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Analysis of Stability of PV System using the Eigenvalue according to the Frequency Variation and Requirements of Frequency Protection

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Abstract – Use of photovoltaic (PV) power generation system will become more widespread in the future due to anticipated cost reduction in PV technology. As the capacity of PV systems increases, a variation of power system frequency may prevent the stable output of PV system. However, the standard for the frequency protection of distributed generation in Korea Electric Power Corporation (KEPCO)'s rule does not include the setting of frequency protection. Therefore, this paper analyzes the correlation between the frequency protection requirements and the stability of grid-connected PV system for the adjustable operating setting of frequency protection. The distribution system interconnected with 3 MW PV system is modeled by Matlab/Simulink. The various values of frequency are simulated. For studied cases, the stability of PV system is analyzed. It is concluded that the setting of frequency protection is necessary to consider the stability of PV system.

Keywords: Eigenvalue, Frequency protection, Matlab/Simulink, Photovoltaic system, Stability

1. Introduction

We expect that several distributed generation (DG) technologies, e.g. the wind turbine, fuel cells, and PV systems, will be connected to the distribution system. The interconnection of the DG can cause the deterioration of power quality and reliability and threaten protection coordination, transient stability, and etc [1-3]. An increase in PV capacity results in an increase in the loads served by PV, and hence the stability of PV systems becomes important. However, the PV system suffers from nonlinear behaviour, such as the faults and transients of a power system, which does not occur with a generic inverter, and this may cause the output of the PV system to become unstable [4-6].

Therefore, IEEE std. 1547 for interconnecting of DG is developed to ensure the stable operation of DG [7]. The Korea Electric Power Corporation (KEPCO) also makes the rule for interconnecting of DG. These include the operation criteria of DG for harmonics, flicker, power factor, and etc. in steady state and the clearing time of DG at abnormal conditions. However, these do not include the operating setting of the frequency protection. These only state that the frequency set points shall be field adjustable and adjustable underfrequency trip settings shall be coordinated with operations of distribution system [7]. Also, these do not consider the stability of DG.

Therefore, this paper analyzes the operating setting of the frequency protection based on the stability of grid-connected PV system. First, we discuss the protection of the DG for the abnormal frequency in KEPCO's rule, IEEE Std. 1547 [7], and IEEE Recommended Practice [8]. Second, the equivalent circuit of grid-connected PV system is discussed. Also, the 'AY' PV system of 3 MW, which is connected to the KEPCO's distribution system, is modeled by using Matlab/Simulink based on the equivalent circuits of a PV cell [9, 10]. Third, the stability of PV system using eigenvalues equivalents of PV system is discussed. Fourth, the KEPCO's distribution system with the 'AY' PV system is modeled by using Matlab/Simulink. Besides, the various simulations according to the change of frequency are performed. For the simulated cases, the stability of PV system is analyzed to determine the operating setting of frequency protection.

2. The Protection of DG against Abnormal Frequency

The unbalance between generation and load cause the abnormal frequency. Table 1 shows the protection of the DG for the abnormal frequency in KEPCO's rule, IEEE Std. 1547, and IEEE Recommended Practice.

The KEPCO regulates that the DG in abnormal frequency must be disconnected from the distribution system. IEEE Std. 1547 and IEEE Recommended Practice make a distinction between DG sizes. For DG less than or equal to 30 kW in peak capacity, IEEE Std. 1547 states that for frequency less than 59.3Hz, recommended clearing

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time is 0.16s, and for frequency greater than 60.5Hz, it is 0.16s. For IEEE Recommended Practice, the range of frequency is equal to that of IEEE Std. 1547 while their recommended clearing times are different. For DG greater than 30 kW in peak capacity, both IEEE Std. 1547 and IEEE Recommended Practice state that the frequency set points shall be field adjustable [7, 8].

