J Electr Eng Technol.2017; 13(?): 1921-718
http://doi.org/10.???/JEET.2017.13.1.1921

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Overvoltage Protection Controller Design of Distributed Generation Connected to Power Grid Considering Islanding Condition

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Abstract – Distributed generation (DG) is being highlighted as an alternative for future power supplies, and the number of DG systems connected to conventional power systems is steadily increasing. DG generators are designed using power electronics and can give rise to various power quality problems, such as overvoltage or overcurrent. Particularly, unintentional islanding operation can occur in a conventional power system when the power grid is separated from the DG systems. Overvoltage may occur in this situation, depending on the power generation and power consumption. However, overvoltage phenomena might not happen even when islanding occurs. Therefore, it is necessary to analyze the fault characteristics during islanding. In this study, a fault analysis of islanding operation was carried out using PSCAD/EMTDC, and a countermeasure for the overvoltage problem is proposed.

Keywords: Distributed generation, Islanding, Overvoltage, Distribution system, Microgrid

1. Introduction

Various types of renewable energy sources are being developed globally to cope with environmental problems. Electric generation from photovoltaic and wind power is continually increasing [1], and these technologies could solve many current problems and provide new services. Particularly, distributed generation (DG) can be operated in stand-alone mode to develop and supply power locally using an appropriate control scheme. It is also possible to improve the continuity of the power supply and to enable new services. Therefore, the introduction of DG will continue to increase in the future.

However, one of the major issues is maintaining power quality within acceptable limits for power system operators and users. In addition, the maintenance of power quality in existing distribution systems is based on unidirectional power flow without DG. Therefore, when a DG system based on a power conditioning system (PCS) is introduced into the distribution system, it is difficult to maintain the power quality in operation facilities and to protect the conventional distribution system. The DG system and the protection scheme of the conventional distribution system must cooperate with each other [2, 3, 4].

Overvoltage is one of the power quality problems that occur when a DG system that operates in a bidirectional loop is introduced to an existing distribution system [5]. Five types of overvoltage problems have mainly been considered: single-line ground fault, resonance, third harmonic, islanding operation, and line open overvoltage [6, 7, 8]. Particularly, overvoltage associated with islanding operation of the DG or line opening can cause very serious damage to the consumer loads within a few milliseconds [9].

As a countermeasure against overvoltage, it is possible to limit the connection capacity of the DG or to apply the direct transfer trip (DTT) method. However, the introduction of DG systems is increasing, and DTT has a disadvantage of the cut-off time not being fast enough in comparison with the occurrence time of the overvoltage when considering all processes of fault detection and cutoff [10].

In this paper, a control technique is proposed to prevent the overvoltage phenomenon during islanding conditions that occur when a distributed power source is introduced to an existing distribution system. First, a method for controlling the output according to the operation mode of the DG is examined, and then the overvoltage phenomenon is theoretically investigated. Next, the proposed controller design is presented. The application of the controller to a DG model is then discussed, which was carried out using the PSCAD/EMTDC software package.

2. Control Structure of Distributed Generation

DG systems can operate in grid-connected mode or stand-alone mode. Fig. 1 shows the configuration of an AC grid with distributed generators. In grid-connected operation, active and reactive power is output according to a reference value set by the current controller. Then, the microgrid

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Received: August 10, 2017; Accepted: October 20, 2017

