voltage violations in the distribution network due to the penetration of solar photovoltaic power generation. However, options for reactive power control are limited during variations in irradiation and daily load on the feeder. This study aims to investigate the performance difference between four reactive power control techniques including Q(V) control, Q(P) control, fixed Q-Var, and fixed power factor (PF) available in smart inverters to reduce voltage violations due to PV integration and comply with the grid-code. Three-phase balanced power flow was simulated in a medium voltage distribution network (MVDN) considering the reactive power control mode of the inverter under variations in solar radiation and daily load. The results showed that the Q(V) control was more effective in improving distribution feeder voltage than other techniques and showed its compliance with the grid-code. The limiting setting point for var injection or power factor limit should be proportional to the daily grid load profile.

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1. INTRODUCTION

Renewable energy is observed to be increasingly utilized across different countries in recent years. It is considered one of the solutions to support the energy transition target designed to achieve net-zero carbon emissions. This is indicated by the introduction of renewable energy technology to decentralize power generation and one of the sources mostly developed for this purpose in recent times is solar power plants. The Indonesia government also targets the installation of a solar power plant capacity of 6,379 MW by 2025 as well as to provide infrastructure, requirements to connect solar photovoltaic (PV) generator to grid utility, and promote energy price policies to support the achievement of the 23% new renewable energy mix target in stages. However, the integration of solar PV generation power into grid utilities presents a technical challenge for distribution network operators (DNOs) and solar PV owners (SPVOs).

The integration of a PV generator in the medium voltage distribution network has a positive technical impact as indicated by its ability to balance active and reactive power flows, reduce voltage drops, and decrease power losses in distribution network [1], [2]. However, the integration of large-scale PV generator into medium-voltage network has a negative impact on power quality as indicated by harmonics, voltage flicker, voltage sag, frequency variation, voltage unbalance, and small signal stability [3], [4]. Another problem is the fault current contributed by the photovoltaic power plants (PVPPs) connected to the distribution network which can cause malfunctions in the protection devices [5], [6]. This is particularly observed from the high-power penetration of the PV inverter when the sunlight is at peak but the load is low, thereby leading to overvoltage. This means there is a need to control the PV inverter operation with intermittent characteristics in order to ensure compliance with grid-code requirements.

Traditionally, inverter in PV system operates under normal conditions at a power factor (PF) of one but smart inverter technology has currently provided reactive power management features in addition to the active power. This is due to the ability of smart inverter to provide reactive power regulation in order to compensate for the remaining unconverted power from the inverter's kVA capacity. It is important to note that there is a need to recalculate the impact of inverter reactive power compensation on voltage increase when it is used to supply or absorb reactive power. Therefore, the supply or absorption limits on the PV system need to be controlled by varying solar irradiance and fluctuations in grid load over time. The PF value is usually theoretically less than one when reactive power is being supplied or absorbed which normally causes a decrease in the active power output. This condition usually causes an economic loss for SPVOs because only the kWh of exports is calculated by the utility while the kVarh of exports is not valued. However, the PV inverter system needs to actively support the grid voltage through reactive power compensation according to the needs of the distribution network.

Several studies reviewed and measured the impact of active and reactive power control in PV inverter. It was discovered that the control of active and reactive power in large-scale photovoltaic power plants (LS-PVPPs) has been studied with consideration for the varying output of the PV generator due to changes in solar radiation, temperature, input DC voltage, and modulation index [7]. The reactive power constraint limit to the active power of the inverter has also been proposed to suppress voltage fluctuations at the point of common coupling (PCC) [8]. Other studies also suggested the application of reactive power control for voltage control in PCC using open-loop control (Q_{ref}) and close-loop (V_{ref}) [9]. Furthermore, [10] tested inverter reactive power control using PF and Var to improve power quality and fulfill grid-code requirements. Another study also controlled the increase in overvoltage using a Var injection with consideration for the inverter location, capacity, and minimum PF limits [11]. The activation of reactive power regulation feature on smart inverter using different control modes such as watt/Var, volt/Var, volt/watt, and PF to mitigate voltage increase on the network has also been investigated [12]–[17]. However, these studies were observed to only focus on PV inverter connected to low voltage distribution network (LVDN) and in most roof-top systems without explicitly reviewing the inverter generation system model. It is pertinent to state that the active and reactive load of the PV inverter connected to LVDN is the load on the local transformer directly connected to the electricity consumer. This system is certainly different from the PV system which is connected to the medium voltage distribution network (MVDN) using a step-up transformer. This is because the active and reactive loads served by the PV system connected to the MVDN are associated with all transformers in one distribution feeder. Therefore, the system needs to be measured for its broad impact on all transformer voltages contained in one distribution feeder.

The measurement of inverter performance on PV system in the distribution network has been evaluated using the volt-watt and var-volt control methods at different levels of PV penetration [18]. However, there are usually low electrical loads from morning to noon period because the solar irradiance has reached its peak but there are high loads in the afternoon when solar irradiance is low. This means there is a need to compare the distribution feeder load characteristics that vary from time to time during the operating period of the PV system with its performance at the same time. More specifically, it has been previously stated that the control of active and reactive power in centralized PV system operation with PF non-unity can reduce energy losses [19]. Vlahinić *et al*. [20] also showed that reactive power compensation of PV inverter with variations in the specific PF and load levels led to a decrease in different losses in the system. The study further suggested that the reactive power compensation with different control techniques currently available on smart PV inverter needs to be compared with their varying effects on the voltage gain and power losses in the system.