Table 1. The Protection of the DG for the abnormal frequency in KEPCO's rule, IEEE Std. 1547, and IEEE Recommended Practice

KEPCO's rule	IEEE Std. 1547			IEEE Recommended Practice		
	DG size	Frequency range(Hz)	Clearing time	DG size	Frequency range(Hz)	Clearing time
The DG in abnormal frequency must be disconnected from the distribution system.	≤30 kw	>60.5	0.16s	≤30 kw	>60.5	0.1s
		<59.3	0.16s		<59.3	0.1s
	>30 kW	>60.5	0.16	>30 kW	adjustable	
		<{59.8-57.0}	adjustable			
		<57.0	0.16			

The KEPCO's rule and IEEE Std. 1547 make no distinction between different types of DG unit. The IEEE Recommended Practice is only related to the utility interface of PV system.

3. Stability of the PV Cell

The stability of the PV cell can be discussed in the simplified equivalent circuit of the PV cell with output elements as shown in Fig. 1 [12]. The inductance and capacitance is introduced to represent the distribution lines, a capacitor bank, and etc., considering the configuration of distribution system and the power load is inserted.

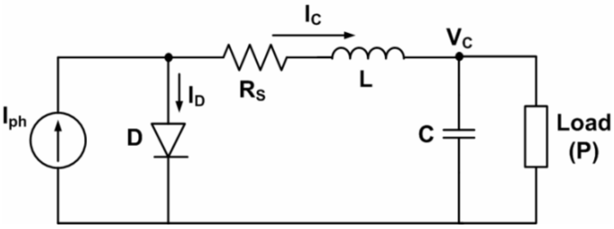


Fig. 1. Simplified equivalent circuit of the PV cell with output elements

Kirchhoff's current laws at both nodes in Fig. 1 yield,

$$\begin{aligned} &I_{ph} - I_D = I_{ph} - I_0\{\exp[\alpha(V_C + R_S I_C + L\frac{dI_C}{dt})] - 1\} = I_C \\ &I_C = C\frac{dV_C}{dt} + \frac{P}{V_C} \end{aligned} \tag{2}$$

where

$$\alpha = e / AkT_C$$

The series resistance of the PV cell in Fig. 1 is little. Therefore, the stability of the PV cell is given by

$$\begin{aligned} &\frac{dI_C}{dt} = \frac{1}{L}[\frac{1}{\alpha}\ln\left(\frac{I_{ph} - I_C}{I_0} + 1\right) - V_C] \\ &\frac{dV_C}{dt} = \frac{1}{C}[I_C - \frac{P}{V_C}] \end{aligned} \tag{3}$$

Because (3) includes the nonlinear equation, we cannot find the correct eigenvalues. Therefore, we apply the numerical solutions to solve the nonlinear equation. By using the Newton-Raphson Method $x_{n+1} = x_n + f(x_n)/f'(x_n)$, we can get the numerical solution of $f(x_n)$. Let's define $\Delta x = x_{n+1} - x_n = f(x_n)/f'(x_n)$. Then, we can find the $f(x_n) = \Delta x \cdot f'(x_n)$. If this concept is applied to (3), the matrix form of (3) is

$$\begin{bmatrix} \frac{d\Delta I_C}{dt} \\ \frac{d\Delta V_C}{dt} \end{bmatrix} = J\begin{bmatrix} \Delta I_C \\ \Delta V_C \end{bmatrix} \tag{4}$$

Where,

$$J = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} = \begin{bmatrix} -\frac{1}{\alpha L}\left(\frac{1}{I_{ph} - I_C + I_0}\right) & -\frac{1}{L} \\ \frac{1}{C} & \frac{P}{CV_C{}^2} \end{bmatrix}$$

The stability of (4) is determined by the eigenvalues. The eigenvalues are found through $\det(\lambda I - J) = 0$ .The roots of $\det(\lambda I - J) = 0$ is

$$\lambda_{1,2} = \frac{(J_{11} + J_{22}) \pm \sqrt{(J_{11} - J_{22})^2 + 4J_{12}J_{21}}}{2} \tag{5}$$

