Flexible Control of Three-Phase Distributed Generation Systems for Voltage Rise Mitigation in Microgrid

Abstract. Microgrid integrated with renewable energy source (RES) is experiencing a rapid development nowadays. Many technical challenges appear with the high penetration of RES into the microgrid. One of the most important issues is the voltage rise at the point of common coupling (PCC). The voltage profile of PCC not only depends on the active and reactive powers, but also on the ratio (R/X) of line impedance. In order to mitigate the voltage rise, two control strategies are discussed, namely, active power curtailment and reactive power absorption. Theoretical analysis and experiment results are presented to validate the effectiveness of the proposed control schemes for voltage rise mitigation. It indicates that both control strategies may work well, but reactive power control enables the higher penetration of RES.

Keywords: Microgrid, distributed generation, grid-interfaced inverter, voltage rise

Słowa kluczowe: microgrid, sieć dystrybucyjna, wzrost napięcia

Introduction
The environmental concerns and electric utility deregulation promote the development of distributed generation (DG) in a rapid pace [1-5]. The high penetration of DG brings about a concept of the microgrid [4]. It is defined as a cluster of DG units (such as wind turbines and photovoltaics), storage devices and loads, which can operate in the grid-connected mode, autonomous mode, and ride-through between two modes. However, with the increasing penetration of DG systems in a microgrid, many technical challenges should be dealt with. One of the most important issues is the voltage rise at the PCC [6-9]. Conventionally, On-Load Tap Changer (NLTC) or Automatic Voltage Control Relay (AVCR) has been widely used for voltage regulation in power systems. In practice, however, it is expensive with poor dynamic responses. On the other hand, with the development of power electronics, many interesting electronically-interfaced compensation devices have been put into use, such as Static Var Generator (SVG), which can regulate the voltage profile by injecting the reactive power into power systems [10]. But installation of a specific voltage regulation device needs the additional investment and maintenance cost. Another interesting solution is to integrate the voltage regulation function into DG systems. That is, DG not only provides the active power to microgrid, but also has the additional function of voltage regulation.

The objective of the paper is to discuss the feasibility of two possible solutions to voltage rise mitigation. Performance evaluations of both solutions are provided in this paper, along with the experimental validity.

Voltage Rise Issue
Fig.1 illustrates the schematic diagram of the microgrid. It comprises of the primary energy sources (PV, wind, et al.) with optional energy storages, dc/dc or ac/dc converters and dc/ac inverters. The inverters can provide an interface for the flexible functions such as energy conversion and power quality improvement. The inverter output may either feed the local loads independently in autonomous mode or in conjunction with the electric utility by static switch (STS) in grid connected mode. This paper will focus on the latter mode.

For simplicity, only the DG unit is considered. And it can be extended to other DG units. As shown in Fig.2, the simplified model consists of DG unit, local load, line impedance, and microgrid bus. Note that \(V_c\) represents the microgrid bus voltage. \(Z\) is the impedance of the transmission feeder, which consists of the resistance component \(R\) and the inductance component \(L\); \(P\) and \(Q\) represent the active and reactive powers from the microgrid bus. \(P_L\) and \(Q_L\) are the local load active and reactive powers. \(V_{PCC}\) is the voltage of the PCC. \(P_Q\) is the active power from DG, and \(Q_Q\) is the reactive power exchange between DG and PCC.

For (1) and Fig.2, the current through the line impedance \((Z)\) can be obtained.
The voltage drop between microgrid bus and PCC is:

\[
\Delta V = V_0 - V_{pcc} = I(R + jX)
\]

Substitute (2) into (3), it can be obtained that

\[
\Delta V = V_s - V_{pcc} = \frac{R \cdot P + X \cdot Q}{V_{pcc}} + j \frac{X \cdot P - R \cdot Q}{V_{pcc}}
\]

where \( X = \omega L, P = -P_G + P_L \) and \( Q = \pm Q_G + Q_L \).

Considering \( V_{pcc} \) as the voltage reference with zero angle, i.e., \( V_{pcc} = V_{pcc} \angle 0^\circ \). In practice, the real part is much greater than the imaginary part in (4), so the imaginary part may be neglected, and equation (4) can be rewritten as:

\[
V_{pcc} \approx V_s + \frac{R \cdot P + X \cdot Q}{V_{pcc}}
\]

From the analysis above, it can be concluded that the PCC voltage may rise to a certain level when many DG systems are integrated into the microgrid. More specifically, the voltage of PCC not only depends on the active and reactive powers, but also the ratio (R/X) of line impedance. Note that the distribution network and microgrid with different voltage levels have the unequal value of line impedance, as shown in Table I.

<table>
<thead>
<tr>
<th>Parameters of the line impedance in Microgrid</th>
<th>( R ) (Ω·km)</th>
<th>( X ) (Ω·km)</th>
<th>( R/X )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Voltage</td>
<td>0.642</td>
<td>0.083</td>
<td>7.7</td>
</tr>
<tr>
<td>Middle Voltage</td>
<td>0.161</td>
<td>0.190</td>
<td>0.85</td>
</tr>
<tr>
<td>High Voltage</td>
<td>0.060</td>
<td>0.191</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Voltage Rise Mitigation

This section will discuss the feasibility of the voltage rise mitigation with the DG system. Fig.3 shows an extended model of Fig.2. Note that the dc-link bus is supported by the first power stage (See Fig.1), and thus it is reasonably assumed to be constant as \( U_{dc} \).

