Impact of Photovoltaic Penetration on Small Signal Stability considering Uncertainties

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Abstract—**This paper applies cumulant method to analyze the influence of Photovoltaic Penetration (PV) considering fluctuations in small signal stability The cumulant method for small signal stability is mainly based on sensitivity analysis which is then used with Gram-Charlier expansion to obtain the valuable information of probability density function (PDF) and Cumulative Density Function (CDF) of the real part of the critical eigen value and damping factor. A supplementary controller to enhance small signal stability is also presented and its performance is also analyzed. The test system is a modified IEEE 16 machine, 68 bus system which is benchmarked to study small signal oscillatory dynamics in power systems. The results show that the PV fluctuations have potential to cause oscillatory instability and the future large PV farms should also contain Power Oscillation Damper (POD) to damp these oscillations.**

Index Terms—**Cumulant Method, Power Oscillation Damper, Probabilistic Analysis, Probability Density Function**

I. Introduction

Recently, there is a large proliferation of Photovoltaic Power Generation (PVG) in electric power system and their aggregated production capacity is rapidly approaching towards the conventional generation capacity. However, Photovoltaic Power greatly suffers from intermittency which could severely hamper the power system. Moreover, PV resources in nearby places could be correlated due to insolation, temperature and other environmental factors and can cause different electrical issues in power system [1]. There has been a great effort in understanding their effects in power system stability especially small signal stability. However, most of the works are based on deterministic analysis [2-3] or are considered only for small penetration in distribution level [4].

The PV power fluctuations can be studied by using probabilistic method. This method characterizes uncertainties by describing the variation by suitable probability distribution. Probabilistic Method gives system planners better idea about future system conditions which helps them to make well decision to operate power system in a reliable manner [5].

Broadly speaking, the current probabilistic method to analyze small signal stability can be categorized into analytical and non-analytical method. The analytical method is based on the assumption that the system eigen values are a function of some uncertain input parameters. These methods employ complex mathematical approximations to infer the probability distribution of important electrical variables such as eigen values and damping factor [5].

The non-analytical method uses Monte Carlo Simulation [MCS] technique to obtain the information about system eigen value distribution. This technique is a numerical method which needs running of multiple deterministic small signal stability analysis [5]. This leads to huge computation burden and many researchers only use it to comparison purpose.

This paper uses an analytical method based on cumulants to analyze the effect of PV generation in small signal stability. The cumulant method was chosen as it gives better results when compared with other analytical methods such as Point Estimate Method or Probability Collocation Method [6]. The output of the cumulant method is used with Gram-Charlier Expansion technique to obtain the Probability density function (PDF) and Cumulative density function (CDF) of real part of critical eigen value and its damping factor. The results obtained for different cases are all compared with the MCS output. Moreover, a Power Oscillation Damper (POD) is designed to damp the oscillation and its performance is also seen.

The paper is organized as follows: Section II gives theoretical background on some essential ideas such as PV converter and POD modeling as well as the probabilistic method. Section III discusses about the PV irradiance modeling. Section IV contains the results of the analysis for different cases which is followed by conclusion in section V.

II. NECESSARY THEORETICAL BACKGROUND

A. POD Model

The Power oscillation damping model is shown in Fig.1. The POD provides a supplementary signal in the PV controller which helps to damp the oscillation. It has a similar

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structure to a Power system stabilizer (PSS). The input to POD can be any signals like bus voltage, line current, active or reactive power etc. The POD has a washout block with a gain K and Time constant T_w. This output is then given to lead lag compensator which has time constants T_1, T_2, T_3 and T_4. The output is then fed as a modulating signal to the converter reactive power controlling loop as described before.