The PV system will be stable if

$$(J_{11} + J_{22}) \pm \sqrt{(J_{11} - J_{22})^2 + 4J_{12}J_{21}} < 0 \tag{6}$$

To satisfy (6), $(J_{11} + J_{22})$ must be less than zero and the following equation must be satisfied.

$$|J_{11} + J_{22}| > \left|\sqrt{(J_{11} - J_{22})^2 + 4J_{12}J_{21}}\right| \tag{7}$$

Eq. (7) is rewritten as following:

$$\begin{aligned} &(J_{11} + J_{22})^2 > (J_{11} - J_{22})^2 + 4J_{12}J_{21} \\ &J_{11}J_{22} > J_{12}J_{21} \end{aligned} \tag{8}$$

Substituting (8) to (4), we compute

$$V_C^{\,2} > \frac{P}{\alpha(I_{ph} - I_C + I_0)} \tag{9}$$

As a result, the stability of the PV cell is determined by (9). I_{ph}, I_0, and α are constant and thus the stability of the PV system depends on the I_C, V_C, and P. The effects of MPPT algorithm is concerned with P in (9). If the MPPT algorithm is applied, the PV system will be operating at MPP. This means that P is maximum power of PV system. Therefore, in transient state, the small variation of P can make PV system unstable.

4. Modeling of the Grid-Connected Photovoltaic System using Matlab/Simulink

4.1 Grid-connected photovoltaic system model

The capacity of the PV cell used in the 'AY' PV system is 175 W. The short circuit current and the open circuit voltage of the PV cell are 5.14 A and 45.8 V, respectively.

Fig. 2 shows the model of 'AY' PV system. 'AY' PV system is located in the south-west part of the Korea. Also, 'AY' PV system is interconnected with a real distribution system in KEPCO. Each array is the combination of 17 cells in series and 126 cells in parallel of the 175 W cell; hence an array generates 375 kW. 'AY' PV system is composed of eight arrays. Therefore, the total power generated by the 'AY' PV system is 3 MW. The DC power generated by each array is converted to the AC power of 380 V by an inverter. The output of four inverters in parallel is converted to 22.9 kV (voltage of distribution line in KEPCO) by a single transformer. The windings, ratings, and % impedances of the transformer is Δ-Y, 1500 kVA, and 6%, respectively. The secondary side of two transformers operating in parallel is connected to the distribution system [11].

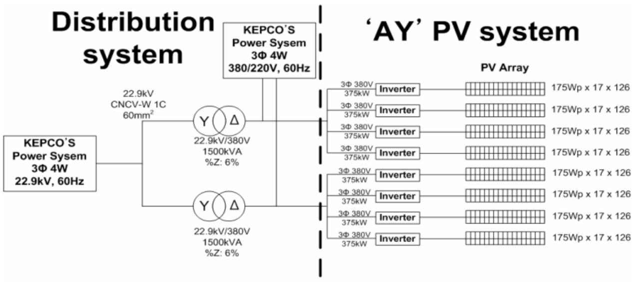


Fig. 2. The model of the 'AY' PV system

4.2 Modeling of grid-connected photovoltaic system model

To analyze the stability of the PV system with regard to frequency, the accurateness of the modelled PV system must first be discussed. Fig. 3 shows the 'AY' PV system modeled by Matlab/Simulink. In this step, the power system is not modeled and the output power of the PV supplies the load of 3 MW via the inverter and transformer. Fig. 4 shows the P-V and I-V characteristics of the PV array. The voltage of the PV system starts at 778.6 V (①), which is the open circuit voltage of the PV system, and moves to the maximum power point (MPP) (②). The open circuit voltage of a single PV cell used in the 'AY' PV system is 45.8 V. The 17 cells in series are connected in the single PV array, and therefore the open circuit voltage for the single PV array is 45.8x17=778.6 V. This is in agreement with the simulation results shown in Fig. 4.