Fig. 3 Extended model of Fig.2

A. Voltage regulation with active power

Assuming that the line impedance is dominantly resistive (first case), a voltage rise may appear if any DG in microgrid injects an active current \( I_{a0} \) through the line impedance, as shown in Fig.4a, from which it can be observed that the PCC voltage is increased from \( U_{pcco} \) to \( U_{pcc} \). On the other hand, if DG injects a compensated current \( I_c \), the PCC voltage rise will be mitigated, as illustrated in Fig.4b.
After 0.3s, DG injects the reactive current. And local loads are shed at 0.2s. And the DG output voltage increases from 50V to 55V (peak value) after the output current $I_{aout}$ is flowing through the line impedance totally, that is, $I_w = I_{aout}$. After 0.3s, DG output current $I_{aout}$ is decreased, so is the line impedance current $I_w$. And then the PCC voltage rise is mitigated as shown in Fig.6b.

From the evaluation results, it can be concluded that the above solution is feasible.

**B. Voltage regulation with reactive power**

Assuming the line impedance is dominantly resistive (second), a voltage rise may appear if any DG in microgrid injects an active current $I_a$, through the line impedance, as shown in Fig.7a, from which it can be observed that the PCC voltage is increased from $U_{PCC}$ to $U_{PCC}$. On the other hand, if DG injects a compensated current $I_C$, the PCC voltage rise will be mitigated, as illustrated in Fig.7b.

![Voltage rise mitigation](image)

Fig.7 Phasor diagram of voltage rise mitigation

Fig.8 shows the control diagram of voltage rise mitigation with reactive current regulation. Following will provide a performance evaluation of the abovementioned solution.

![Control diagram](image)

Fig.8 Control diagram of voltage rise mitigation

From Fig.9a and Fig.9b, it can be observed that the PCC voltage increases from 50V to 55V (peak value) after the local loads are cut off at 0.2s. And the DG output current $I_{aout}$ is flowing through the line impedance totally, that is, $I_w = I_{aout}$. After 0.3s, DG injects the reactive current. And then the PCC voltage rise is mitigated as shown in Fig.9b.

From the evaluation results, it can be concluded that the above solution is feasible as well.

**Experimental results**

In order to verify the effectiveness of the above solutions, the experimental tests are carried out. And the system parameters are listed in Table II.

<table>
<thead>
<tr>
<th>Table II System Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_{ref}$</td>
</tr>
<tr>
<td>$u_{abc,ref}$</td>
</tr>
<tr>
<td>$I_{abc}$</td>
</tr>
<tr>
<td>$C_{abc}$</td>
</tr>
<tr>
<td>$R$</td>
</tr>
<tr>
<td>$L$</td>
</tr>
</tbody>
</table>

Where $k_p$ and $k_i$ are the proportional and integral gains of the current loop; $k_v$ and $k_{ii}$ are the proportional and integral gains of the voltage loop. $I$ represents of rated current of the inverter. $R$ represents of the load connected at PCC. The line impedance $R/X$ ratio is set as 1 to test the effect of the line impedance ratio on the voltage regulation.
Fig. 10 Pictures of experimental platform

Fig. 11 (a) shows the steady-state waveforms of voltage and current before load shedding. It can be observed that DG works in unity power factor mode, namely the output current of DG is in phase with the PCC voltage, and the difference between DG current $I_{\text{out}}$ and load current $I_{\text{load}}$ is the line impedance current $I_{\text{z}}$.

After load shedding, as shown in Fig. 11 (b), the DG output current $I_{\text{out}}$ flows through the line impedance totally, that is, $I_{\text{z}} = I_{\text{out}}$. And the PCC voltage rise appears due to the voltage drop variation across the line impedance.

A. Voltage regulation with active power

Fig. 12 shows the experimental results with active power compensation. It can be observed that this solution can regulate the PCC voltage to a reasonable level when the PCC voltage rises. However, the DG output current is significantly reduced in this case, which implies that this solution can’t make full use of DG, and thus could prevent the high penetration of DG systems. On the other hand, the output current of DG is in phase with the PCC voltage,
as shown in Fig.12b, which indicates that the DG works in unity power factor mode.

![Image](image.png)

(a) Transient with compensation

![Image](image.png)

(b) Steady state after compensation

Fig. 13 Experimental results with compensation

Voltage rise is one of the most important issues in case of integration with renewable energy sources into microgrid. This paper has discussed two solutions for voltage rise mitigation with consideration of the ratio (R/X) of line impedance. From the theoretical analysis and experimental results, it can be concluded that both solutions are theoretically feasible, but the reactive power compensation solution will be preferred for high penetration of DG systems. In practice, however, further consideration should be noted such as the physical constraints of DG systems. For example, the reactive power compensation should not exceed the DG capacity to prevent the system overcurrent. Another interesting solution is the combination of the active and reactive power compensation, which will be reported in the future paper.

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REFERENCES


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