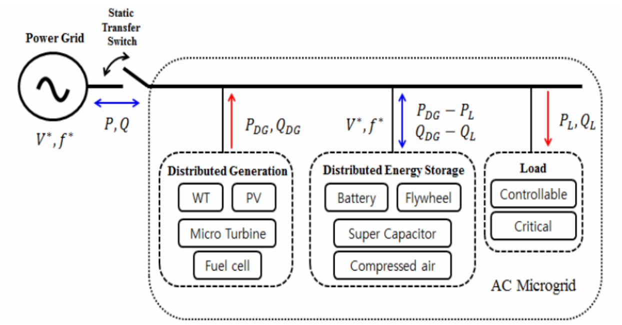
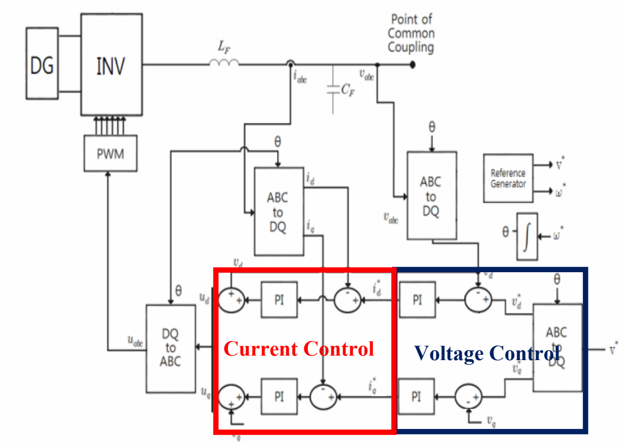
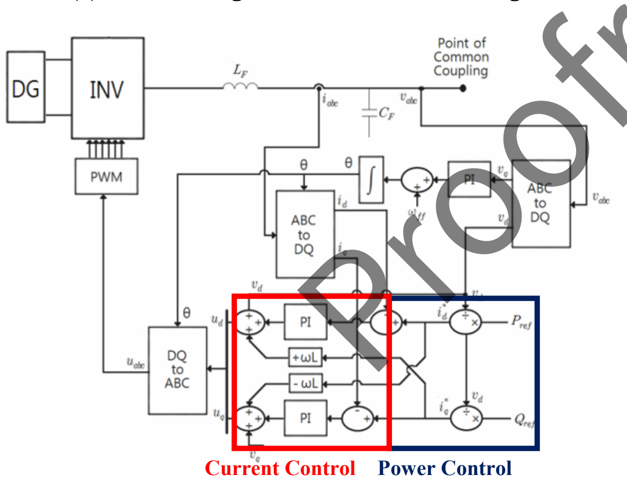


Fig. 1. Configuration of an AC grid with DGs



(a) Grid-feeding control of DG in an AC grid



(b) Grid-forming control of DG in an AC grid

Fig. 2. Control structure of distributed generation

follows the voltage and frequency of the power grid. In stand-alone mode, there is no reference voltage or frequency, so the microgrid cannot be operated in this mode if it is separated from the power grid.

The DG can be divided into two control structures: grid-feeding and grid-forming converters [11]. Grid-feeding converters can be represented as an ideal current source. This control method is suitable for operation in parallel with other converters in grid-connected mode and cannot be operated in stand-alone mode. Most DG systems connected with the grid are current controlled. To precisely control the active and reactive power exchanged with the power grid, it is important to synchronize accurately with the voltage at the point of common coupling (PCC), and a phase locked loop (PLL) is used for this purpose. P_{ref} and Q_{ref} represent the active power and reactive power to be transmitted, and the voltage and frequency can be controlled by adjusting these reference values. The control structure of grid-feeding is shown in Fig. 2(a).

A grid-forming converter is generally designed as a voltage control source. This converter maintains a constant voltage and a constant frequency (CVCF). The CVCF control method is used in stand-alone operation mode and provides a reference source when the DG is operated in parallel with other DG systems. The control structure of grid-forming mode is shown in Fig. 2(b) [11].

3. Overvoltage Phenomenon of DG during Islanding Operation

Most DG systems are grid-connected, and active and reactive power output by current control is required. Due to unintentional islanding operation in the event of a power grid fault, the grid can be separated from the system or shut down to protect the power grid, consumer equipment, and operators. Therefore, many studies have been carried out on detection methods for islanding [12, 13]. The blocking time is determined according to the country of operation, and the DG must be separated from the power grid within the shortest time possible when islanding is detected. Table 1 shows the standards for stand-alone operation detection and prevention.