This study aims to investigate the differences in var-watt Q(P), var-volt Q(V), fixed Q-var, and fixed PF (PF unity and PF non-unity) control techniques available on current PV smart inverter features to ensure compliance with grid-code requirements. The process involved using the real North Gorontalo-Indonesia medium voltage distribution network currently connected to a 2 MWp solar PV generator as well as including the active power losses in PV and distribution systems in the analysis. A comprehensive analysis was conducted on the 2 MWp solar PV generator (68 units of 30 kWp string smart inverter) with changes in the feeder daily load and solar irradiance. The findings are expected to serve as a consideration for SPVOs in applying reactive power control to support grid quality as well as indicate the ability of DNOs to reduce the cost of losses and avoid problems with voltage violations which can increase operational, maintenance, and equipment replacement costs.

2. METHOD

2.1. Regulation of reactive power on PV inverter connected to MVDN

The current smart inverter technology has both active and reactive power handling functions [21]. The reactive power is normally used to keep the electric current flowing and maintain the stability of the voltage. It is usually generated by ensuring the inverter produces a voltage in phase with the grid voltage and higher amplitude. However, inverters usually absorb reactive power when the amplitude is lower and export the power based on their capacities. It is also important to note that the active power output is normally low when the sky is cloudy and the inverter does not obtain the maximum input power from the PV array, thereby, leading to the supply of reactive power from the remaining available capacity. The ability of a PV inverter to supply reactive power (Q) is generally expressed in the (1).

$$Q_{inv}^{max} = |Q| \leq \sqrt{S_{inv}^2 - P_{inv}^2} \tag{1}$$

Where, S_{inv} is the inverter's apparent power capacity rating, P_{inv} is the inverter active power output, and Q_{inv}^{max} is the reactive power limit on the inverter when supplying active power.

The IEEE 1547-2018 standard requires that the inverter-based distributed energy resources also provide support to the grid through reactive power regulation [22]. The Q-Var switch operating mode on the smart inverter is designed to limit the process of sending and absorbing reactive power from the grid and this is considered important because unnecessary reactive power compensation can damage the network voltage. It is also pertinent to state that reactive power compensation can be implemented using different techniques as mandated in IEEE standard 1547-2018. Furthermore, it is possible to control the inverter to supply or absorb a certain ratio of reactive power or be dynamically adjusted according to the network load which changes over time. This study measured the PV inverter performance based on four reactive power management techniques and also assessed their impact on the distribution network.

2.1.1. Active-reactive power control

The Q(P) technique is an inverter operating mode with reactive power control as a function of active power output. It controls PF based on the low and high-power limits of the inverter's active power output [13]. The reactive power regulation curve for the Q(P) control technique is shown in Figure 1 while the watt-Var control technique algorithm is expressed in (2).

$$PF = \begin{cases} Upper\ PF_{cap}\ ; if\ \frac{P_{ac}}{P_{nom}} < P_1 \\ Normal\ PF_{cap}\ ; if\ P_1 \leq \frac{P_{ac}}{P_{nom}} < P_2 \\ Normal\ PF_{ind}\ ; if\ P_2 \leq \frac{P_{ac}}{P_{nom}} < P_3 \\ Lower\ PF_{ind}\ ; if\ \frac{P_{ac}}{P_{nom}} \geq P_3 \end{cases} \tag{2}$$

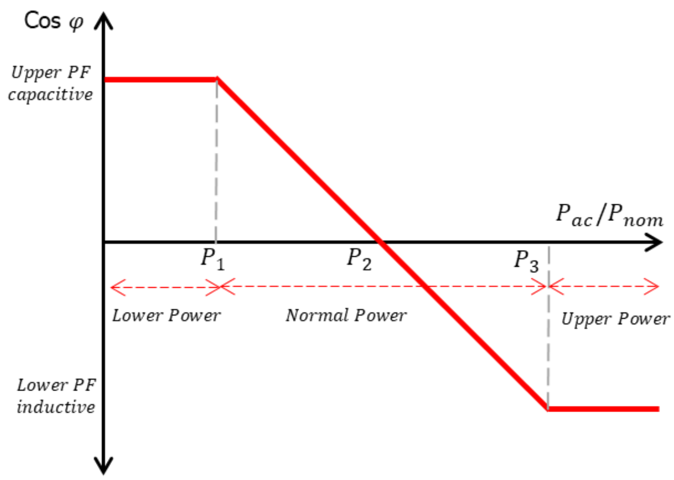


Figure 1. Reactive power regulation curve in Q(P) control

When the active power of the inverter is less than P_1 (lower power), the maximum PF is 1 (upper PF capacitive). This means that the inverter does not inject reactive power but PF is less than 1 when its active power is in the normal range of the capacitive power ($P_1 \sim P_2$) and this is the description of the injection process into the grid. Meanwhile, when the inverter power output is in the normal range of inductive power ($P_2 \sim P_3$), reactive power is absorbed and the range value limits are required to be determined by the SPVOs according to utility needs. It is pertinent to note that the active power point setting value (in %) proposed in this study was [P_1; P_2; P_3] = [50; 90; 100]% and the maximum reactive power limit injected or absorbed by the inverter was observed to depend on the capacitive and inductive PF values [+PF; -PF] = 0.95.