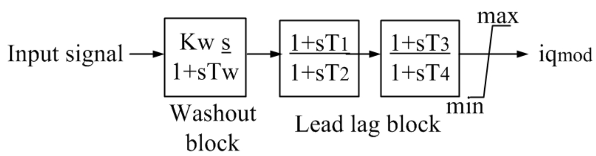

Figure 1. POD Model

B. PV Model

The PV model is developed as suggested by NERC and WECC and is similar to the grid side converter model of wind turbine generators (Type 4 WTG) [7]. The model considers PV as a Voltage Source behind internal impedance and is connected to the grid as shown in Fig. 2.

The PV source injects real (p) and reactive power (q) to the grid via transformer which is modeled as impedance with resistance (r) and reactance (x). The magnitude of point of common coupling (PCC) voltage is denoted by V_T and the phase angle is ϕ_v.

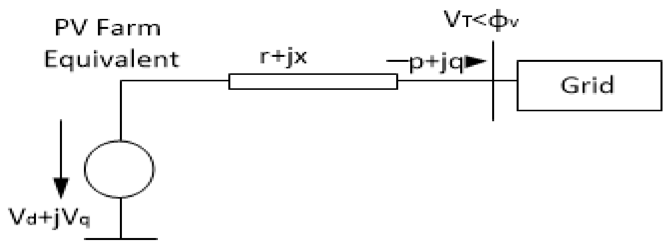

Figure 2. PV Farm connected to the Grid

Fig.3. shows the converter model of the PVG. The voltage source can be decomposed into direct axis voltage (V_d) and quadrature axis voltage (V_q) which is supplied by two delay blocks representing the converter delay (T_V) [8]. This portion of the converter is in synchronously rotating grid reference frame. The controller part represented by PI controller is in terminal voltage oriented frame where the real part of the current controls the active power and the imaginary part of the current controls reactive power. The active and reactive power is controlled from reference real power (P_{ref}) and reference reactive power (Q_{ref}) respectively.

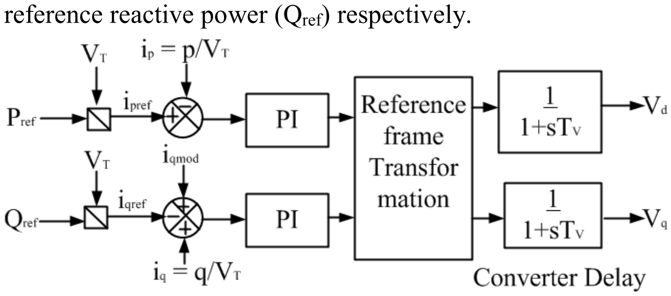

Figure 3. Model of PV controller

The output (i_{qmod}) from POD described in the last heading is connected to the reactive control loop to enhance the system damping. This paper uses reactive power modulation technique as the system damping increases more with more real power injection in this scheme [9].

The whole model was built in DIGSILENT.

C. Probabilistic Small Signal Stability

It is generally considered that the Beta distribution is the most applicable distribution to describe the PV irradiance fluctuation [10]
The probability density function (pdf) of the solar irradiance can be written as:

$$f(S) = \frac{1}{B(a,b)} S^{a-1}(1-S)^{b-1} \tag{1}$$

Where, S is the irradiance, a and b are the shape parameters and B is the beta function.

The power output of the PV generation varies linearly with the irradiance [1] and thus, the PDF of the power output (f_p) can be derived using the well-known transformation method as:

$$f_p(P) = \frac{1}{P_{rated}} \frac{1}{B(a,b)} \left(\frac{P}{P_{rated}}\right)^{a-1} \left(1 - \frac{P}{P_{rated}}\right)^{b-1} \quad for 0 < P \le P_{\max} \qquad \text{(2)}$$
$$0 \quad else$$

Where, P is the PV power injection, P_{rated} is the rated PV output power and P_{max} is the maximum output power.

The PV power fluctuation is defined as $\Delta P_i = P_i - P_d$, where P_d is the deterministic PV power generation.