The ratio of the power generation to the load has the biggest influence on the overvoltage due to islanding. This is an important factor because the overvoltage is determined by the total load during the islanding operation. In general, the amplitude of the overvoltage of the DG during islanding is determined by [14]:

$$V_{islanding(p.u.)} = \frac{Total\ amount\ of\ \ power\ generation}{Total\ amount\ of\ load\ demand} \tag{1}$$

Table 1. Standards of anti-islanding requirements

Name	Detection Method	Requirements
IEEE 1547 IEC 61727 [19, 20]	Active or Passive	Cease to energize within 2 seconds of the formation of the island
VDE-AR-N 4105 [21]	Active or Passive	Disconnect in 5 seconds
BDEW 2008 [22]	Not specified	Network operator may have special requirements
JEAC 9701-2012 [23]	Active	Detect within 0.5–1.0 seconds
	Passive	Detect within 0.5 seconds
KEPCO Guideline [24]	Active or Passive	Cease to energize within 0.5 seconds of the formation of the island

The equation shows that the output of the DG is linearly proportional to the amplitude of the load to be supplied when the DG is operated in stand-alone mode. However, the equation does not accurately represent the relationship between the output of the DG and the voltage following on the load. The voltage amplitude depends on the characteristics of the load, even for loads with the same capacity. Loads can be classified into three types: constant power loads, constant current loads, and constant impedance loads [15]. The load in a power grid includes one or complex loads. Fig. 3 shows the relationship between power and voltage for each type of load

The relationship between the voltage and power for different load types can be expressed as [16]:

$$\frac{S}{S_o} = \left(\frac{V}{V_o}\right)^k \tag{2}$$

where a constant power load is indicated by k=0, a constant current load is indicated by k=1, and a constant impedance load is indicated by k=2. S_o is the power at the rated voltage V_o, and S is the power at the voltage V. In this paper, only the constant impedance load is assumed. When the DG operates in conjunction with the power grid, the power flow behaves as shown in Fig. 4.

In Fig. 4, the relation of the power flow between the DG, the power grid, and the load is the following [17]:

$$\sqrt{P_{Grid}^2 + Q_{Grid}^2} = \sqrt{(P_L - P_{DG})^2 + (Q_L - Q_{DG})^2} \tag{3}$$

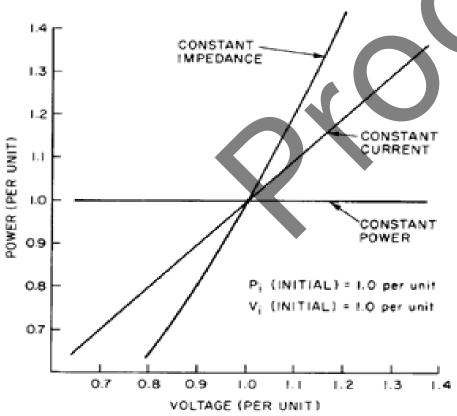


Fig. 3. Effect of voltage variations for three types of loads [IEEE Std. 399]

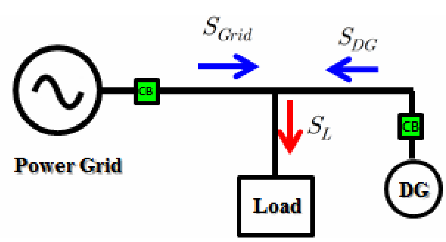


Fig. 4. Power flow in AC grid with DG

where P_L and Q_L are the active and reactive power of the load, P_{DG} and Q_{DG} are the active and reactive power output from the DG, and P_{Grid} and Q_{Grid} are the active and reactive power of the power grid. The expression for a constant impedance load is expressed as follows:

$$\sqrt{P_L^2 + Q_L^2} = \sqrt{P_0^2 + Q_0^2}\left(\frac{V_L}{V_0}\right)^2 \tag{4}$$

Here, P_o and Q_o are the active and reactive power at the rated voltage V_0, and V_L is the amplitude of the voltage when $P_L + jQ_L$. If islanding operation occurs, there is no power flow on the power grid, so P_{Grid} and Q_{Grid} become zero. Thus, the relationship between the power flow and the voltage in islanding operation can be expressed as :

$$\sqrt{P_{DG}^2 + Q_{DG}^2} = \sqrt{P_L^2 + Q_L^2}\left(\frac{V_{is}}{V_L}\right)^2 \tag{5}$$

where V_{is} is the voltage amplitude at the load during islanding operation. Eq. (5) then becomes [18]:

$$V_{is} = V_L \frac{\sqrt{\sqrt{P_{DG}^2 + Q_{DG}^2}}}{\sqrt{\sqrt{P_L^2 + Q_L^2}}} \tag{6}$$