2.1.2. Reactive power - voltage control

In the Q(V) control technique, the inverter controls the reactive power as a function of the grid voltage. This means the reactive power compensation depends on the var-volt point setting determined by the utility [12]. Therefore, the reactive power regulation curve for the Q(V) control technique is presented in Figure 2 while the var-volt control technique algorithm is expressed in mathematical (3).

$$\frac{Q}{S_n} = \begin{cases} Q_{max} & ; if\ V_{grid} \le V_1 \\ \frac{V_2 - V_{grid}}{V_2 - V_1} Q_{max} & ; if\ V_1 < V_{grid} \le V_2 \\ 0 & ; if\ V_2 < V_{grid} \le V_3 \\ -\frac{V_3 - V_{grid}}{V_3 - V_4} Q_{max} & ; if\ V_3 < V_{grid} \le V_4 \\ -Q_{max} & ; if\ V_{grid} > V_4 \end{cases} \quad (3)$$

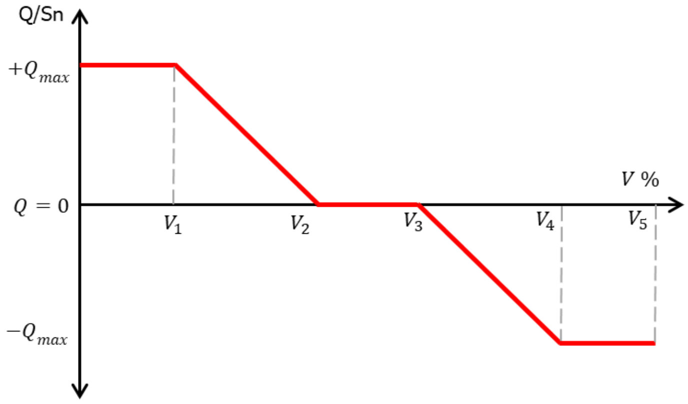


Figure 2. Reactive power regulation curve in Q(V) control

The figure shows that the inverter injected reactive power when the grid voltage V_{grid} is less than the V_2 value but the reactive power changed to 0 when in the range of $V_2 \sim V_3$ and was absorbed by the inverter when it is greater than V_3. Moreover, it was discovered that the maximum reactive power that an inverter can inject was recorded when the grid voltage is less than V_1 while the one that can be absorbed is limited when it is greater than V_4. The voltage setting point value (in %) proposed in the Q(V) control technique was [V_1; V_2; V_3; V_4; V_5] = [85; 90; 95; 105; 110]% and the maximum reactive power limit injected or absorbed was [$+Q/S_n$; $-Q/S_n$] which is 25% of the inverter capacity.

2.1.3. Fixed reactive power control

In the fixed Q-var control technique, the inverter is required to maintain a constant reactive power value during daily operation regardless of the variations in the solar radiation [23]. Moreover, the reactive power value is usually determined by the PV generator operator depending on the observations made regarding the distribution network load. The reactive power injected or absorbed by the inverter also needs to be within the inverter Va capacity limit. In this mode, the PF value changes dynamically to the active power output of the inverter to fulfill the reactive power target. Figure 3 shows the characteristics curve of the reactive power capability of the inverter for the fixed Q-var control technique through the red line.

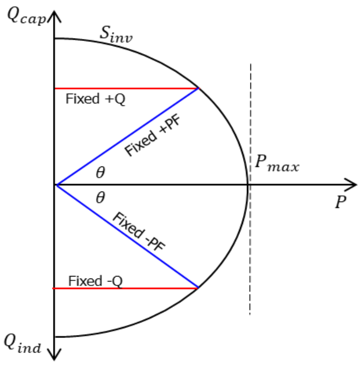


Figure 3. Reactive power capability curve of PV inverter

2.1.3. Fixed power factor control

The inverter with fixed PF mode was set to operate at a constant PF value. The target PF was determined by the PV generator operator allowed by the utility. Moreover, it is possible to set the fixed PF in a unity or non-unity PF value (capacitive/inductive) by considering the capacity of the inverter. In the unity PF mode (fixed PF = 1), the inverter does not transmit or absorb reactive power regardless of the variation in the active power output while the non-unity PF mode (PF<1) requires that the inverter produces or absorbs reactive power according to the specified PF target. The characteristic curve of the inverter reactive power capability for the fixed PF control technique is presented through the blue line in Figure 3.

