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슬립모드 방식을 이용한 단독운전 검출기법의 모델링과 평가

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Modeling and Evaluation of Slip-Mode Frequency Shift Method for Anti-islanding Method

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ABSTRACT

Islanding phenomenon is undesirable because it lead to a safety hazard to utility service personnel and may cause damage to power generation and power supply facilities as a result of unsynchronized reclosure. In order to prevent this phenomenon, various anti-islanding methods have been studied. Even though the slip mode frequency shift (SMS) method has been regarded as a highly effective anti-islanding method, the analytical design method of that was not cleared. This paper proposes a modeling of the SMS method using non-detection zone (NDZ) and evaluation of the method according to the test conditions of IEEE Std. 929-2000. The SMS method is derived analytically through the modeling and verified visually by simulation and experiment.

1. Introduction

Islanding phenomenon of grid connected PV inverters refers to their independent powering to a portion of the utility system even though the portion has been disconnected from the remainder of the utility source. To prevent this phenomenon, various anti-islanding methods have been studied, which are classified into passive and active methods[1].

Among active methods, the slip mode frequency shift method has received recent attention [2]. Even though the SMS method has been regarded as a highly effective method, the analytical design method of that was not cleared. This paper proposes the modeling of the SMS method using non-detection zone (NDZ) and evaluation of that method according to the test conditions of IEEE Std. 929-2000.

2. Design of the SMS method

2.1 Concept

In the SMS method, the current-voltage phase angle of the inverter, instead of always being zero, is controlled to be a function of the frequency of PCC(Point of Common Coupling) voltage. The SMS is implemented by the design of PLL(Phase Locked Loop) input filter as Figure 1 [1].

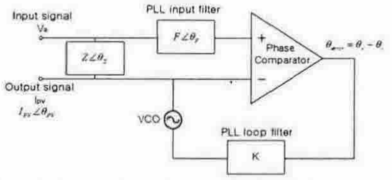


Fig. 1 PLL structure of the SMS method

2.2 Load Line Calculation

In the circuit as shown in Figure 2, the islanding test procedure of the IEEE Std. 929-2000 is based on having the quality factor Q_f of the islanded circuit set to 2.5. Therefore the load line for the specific power capacity can be achieved. In this paper, 3kW inverter will be used for the analysis.

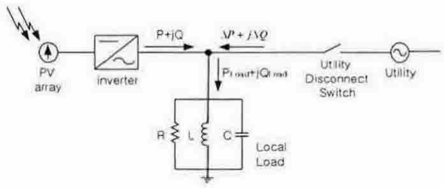


Fig. 2 Non-islanding inverter test circuit

$$Q_f = \frac{\sqrt{Q_L \times Q_C}}{P} \quad (1)$$

$$\theta_Z = -\tan^{-1}\left[R\left(2\pi fC - \frac{1}{2\pi fL}\right)\right] \quad (2)$$

where : θ_Z is the phase angle of the local load

According to the islanding test condition of the IEEE Std. 929-2000, the power flow to the grid is nearly zero with the quality factor 2.5. The first load line(θ_{Z1}) can be found from equation 1 and equation 2. After the islanding test on the stated condition, one parameter, which may be load inductance L or load capacitance C, has to be adjusted within a total range of ±5% for the practical verification[4]. In this paper, load inductance L is adjusted to ±5%. In Figure 3, the other load lines are presented as θ_{Z2} for +5% load inductance and as θ_{Z3} for -5% load inductance.

2.3 SMS Line Calculation

Based on a power mismatch space representation (PMS), the quantitative NDZ is already derived as following for the given standard relay trip windows[3].

$$-17.36\% \le \frac{\Delta P}{P} \le 29.13\% \quad (3)$$

$$-5.94\% \le \frac{\Delta Q}{P} \le 4.11\% \quad (4)$$

The typical SMS Line is represented in equation 5.

$$\theta_F[K] = \theta_M \sin\left[\frac{\pi}{2}\frac{(f_{Line,[K-1]} - 60)}{f_M - 60}\right] \quad (5)$$

where: $\theta_F[K]$ is the starting phase of output current

$f_{Line,[K-1]}$ is the measured frequency of the previous voltage cycle

There are two design parameters, which are θ_M and f_M. Firstly, in order to have proper θ_M, the power factor is considered because the effective and reactive power can be represented by the power factor as equation 6, if the distortion power factor is negligible. That means the amount of the reactive power, which can be beyond the NDZ range, can be generated by the controlled power factor as equation 7. Secondly, the slope of SMS line at the nominal line frequency must be higher than that of the inverted load line as equation 8.

$$pf = \cos\theta = \frac{P}{S} = \frac{1}{\sqrt{1+\left(\frac{Q}{P}\right)^2}} \quad (6)$$

$$\theta_M = \cos^{-1}\left(\frac{1}{\sqrt{1+\left(\frac{Q}{P}\right)^2}}\right) \quad (7)$$

$$\left.\frac{d\theta_F}{df}\right|_{at\ 60Hz} = \frac{\theta_M \pi}{2(f_M - 60)} > \frac{d\theta_z}{df} \quad (8)$$