Fig. 5 shows the power flow condition during islanding. The grid-connected DG output is controlled according to a set reference value. Thus, the imbalance between the power generation amount and the load continues during the islanding. Moreover, since the DG cannot maintain the output value during islanding, the active power P and reactive power Q of the DG fluctuate. As a result, the amplitude of the overvoltage is difficult to predict accurately and is determined by the varying output of each DG.

To avoid this situation, many standards have been established to prevent unintentional islanding in various countries. However, these standards have different details, such as the acceptable time, because the properties of

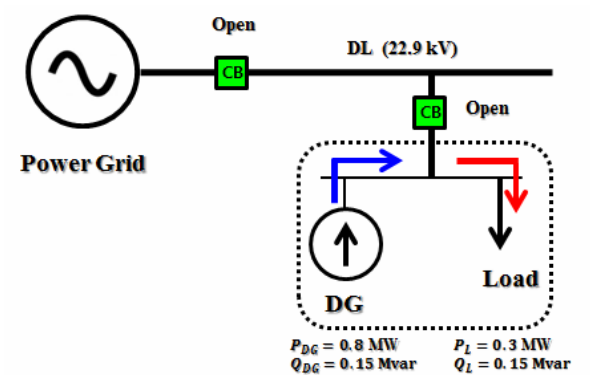


Fig. 5. Power flow condition in islanding

power systems also differ from each other. This means that negative effects from islanding may happen when applying particular standards despite thorough compliance. Hence, it is necessary to modify the standards in a strict way and to consider additional conditions to prevent unintentional islanding.

4. Simulation and Analysis

A following system model was constructed to simulate the overvoltage phenomenon. The model comprises an AC microgrid connected to a 22.9-kV distribution line through a 154-kV/22.9-kV substation transformer. The DG is an energy storage system (ESS) with a capacity of 500 kW and is connected to the distribution line through a dedicated transformer (Y-Delta). The load is assumed to be a constant impedance load connected to the distribution line through a 22.9-kV/0.38-kV transformer (Y-Y).

Fig. 6 shows an example of islanding operation where a ground fault occurs on the power grid side during grid-connected operation. The modeling was carried out with PSCAD/EMTDC, and the simulation was done using different load conditions. As shown in Table 2, the outputs of DG1 are 500 kW and 0 kVar, while those of DG2 are 300 kW and 150 kVar. Table 3 and 4 show simulation load condition and scenarios. The load in the simulation is a constant impedance load, and the other load conditions are shown. An A-phase SLG fault occurs in the 22.9-kV distribution line and lasts for 10 seconds. The main breaker CB1 is opened after 0.1 seconds (6 cycles) to disconnect the corresponding line, and CB2 is also cut off at 0.1 seconds simultaneously. After CB1 and CB2 are cut off, CB4 and CB5 operate in 2.6 seconds to prevent islanding

Table 2. DG output power conditions of simulations

DG power	P_{DG}	Q_{DG}
DG1	500 kW	0
DG2	300 kW	150 kVar

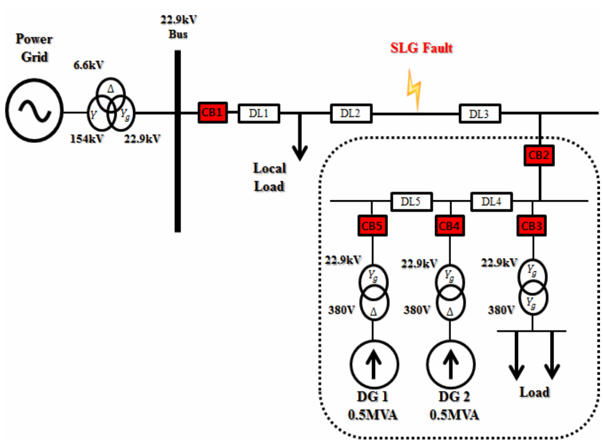


Fig. 6. System configuration of the AC grid

operation in the dispersed power source. At this time, islanding operation occurs for 0.5 seconds from the initial operation of CB1 to the disconnection of the DG. Table 5 shows specific information on the simulated system.