2.2. PV Inverter system description

The 2 MWp solar PV generator connected to the medium voltage distribution network and tested in this study is located in North Gorontalo, Indonesia. Moreover, the system has a total of 68 parallel inverter units with a capacity of 30.00 kWp/33.12 kVa in a string configuration. It was further divided into two subsystems with each having 34 inverter units connected to a 0.4/20 kV step-up transformer at a capacity of 1250 kVa. It is important to note that the field measurements on the PV inverter electricity output for one day of solar irradiance were obtained using a power meter while the intensity of solar radiation was determined using a pyranometer, and recorded using a logger control unit. Furthermore, the single-line diagram of the inverter PV generator system is indicated in Figure 4.

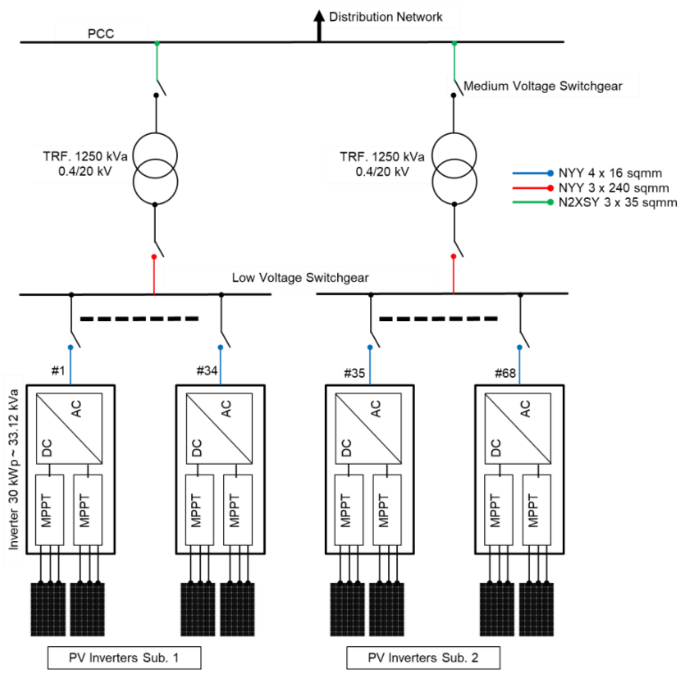


Figure 4. The Single line diagram of grid-connected PV system in North Gorontalo-Indonesia

2.3. Medium voltage distribution network (MVDN) test

The balanced three-phase power flow analysis was simulated before PV inverter integration by considering the load profile of 111 transformer units in one radial distribution line feeder. The real radial distribution network in North Gorontalo-Indonesia is presented in Figure 5 and the channel was observed to have used 150 mm^2 and 95 mm^2 AAAC-type conductors. The inverter-based 2 MWp capacity PV system was connected to 20 kV MVDN at a point between ID 141 and 142 transformers. Furthermore, Figures 6(a) and 6(b) show a daily load profile chart of the transformer's active and reactive power while Figure 6(c) indicates the solar irradiance variation curve associated with the total feeder load for 10 hours of observation. The data on the solar irradiance and feeder load profiles were recorded on 01/27/2022 from 07.00 am to 04:00 pm with an interval of 1 hour. This is necessary because this study focused on the power and voltage output performance data of the 68 PV inverter units by varying the solar irradiance and feeder load at the same time. However, the active power output of all inverters was assumed to be the same in the simulation considering the average power. It was also observed that the daily feeder load fluctuates from morning to evening while the active and reactive power load started increasing from 01:00 pm and peaked at 04:00 pm. The load normally increases continuously when consumers use electricity at night but the inverter PV generator was not designed to operate at night because the system does not use batteries to store electrical energy. Moreover, the three-phase power flow on the radial distribution network was simulated using a constant PQ load type. The main power supply was discovered to have come from the substation and the PV generator in the middle of the MVDN.