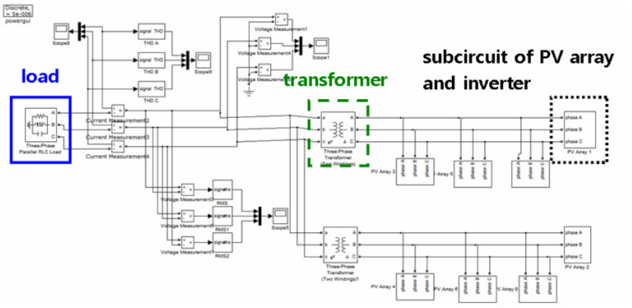
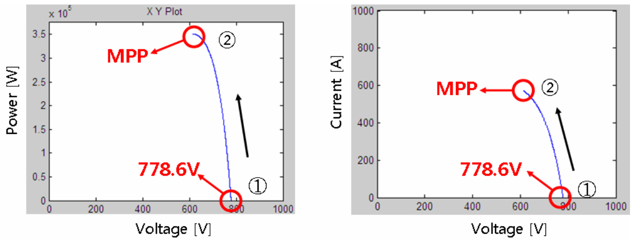


Fig. 3. 'AY' PV system modeled by Matlab/Simulink



(a) P-V curve (b) I-V curve

Fig. 4. Output characteristics of the PV array

The simulation results are compared with the power quality data recorded in the field. The total harmonic distortion (THD) in the power quality data recorded in the field is 10.1%, and does not satisfy the standard for the harmonics of DG in KEPCO's rule. The result of the THD calculation for the simulation results is 10%. The accurate operating conditions are not available, however, the error is little and the simulation result also does not satisfy the standard for the harmonics of DG in KEPCO's rule.

5. Stability analysis of the PV system according to the frequency variation

5.1 The distribution system model with the 'AY' PV system

Fig. 5 shows the KEPCO's distribution system inter-connected with the 'AY' PV system. The types of the line

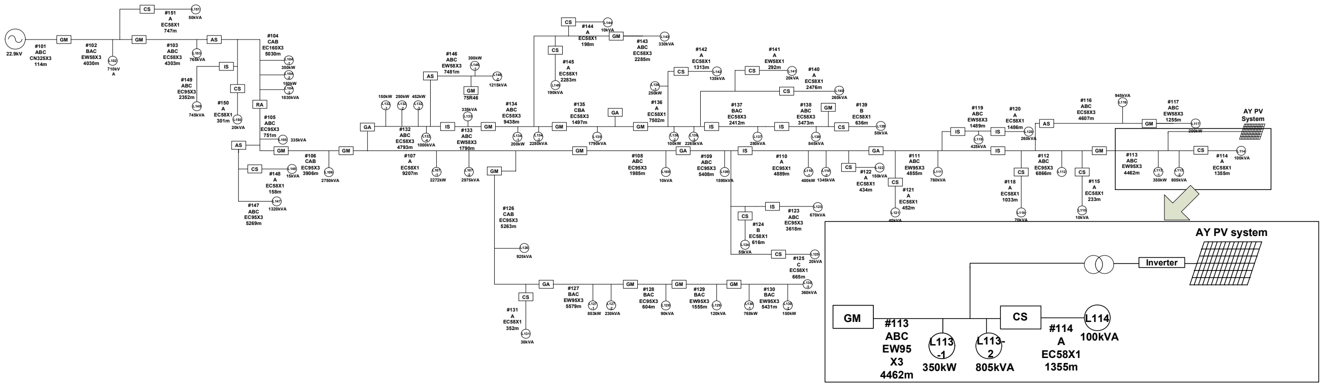


Fig. 5. Distribution system model with the ‘AY’ PV system

used in the distribution system are EW58, EC58, EW95, EC95, and EC160. The ‘Compute RLC Line Parameter’ method from the analysis tools supported by Matlab/ Simulink calculates the impedance of each line with consideration of the conductor data and geometric arrangement of the distribution poles. These calculation results are inputted to the PI model of Matlab/Simulink to model the distribution line.

The capacity of the total loads of the distribution system is 7195 kW for high voltage loads and 33400 kVA for low voltage loads. However, the power consumption at the measured time was 3700 kW, and the current recorded in the field at that time was 103.1 A. To ensure the accurate performance of this model, 10% of total loads is assumed, i.e., 719.5 kW for high voltage loads and 3340 kVA (power factor of 0.9) for low voltage loads.