Fig. 7 and 8 show the fault currents from the grid side and the DG side. In general, most unbalanced fault currents are determined by the line impedance and fault voltage. Therefore, the fault current is the same in all cases in the simulations. Regardless of the load conditions, the fault currents from the grid-side and the DG-side are about 9.24 kA and 0.43 kA

Table 3. Scenario of fault analysis for simulation

Time	0 s	2 s	2.1 s	2.6 s	3 s
SLG Fault					
CB 1			Open		
CB 2			Open		
Islanding Operation (DG1,2)					

Table 4. Load conditions of simulations

Load condition	P_L	Q_L
Case 1	300 kW	150 kVar
Case 2	200 kW	100 kVar
Case 3	100 kW	50 kVar
Case 4	80 kW	15 kVar

Table 5. The specifications of AC grid

Index	Value	Remark
154 kV Grid Source		
Positive Sequence %Z	0.08+j0.99	100 MVA Based
Zero Sequence %Z	0.34+j1.69	
3-Winding Transformer(154 kV-22.9 kV-6.6 kV)		
Rated Power	45/60 MVA	
Positive Sequence % X_{1-2}	j16.16	45 MVA Based
Positive Sequence % X_{2-3}	j6.69	
Positive Sequence % X_{3-1}	j25.38	
Connection Type	$Y-Y_g-\Delta$	
Distribution Line 1(0.5km, CNCV-W 325 mm^2)		
Positive Sequence %Z	0.89+j1.42	100 MVA Based
Zero Sequence %Z	2.66+j0.86	
Distribution Line 2(1.5 km, ACSR 160/95 mm^2)		
Positive Sequence %Z	5.23+j11.62	100 MVA Based
Zero Sequence %Z	13.65+j34.2	
Local Load	500 kW + 250 kVar	Lagging
Distribution Line 3(13.5 km, ACSR 160/95 mm^2)		
Positive Sequence %Z	47.25+j104.62	100 MVA Based
Zero Sequence %Z	122.85+j308.35	
Distribution Line 4,5(0.1km, CNCV-W 60 mm^2)		
Positive Sequence %Z	0.75+j0.37	100 MVA Based
Zero Sequence %Z	2.41+j0.97	
Distribution Generation (380 V_{L-L})		
Type of DG	ESS	2 EA
Rated Power	0.5 MVA	
Transformer Connection	$Y_g-\Delta$	
Positive Sequence %X (TR+DG)	j0.05	1 MVA Based