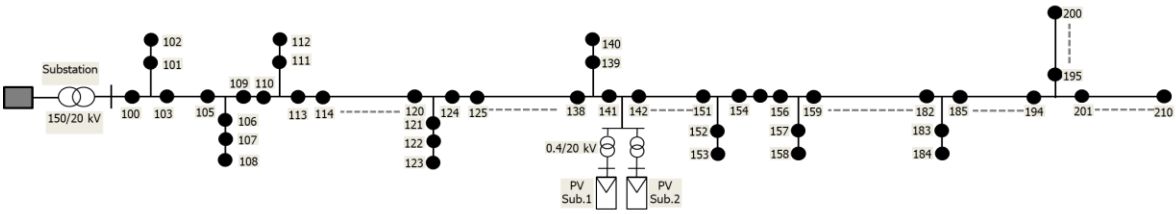


Figure 5. Single line diagram of a radial distribution network test

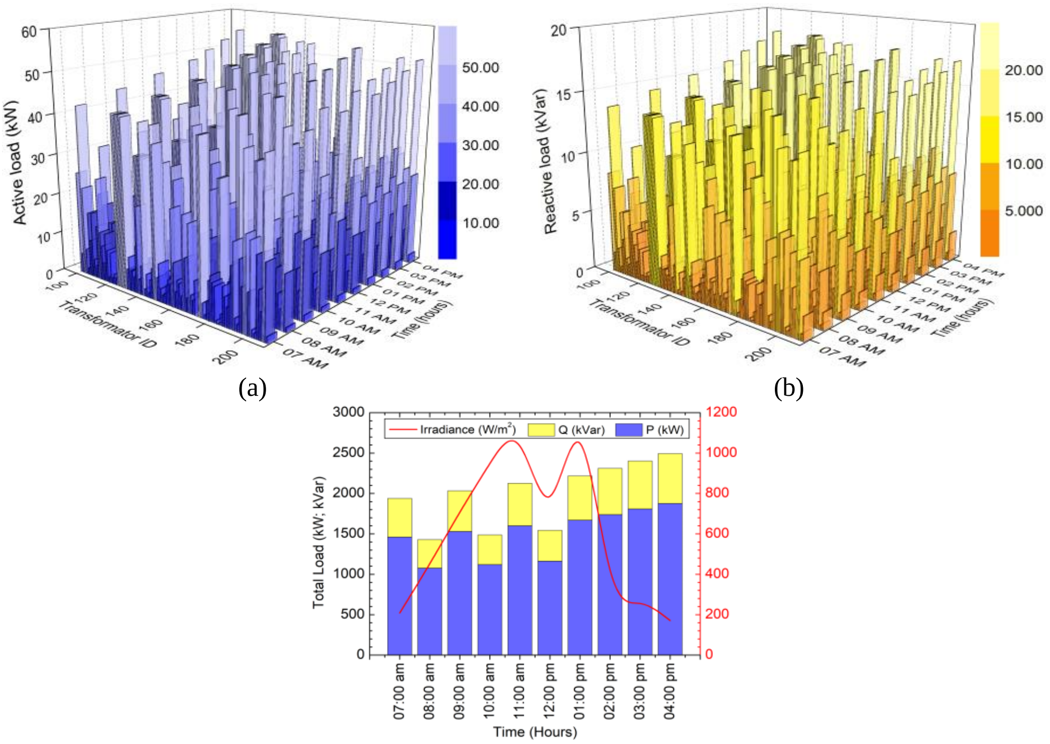


Figure 6. Transformer daily load profile (a) active power load, (b) reactive power load, and (c) solar irradiance profile and total feeder load in one measurement day

3. RESULTS AND DISCUSSION

The parameters investigated in this study include the voltage profile (inverter and in PCC) and power loss (PV and distribution systems). Figure 7(a) shows the difference in the quantity of inverter reactive power supply for each mode of operation at different variations of solar irradiance and feeder daily load. It was discovered that the inverter reactive power ramping (increase/decrease) occurred in the period 11:00 am – 1:00 pm in the control technique Q(P) and fixed PF = 0.95. The fixed mode inverter PF = 1 was observed not to produce reactive power and this means the injection of Q is 0 while the fixed Q-Var mode inverter supplied constant reactive power during the operation. In this technique, the ratio between reactive power to inverter capacity Q/S_n was constant during operation. Meanwhile, in the Q(P) control technique, the inverter did not send reactive power during the morning and evening periods because the active power generated was 50% lesser than its nominal power. The Q(V) control technique also produced higher reactive power injection when the feeder load increased as indicated in Figure 7(b) which shows the different inverter voltage levels for all the simulated control techniques. This means the highest inverter voltage at the beginning and the end of the daily operation was recorded in the fixed Q-var technique. However, when the solar radiation reached its peak and the grid load dropped, the inverter voltage increased significantly as presented in the fixed PF mode = 0.95. This condition needs to be anticipated because unwanted reactive power supply by the grid can cause voltage violations. However, the lowest voltage was achieved when the inverter did not export reactive power but the grid load increased and the solar irradiance decreased, indicating the linearity of capacitive reactive power with inverter voltage.

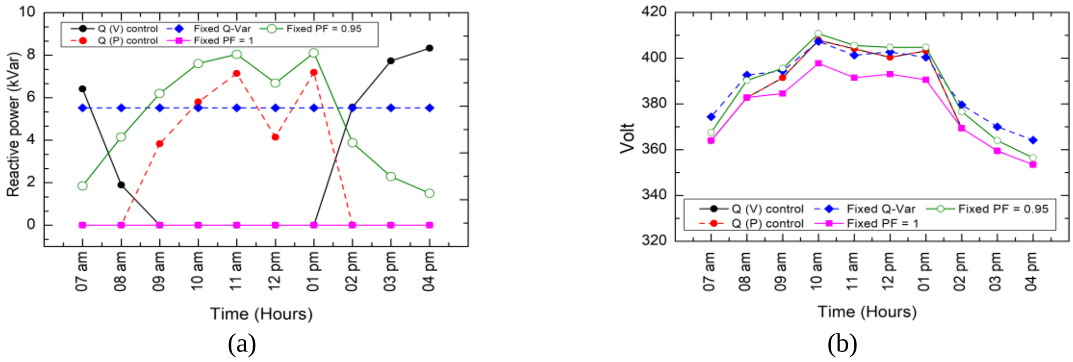
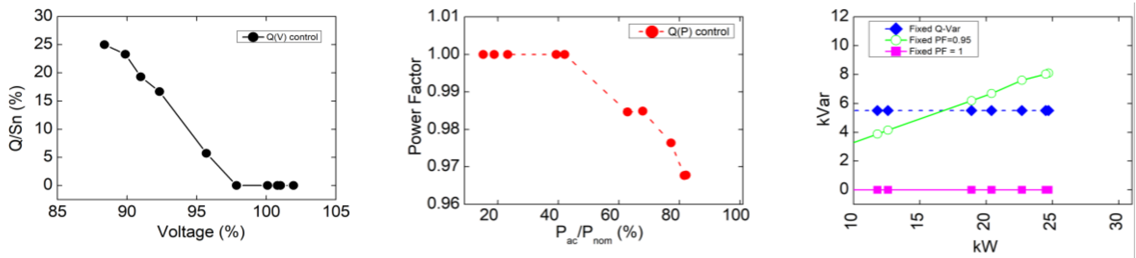