The maximum current among the three phases by simulation is then 101.7 A, and this value is similar with the current recorded in the field. Therefore, the distribution system model is proved to be accurately.

The PV system is connected to downstream of the distribution system. The 1.5 MW PV system was modeled with consideration for the capacity of the loads.

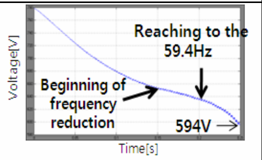
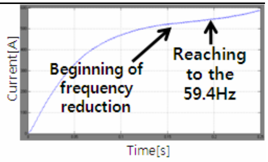
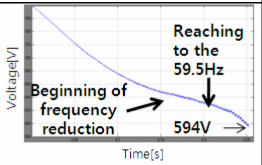
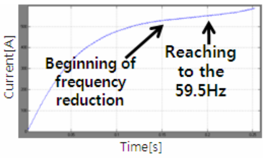
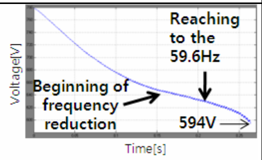
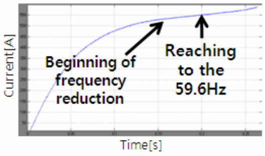
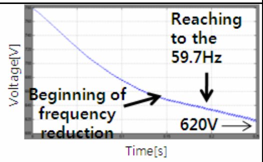
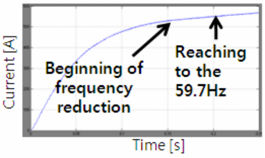
5.2 Underfrequency protection and stability of PV system

The three phase programmable voltage source in Matlab/Simulink is used to simulate the change of frequency. The 60Hz frequency is decreased for 0.05s and the type of variation is ramp. The decreased value is determined by the rate of change.

The various values of frequency are studied. Table 2 shows the output voltage and current of the PV array for some of the studied cases. When the frequency is reduced, the output voltage of PV is reduced and the output current of PV is increased.

We calculate the eigenvalues to evaluate the stability of the PV system. Table 3 shows I_C, V_C, P, and eigenvalues according to the change of frequency. For the frequency greater than or equal to 59.7Hz, the eigenvalues are less than 0, and hence the stability of PV system is maintained. However, for the frequency less than or equal to 59.6Hz, the eigenvalues are bigger than 0, and therefore the PV system becomes unstable.

Table 2. the Output Voltage and Current of the PV Array for Frequency Reduction

Output / Freq -uency	Output voltage of the PV array	Output current of the PV array
59.4Hz		
59.5Hz		
59.6Hz		
59.7Hz		

We find the critical clearing time (CCT) for the change of frequency as shown in Table 4. Fig. 6 depicts the CCT versus frequency curve. The values obtained in Table 3 and 4 depend on the system. The relation between the system and the results is determined by I_C, V_C, and P in (9). The frequency reduction means that the output capacity of the PV system is smaller than load capacity. This causes the increasing of output P of the PV system. In Table 2, when the frequency becomes to the specific frequency, the output voltage V_C and current I_C of PV is reduced and increased, respectively. As the reducing of frequency becomes severe, the slop on the changing of the V_C and I_C also becomes severe. Therefore, as the frequency reduction becomes more severe, the CCT becomes faster. In Table 3, the power variation is relatively small. However, the PV system is already operating near at maximum power point (MPP). Therefore, the small variation of PV output can make PV system unstable. These results can be useful to determine the setting of underfrequency protection of grid-connected PV system.