To get out of the NDZ range in equation 4, the reactive power flow to the grid is chosen to be 6%. Therefore the two parameters can be defined as follows.

$$\theta_M = 3.4336\ °,\ f_M < 61.07\text{Hz} \quad (9)$$

The f_M is chosen as 60.7Hz to have power quality as high as possible for the allowed line frequency range. Therefore the new SMS line can be defined by equation 12.

$$\theta_F = \begin{cases} -\theta_M & \text{if } f_{Line,[K-1]} < 59.3Hz \\ \theta_M \sin\left[\frac{\pi}{2}\frac{(f_{Line,[K-1]} - 60)}{f_M - 60}\right] & \text{if } 59.3Hz < f_{Line,[K-1]} < 60.7\text{Hz} \\ \theta_M & \text{if } f_{Line,[K-1]} > 60.7Hz \end{cases} \quad (10)$$

$$\theta_Z + \theta_F = 0 \quad (11)$$

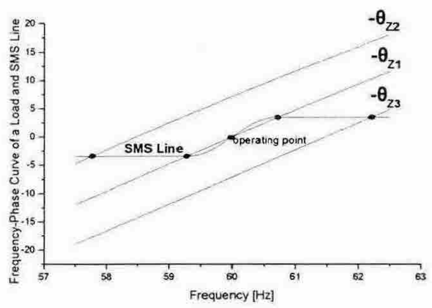


Fig. 3 Frequency-Phase Curve of Load and SMS lines

From the simulation results as Figure 3, all of the new operating points can move out of the given frequency trip limit due to the small perturbation when the islanding occurs

2.4 Experimental results and discussions

To verify the validation of the proposed analysis, the experimental results of islanding test and power quality corresponding to IEEE Std. 929-2000 are presented for 3kW PV inverter as shown Figure 4. In addition, the Total Harmonic Distortion (THD) of the inverter is controlled to be less than 1% under the grid-connected condition for the more exact analysis.

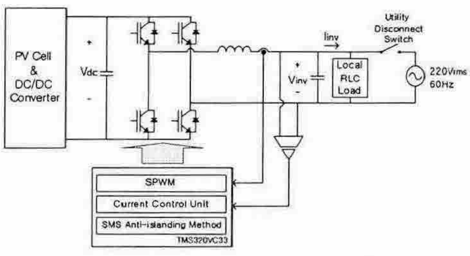


Fig. 4 Experimental Circuit

Figure 5 shows the comparison of analytical and experimetal power factor. Analytical power factor is determined by the only displacement power factor, while the experimental power factor is affected by both displacement power factor and the distortion power factor. The analytically-determined power factor is deemed sufficiently accurate.

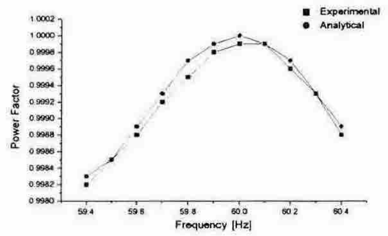
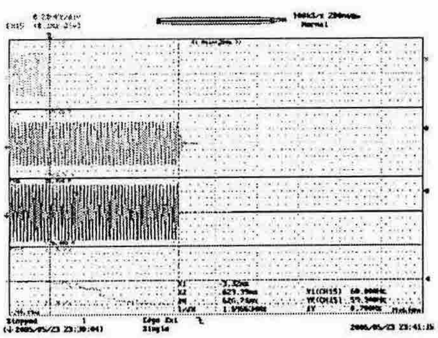
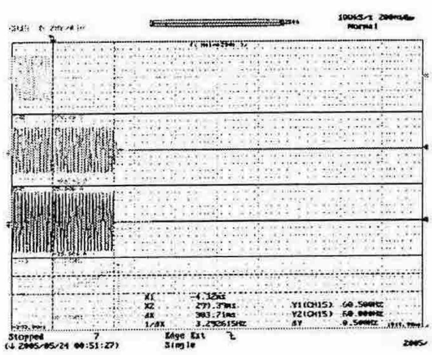


Fig. 5 Power Factor with respect to the line frequency



(a) $\Delta P/P \approx 0.3\%$, $\Delta Q/P \approx -0.2\%$



(b) $\Delta P/P \approx 0.3\%$, $\Delta Q/P \approx 0.2\%$

Fig. 6 Islanding test results (CH1: grid voltage, CH2: inverter output voltage, CH5: inverter output current, CH15: frequency of inverter output voltage)

From the figure 6, the SMS can detect the islanding at around zero power flow to the grid within 2 seconds. The direction of frequency drift is determined by the sign of reactive power flow to the grid. For the other load conditions(θ_{Z2}, , θ_{Z3}), the SMS detects the islanding more faster than the previous load condition(θ_{Z1}) because the phase errors of the PLL output are more greater than that of the previous one at the instance of the islanding occurrence.

3. CONCLUSION

This paper presents modeling and evaluation of the SMS method for the anti-islanding. In order to have a reasonable design of the SMS, the power mismatch space representation of the NDZ is used. For the 3kW PV inverter are used for the verification, which shows the satisfied islanding detection capability and the good power quality to pass the IEEE Std. 929-2000.

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