Figure 7. Inverter daily output of (a) the reactive power supply and (b) the voltage profile under changes in solar irradiance and feeder daily load

Figure 8 shows the characteristics of the PV inverter reactive power regulation curve for each control technique with the active power observed to have been fed to the grid based on the MPPT operation. Figure 8(a) shows the characteristics based on the grid voltage limit as a function of the reference voltage fed to the inverter and the value of the dead-band voltage point was discovered from the curve. This means there was no absorption of reactive power by the PV inverter because the grid voltage was below the dead-band voltage point. Meanwhile, the Q(P) control technique in Figure 8(b) shows the reactive power characteristics based on the active power output of the inverter and the curve indicates the capacitive PF value when the active power output of the inverter increased by more than 50%. It was observed that the inductive PF value was not recorded because the inverter's active power output was still below 90% of its nominal power. Furthermore, the fixed Q-Var and fixed PF techniques presented in Figure 8(c) show the characteristics of the reactive power curve following the target var and PF values.

The voltage deviations at the PCC were compared under different control techniques in Figure 9 and the secondary voltage of the step-up transformer in the PV system was rated. The active and reactive power transferred to the distribution network was the sum of the output power from all inverters arranged in parallel on the combiner panel. An interesting fact displayed on the column chart is the flow of inductive reactive power in the step-up transformer of the PV system when the inverter did not supply reactive power. This condition shows that the transformer used in the PV system connected to the MVDN always requires a reactive power supply regardless of the load (self-consumption). It is also important to note that the inductive reactive power is required to generate magnetic flux in induction devices such as transformers while the capacitive reactive power can be used to vectorially compensate the reactive power requirements on the network. The voltage at the PCC when the inverter was operating based on the Q(P) and fixed Q-Var control techniques were found to have increased to 105% at 10:00 am. The findings also showed that the inverter with the Q(V) control technique improved the voltage in a normal range of 97% to 103% while the fixed PF = 0.95 caused an overvoltage violation that exceeds the +5% upper limit. It was observed that the fixed PF=1 did not cause a significant increase in the voltage compared to other simulated techniques.



(a) (b) (c)

Figure 8. Reactive power regulation curve (a) Q(V) controls, (b) Q(P) controls, and (c) fixed Q-var and fixed PF

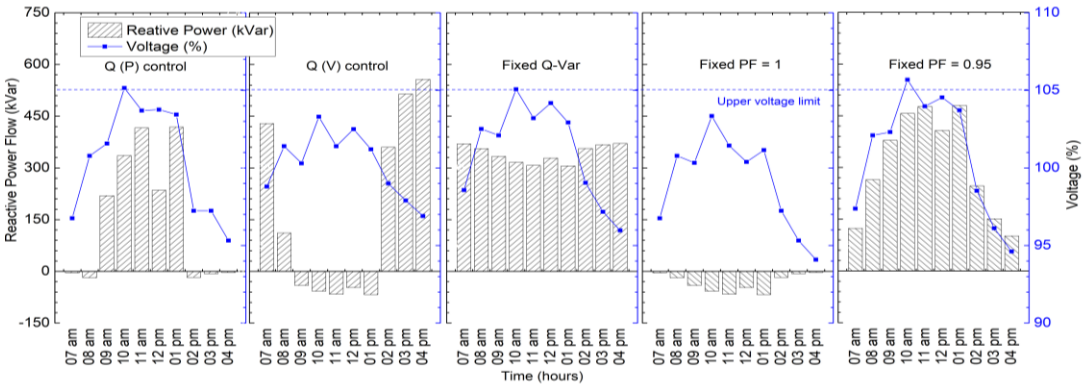


Figure 9. Comparison of inverter reactive power compensation to the voltage at PCC

The reactive power control techniques on the PV inverters connected to the MVDN were analyzed to measure the impact of the increased voltage received by all transformers in the distribution system. The terminal voltage profiles of all the transformers before and after the integration of the PV power plant were compared in Figure 10. It was discovered in Figure 10(a) that most of the transformers at the end of the feeder experienced a voltage drop beyond the standard normal grid operation limit of -10% before the integration but there were variations in the voltage increase after the integration based on the application of different reactive power controls as indicated in Figures 10(b)-(f). However, a wider voltage gain was observed with the Q(V) control technique. Figure 10(c) also shows that the transformer bus voltage closest to the PV generator source increased significantly to the feeder end. The comparison of the simulation results for the four control techniques indicated that the effect of the inverter reactive power compensation limits should be proportional to the conditions of the distribution network to avoid grid-code violations. A summary of the comparison made on the performance impact of all control techniques on the number of violations in the upper and lower limits related to the distribution system voltage is presented in Table 1.