Table 3. The I_C, V_C, P, and eigenvalues according to the frequency reduction

Items Frequency	I_C (A)	V_C (V)	P(W)	Eigenvalues	Stability
59.3Hz	4.673	34.98	163.462	0.416, -31.2914	unstable
59.4Hz	4.673	34.98	163.462	0.416, -31.2914	unstable
59.5Hz	4.673	34.98	163.462	0.416, -31.2914	unstable
59.6Hz	4.673	34.98	163.462	0.416, -31.2914	unstable
59.7Hz	4.425	36.94	163.459	-0.245, -19.599	stable
59.8Hz	4.39	37.18	163.22	-0.341, -18.539	stable
60Hz	4.36	37.4	163.064	-0.425, -17.698	stable

Table 4. The critical clearing time for change of frequency

Items Frequency	Critical clearing time
59.3Hz	0.044s
59.4Hz	0.05s
59.5Hz	0.0582s
59.6Hz	0.069s
59.7Hz	stable
59.8Hz	stable

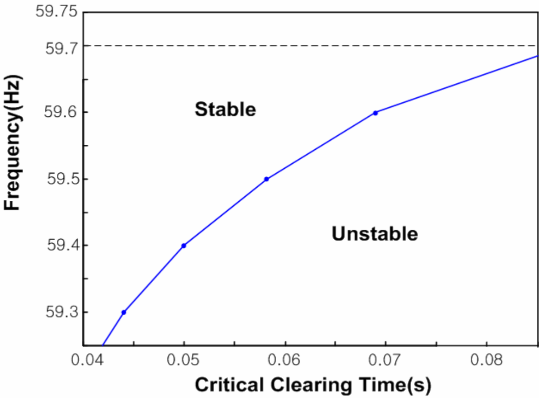


Fig. 6. CCT versus frequency curve

IEEE Std. 1547 makes no distinction between different types of DG units and does not consider the stability of DG [6]. IEEE Recommended Practice does not consider the stability of PV system either. Therefore, we propose that the setting of the underfrequency protection of grid-connected PV system should be distinguished between different types of DG units and can be determined based on the stability of PV systems for the change of frequency. Therefore, in practical application, the setting of the underfrequency protection of a PV system may be changed by finding the CCT of the PV system considering the practical operating conditions of the PV system installed.

5.3 Overfrequency protection and stability of PV system

The various value of frequency is studied. When the frequency is increased, the new operating point of output voltage of PV system is increased to the open circuit voltage and the current is reduced. This indicates that the output power of the PV array is reduced by the increase of frequency. As the increasing of frequency is more severe, the new operating point of output power is lower.

When the frequency is increased, the stability of PV system is maintained. Therefore, the setting of over-frequency protection can't be determined using the CCT of PV system. To find the factors for the setting of overfrequency protection, we study the power quality according to the increase of frequency. When the frequency reaches to the 60.5Hz, the THD oscillates in range of 5.5~7.5%. However, when the frequency reaches to the 60.7Hz, the THD is rapidly increased to the 11%. In case of 61Hz, the THD is increased to the 24%.

The 60.5Hz based on the result of this analysis is equal to the upper limit of overfrequency protection of IEEE Std. 1547 and IEEE Recommended Practice. However, if the technology of pulse-width-modulated (PWM) inverter is more developed, the THD will be lower. Also, the THD will change by the fluctuation of output power depending on the weather conditions. Therefore, we propose that the setting of overfrequency protection of grid-connected PV system can be determined based on the variation of THD according to the increase of frequency. In the practical application, the setting of overfrequency protection of PV system may be changed by finding the THD considering the practical operating conditions of PV system installed.

6. Conclusion

This paper analyzed the stability of a PV system to determine the setting of the frequency protection using Matlab/Simulink. First, the 'AY' PV system of 3MW, which is connected to the KEPCO's distribution system, was modeled. The modeled PV system was verified by comparing the simulation results with the power quality data recorded in the field. Then, the KEPCO's distribution system interconnected with the 'AY' PV system was modeled and the simulations were performed for the various changes of frequency.

By simulation results, we conclude that the setting of underfrequency and overfrequency protection of grid-connected PV system should be distinguished between different types of DG units. The setting of underfrequency protection could be determined based on the stability of PV system for the change of frequency and the setting of overfrequency protection of grid-connected PV system could be determined based on the variation of THD according to the increase of frequency.

Acknowledgements

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