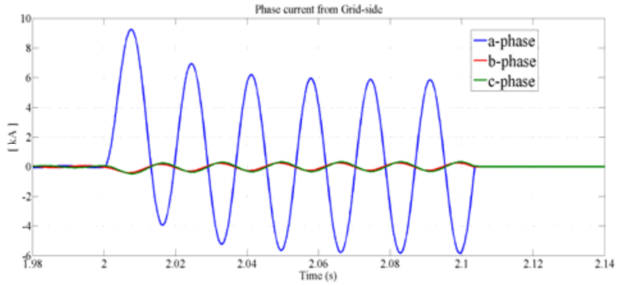


Fig. 7. Phase currents supplied from grid-side during single-line ground fault

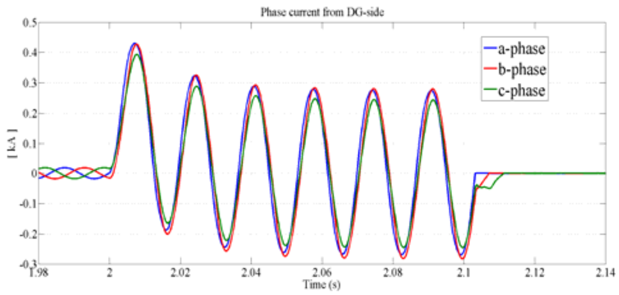


Fig. 8. Phase currents supplied from DG-side during single-line ground fault

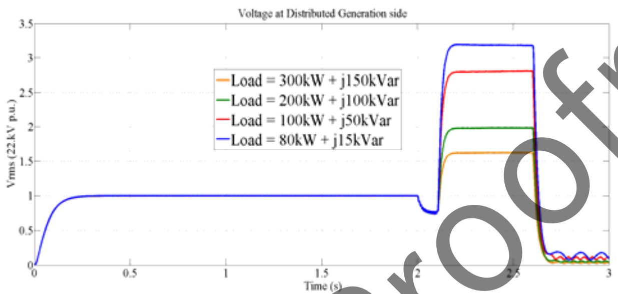


Fig. 9. The average RMS voltage at DG-side

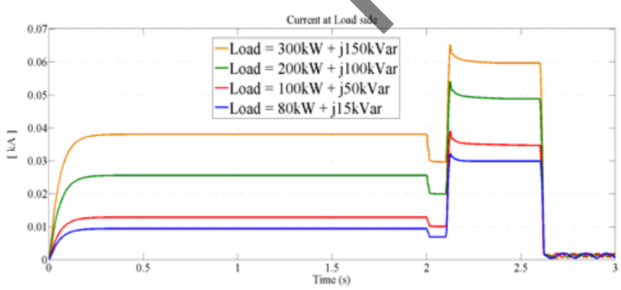


Fig. 10. The average RMS current at Load-side

Fig. 9 and 10 show the voltage and the current results of the simulation during islanding operation under four sets of load conditions. The calculated values obtained using Eq. 6 was also compared with the simulation results, and the results are summarized in Table 6. There was a slight difference due to a loss of reactive power in the line while the output of the DG was transferred to the load. When the loss occurred, the amplitude of the overvoltage was almost the same as the difference in the reactive power shown in the simulation.

Table 6. Comparison of calculation and simulations

Case	$V_{islanding}$ (p.u.)	
	Calculation	Simulation
1	1.61	1.62
2	1.95	1.98
3	2.74	2.80
4	3.19	3.18

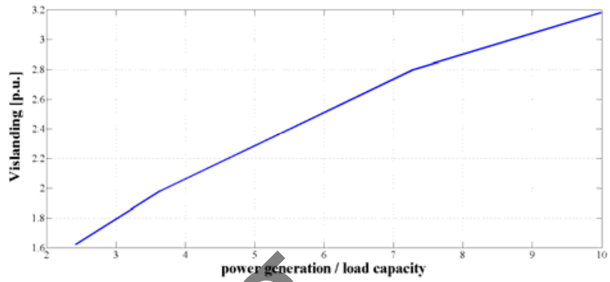


Fig. 11. Curve of voltage and generation/load ratio

Fig. 11 shows the simulation results for the ratio of the power generation to the load capacity and voltage. The voltage changes non-linearly with respect to the power-generation/load-capacity ratio. However, the ratio is difficult to predict because the reactive power varies with the inductive or capacitive load during islanding operation. There may be a difference in the rise time of the maximum overvoltage, depending on the line impedance and characteristics of the load. However, the cut-off within a few milliseconds is likely to malfunction due to noise sources such as surges.

Overall, the overvoltage phenomenon during the islanding operation can be summarized as follows:

1) The grid-connected DG is a constant current source and operates with constant output by current control.
2) The overvoltage during islanding operation is determined by the amount of power generation and the capacity of the load in the separate area.
3) An instantaneous overvoltage may occur even if the cut-off time for the anti-islanding operation is short.

5. Controller Design for Overvoltage Prevention

Fig. 12 shows the simulation result for a load of 80 kW +j15 kVar and the 3-phase instantaneous voltage waveform during islanding operation. The DG circuit breaker operates at 2.1 seconds, and the voltage rises rapidly. In the case of the B-phase, the voltage increases to about 2.73 p.u. around 9 ms. Therefore, to prevent overvoltage during islanding, the operation should be stopped within 0.5 cycles according to the simulation results.