Table 1. Comparison of the number of transformer bus voltage violations

Time	Without PV inverter		Q(P) control		Q(V) control		Fixed Q-Var		Fixed PF = 1		Fixed PF = 0.95	
	<90%	>105%	<90%	>105%	<90%	>105%	<90%	>105%	<90%	>105%	<90%	>105%
7:00 AM	14	0	4	0	1	0	1	0	4	0	3	0
8:00 AM	1	0	0	0	0	0	0	0	0	0	0	0
9:00 AM	28	0	0	0	1	0	0	0	1	0	0	0
10:00 AM	1	0	0	0	0	0	0	0	0	0	0	2
11:00 AM	35	0	0	0	0	0	0	0	0	0	0	0
12:00 PM	1	0	0	0	0	0	0	0	1	0	0	0
1:00 PM	44	0	0	0	1	0	0	0	1	0	0	0
2:00 PM	48	0	5	0	4	0	3	0	5	0	4	0
3:00 PM	53	0	31	0	5	0	6	0	30	0	17	0
4:00 PM	58	0	46	0	12	0	25	0	46	0	38	0

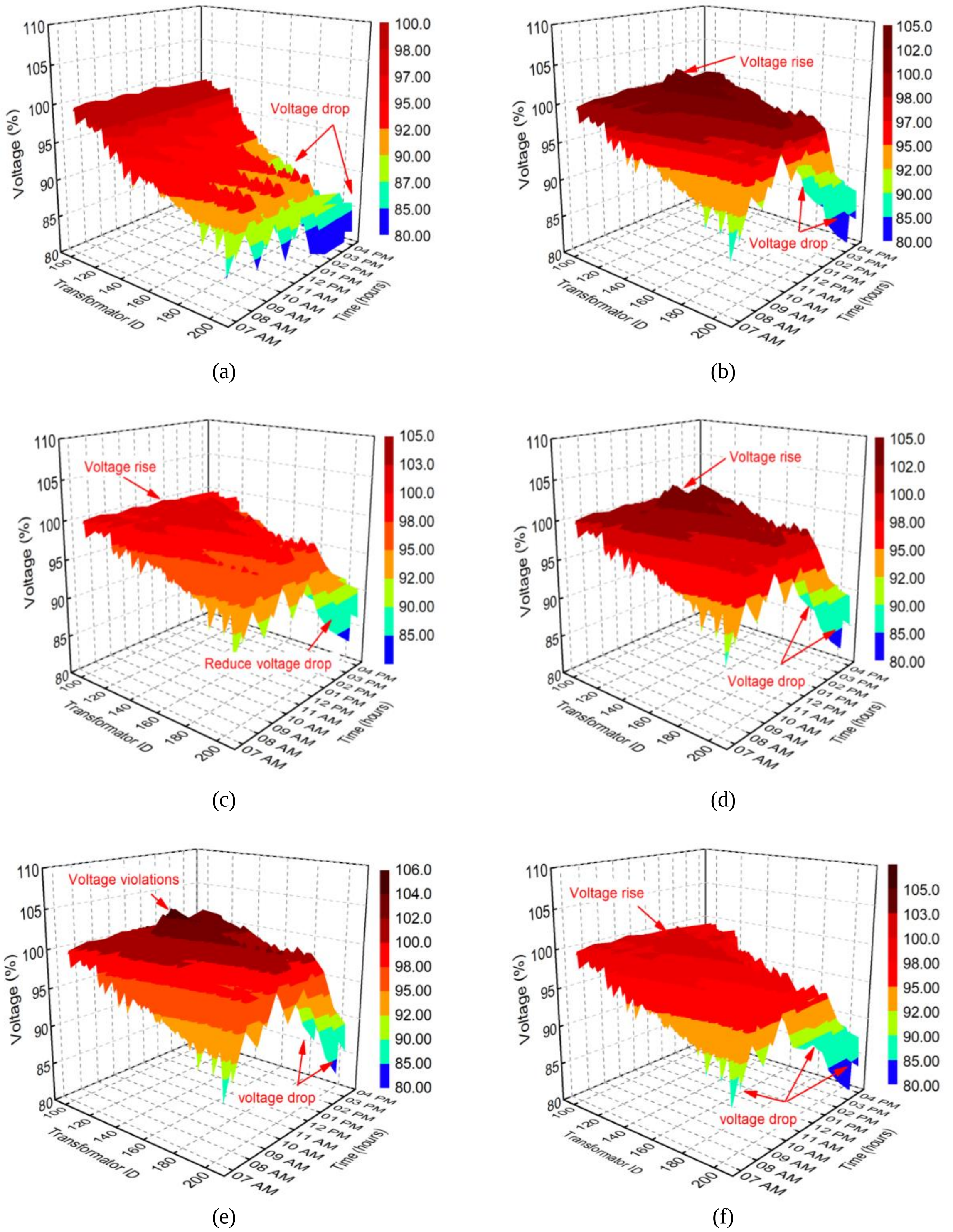


Figure 10. Comparison of the control techniques performance (a) without PV inverters, (b) Q(P) control, (c) Q(V) control, (d) fixed Q-Var control, (e) fixed PF 0.95, and (f) fixed PF 1.0

Figure 11(a) shows a line chart used to compare the total daily power losses in the PV system for all the control techniques proposed. The active power losses of the PV system were found in the transformer and cables, and the total was observed to be linear to the amount of inverter active power supplied to the distribution network. The comparison chart for the daily total losses in the distribution system before and after the PV generator was integrated using reactive power control is presented in Figure 11(b). It was discovered that the active power losses were in the distribution lines and transformer connected to electricity customer loads. The introduction of PV generator into the MVDN was observed to have reduced the power losses in the network but the number of losses was discovered to have increased linearly with an increment in the feeder load. It was also observed that the active power losses in the PV and distribution systems were recorded for all simulated techniques but the amounts are different. The lowest recorded during the peak load (4:00 pm) was with the Q(P) while the least in the distribution system was found using the fixed Q-Var. Furthermore, daily power losses in the PV system were discovered to be inversely proportional to the distribution system. It was discovered that the PV system produced higher power losses during the daytime operation than in the afternoon but the power losses in the distribution system decreased during the day and increased in the evening. This is due to the difference in the voltage level of each control technique based on the active power supply and reactive power compensation of the PV inverter. Another problem according to [24] is the ability of the reactive power injection to induce more thermal stress on inverter components, thereby leading to faster degradation of the capacitor performance due to the power cycles. This means the lifetime of a PV inverter can be reduced due to the reactive power compensation [25].

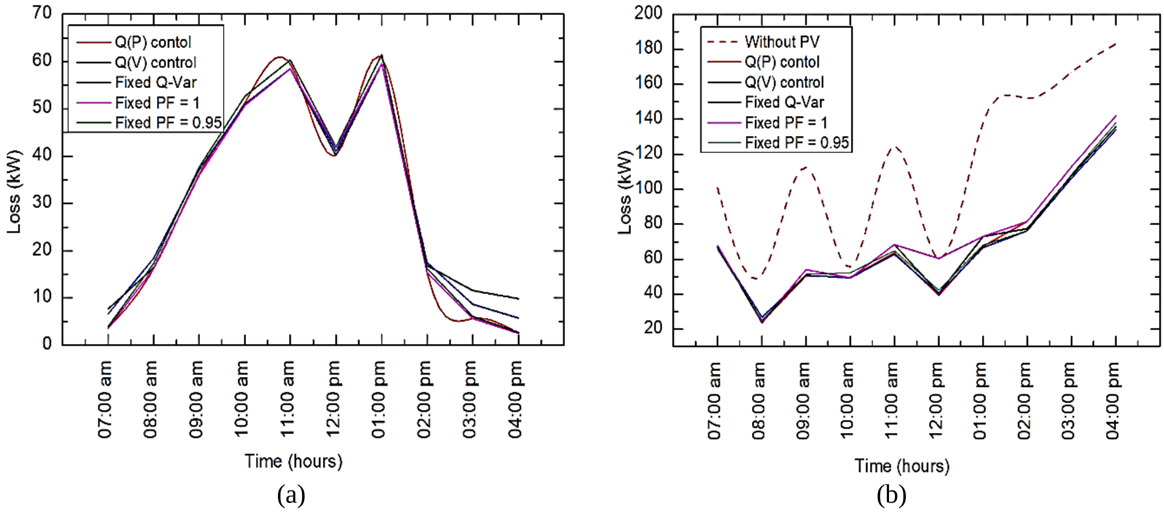


Figure 11. Power losses in (a) PV system and (b) distribution system

4. CONCLUSION

This study investigated the performance of four reactive power control techniques including Q(V), Q(P), fixed Q-Var, and fixed PF (1 and 0.95) on PV inverter connected to MVDN to reduce the problem of voltage violation and power loss. A PV generator with a capacity of 2 MWp designed using a multi-string inverter with a real integrated step-up transformer to MVDN North Gorontalo-Indonesia was applied. A comprehensive analysis was conducted with due consideration for the variations in solar irradiance and the daily load of the radial distribution feeder. Moreover, all the proposed techniques applied constraints to the inverter setting point. The main finding was that all the control techniques increased the voltage in the distribution network. It was also discovered that the existence of high reactive power injection at peak solar radiation but low loads can cause grid voltage violation problems solvable by proportionally considering the maximum injection limit Var or increasing the capacitive PF limit on the PV inverter. Furthermore, the transformer equipment used to connect the PV system to MVDN always requires a limited supply of reactive power due to its induction nature. This is the reason it is a special consideration for DNOs when SPVOs operate their PV inverter at a PF of one all day. It was noted that the problem of reactive power absorption from the grid by PV system transformers will continue to occur but is limited. The results also showed that the variations in active power losses in the PV and distribution systems were affected by the voltage levels due to the differences in the reactive power control techniques applied. Therefore, it is recommended that subsequent studies focus on increasing PV hosting capacity in distribution feeders with inverter reactive power control strategies and tap changers.

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