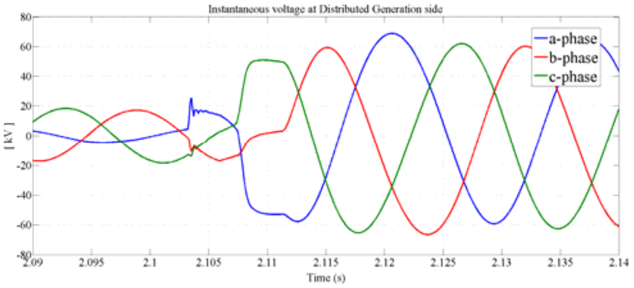


Fig. 12. Phase instantaneous voltages in the 22.9-kV Line (Load: 80 kW, 15 kVar)

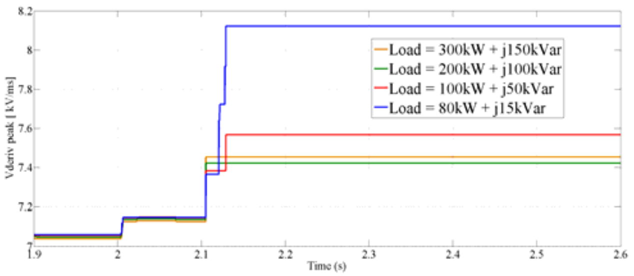


Fig. 13. The voltage derivative peak value in the 22.9-kV line

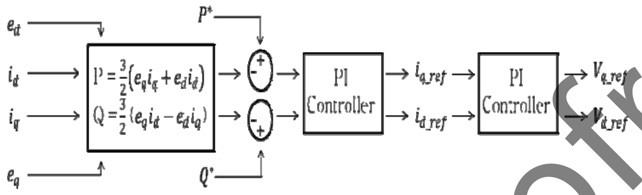


Fig. 14. Power and current controller of grid-connected PCS

5.1 Overvoltage prevention control using the voltage derivative

Overvoltage during islanding operation is determined by the power generation and load capacity. Fig. 13 shows the derivative of the 3-phase voltage for different load conditions. Overvoltage might happen when faults occur. As the difference between the power generation and the load capacity increases, so do the overvoltage and the derivative of the voltage.

The proposed control method overvoltage prevention applies the 3-phase voltage derivative at the DG output terminal to the d-q component. The active and reactive power output of the grid-connected DG is controlled by the voltage and current, as shown in Fig. 14. The calculated active and reactive P and Q are subtracted from the reference values P_{ref} and Q_{ref}. The reference currents i_{d_ref} and i_{q_ref} are determined by a PI controller. These reference currents are used by the current controller to determine the reference voltages V_{d_ref} and V_{q_ref}.

When V_q becomes large during overvoltage, the output of the DG to the load increases. The reference q-axis does not exactly coincide with the voltage vector of the grid and becomes $V_d = 0$. Therefore, the active and reactive power levels of the DG are not appropriately controlled. This makes it necessary to adjust the reference voltage to prevent overvoltage during islanding operation. The output voltage of the DG can be controlled according to the derivative of the voltage during islanding. The output voltage of DG can be adjusted by converting V_{d_ref} and V_{q_ref}.

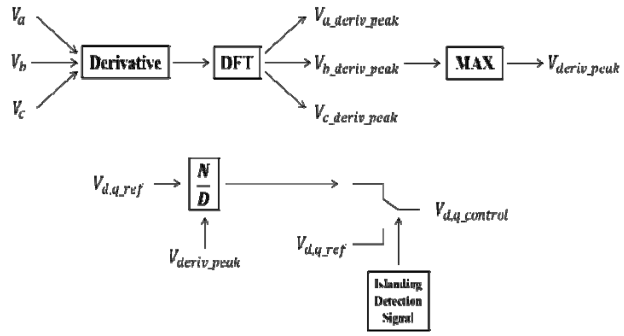


Fig. 15. Block diagram of overvoltage prevention controller

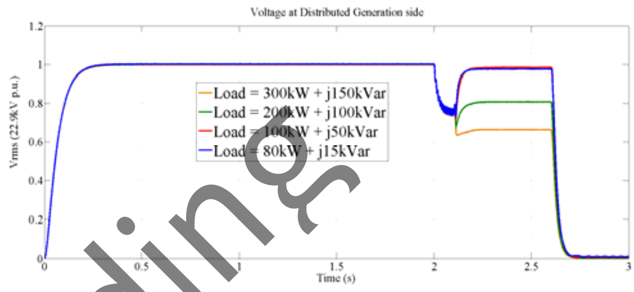


Fig. 16. The average RMS voltage at DG-side

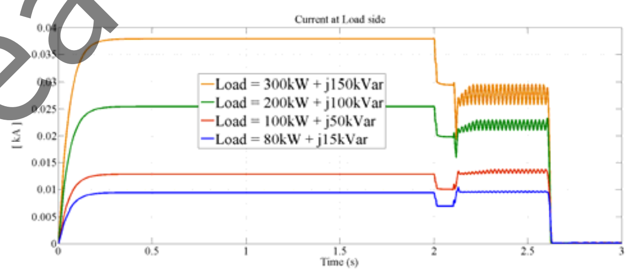


Fig. 17. The average RMS current at Load-side

Fig. 15 shows a block diagram of the proposed overvoltage prevention controller. First, the 3-phase voltage of the DG output terminal is differentiated, and the peak of the derivative function is obtained using the Discrete Fourier Transform (DFT). Next, V_{d_ref} and V_{q_ref} are divided using the maximum value of the 3-phase derivative.

Fig. 16 and 17 show the simulation results of the overvoltage prevention controller. The simulation was performed using the same load conditions as in the

Table 7. Simulation results of the proposed controller

Case	$V_{islanding}$ (p.u.)	
	Without controller	With controller
1	1.62	0.6637
2	1.98	0.809
3	2.80	0.984
4	3.18	1.009

previous simulation, as summarized in Table 7. The results show that the proposed control method can prevent overvoltage during islanding operation. The critical problem of papers published so far is that there is a difficulty in application of their methods proposed because it is impossible practically to figure out all the location of many a load and to measure the real and reactive power of load just before islanding condition. Especially, the authors assumed that all load values are known. Therefore, at this point we proposed a method to solve the problem. The method is to suppress the overvoltage within permissible range with only the voltage derivative and instantaneous voltage measurement value at the PCC without using all load values.

6. Conclusion

Voltage is one of the important power quality factors in power systems, and it is necessary to maintain the voltage within acceptable limits to protect power supply facilities and consumer facilities. In particular, the overvoltage that occurs during islanding operation is becoming a more important issue to solve as the introduction of DG to existing power systems continues to increase. Overvoltage during islanding operation occurs when the power generation of the DG exceeds the load capacity. The voltage amplitude generated is determined by the power generation of the DG, load capacity, and load characteristics.

A new control method has been proposed to prevent this overvoltage phenomenon. First, theoretical modeling was carried out using equations based on an actual system, the overvoltage amplitude, and the load conditions. The calculated results were then compared to the simulation results using the PSCAD/EMTDC software package. The simulation results show that overvoltage is prevented by the proposed controller during islanding operation under all load conditions.

The proposed control scheme does not require any communication technology and can be implemented using simple operation functions such as the DFT and differential functions in a microcontroller unit. This means that it is not necessary to worry about malfunctions due to communication error. On the other hand, the droop control method can be another solution to the overvoltage problem [25].

In the future, further study will be necessary to examine the maintenance of power quality in the event of overvoltage while considering the stability of the power system.

Acknowledgements

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20161210200310)

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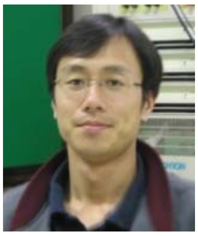

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