The raw moment of the PV power variation can be computed as follows:

$$\begin{aligned} \alpha^{(n)}{}_{\Delta P_i} &= \int_0^{P_{rated}} x^n f_p(x) dx \\ &= \sum_{k=0}^{n} C_n{}^k \frac{(-P_i)^{n-k}}{B(a,b)} * B(k+a,b) \end{aligned} \tag{3}$$

Where, $C_n{}^k = \frac{n!}{(k!(n-k)!)}$, $B(k+a,b) = \frac{\tau(k+a)\tau(b)}{\tau(k+a+b)}$
and τ is the gamma function.

The nth order cumulants can be calculated as follows:

$$\begin{aligned} k^{(1)}{}_{\Delta Pi} &= \alpha^{(1)}{}_{\Delta P_i} \\ k^{(2)}{}_{\Delta Pi} &= \alpha^{(2)}{}_{\Delta P_i} - \alpha^{(1)}{}_{\Delta P_i} \\ k^{(3)}{}_{\Delta P_i} &= \alpha^{(3)}{}_{\Delta P_i} - 3\alpha^{(1)}{}_{\Delta P_i}\alpha^{(2)}{}_{\Delta P_i} + 2(\alpha^{(1)}{}_{\Delta P_i})^3 \\ &\cdots\cdots\cdots \end{aligned} \tag{4}$$

Assuming there are N PV system in the power system and $\lambda_k = \sigma_k + j\omega_k$, which denotes the kth eigen value (critical) of the power system with real part (σ) and imaginary part (ω), the following relationship can be established [11],

$$\Delta\lambda_k = \Delta\sigma_k + j\Delta\omega_k = \sum_{i=1}^{N} \frac{\partial\lambda_k}{\partial P_i}\Delta P_i \tag{5}$$

$$\frac{\partial\lambda_k}{\partial P_i} = \frac{\lambda_k(P_i+\Delta P_i)-\lambda_k(P_i)}{\Delta P_i} \tag{6}$$

The output cumulants ($k^{n}_{\Delta\sigma}$) can be calculated from the input cumulants using (7). It is then used to obtain the output central moments which is used to find the PDF and CDF of the critical eigen value with the help of Gram-Charlier Expansion [5].

$$k^{(n)}{}_{\Delta\sigma}(= \sum_{i=1}^{N}\left[\mathrm{Re}\left(\frac{\partial\lambda_k}{\partial P_i}\right)\right]^{n} k^{(n)}{}_{\Delta P_i} \tag{7}$$

It is easy to derive similar relationship for the damping factor (ζ) of critical eigen value using (8),

$$\xi = \frac{-\sigma}{\sqrt{\sigma^2+\omega^2}} \tag{8}$$

Finally, the following two terms are calculated,

$$P(\sigma<0) = F_\sigma(0) = \int_{-\infty}^{0} f_\sigma(x)dx$$

$$P(\xi<0) = F_\xi(0) = \int_{-\infty}^{0} f_\xi(x)dx \tag{9}$$

Where, F_σ and F_ζ are the CDF of critical eigen value real part and critical eigen value damping factor respectively and f_σ and f_ζ are the PDF of the critical eigen value real part and critical eigen value damping factor respectively.

III. PROBABILISTIC MODEL OF PV GENERATION

The actual daily data collected from 2013 to 2016 by CES Solar Cells Testing Center (CSSC), Thonburi is used to construct the PDF of the PV irradiance. The hourly data between 12pm to 1 pm for the month of May was used to construct the histogram shown in Fig. 4.

The histogram clearly shows a bimodal distribution and was thus, fitted separately to the best possible distribution by using Matlab statistics tool box.

Only the higher irradiance portion was considered as it contained large frequency of data and we might also encounter errors if we consider the total distribution [12]. The best fit was found to be beta distribution and the shape parameters were obtained using maximum log likelihood test whose values are given in Table I.

TABLE I

PARAMETERS OF SOLAR IRRADIANCE

a	b	Mean (pu)	Variance	Base Irradiance (W/m^2)
12.2101	2.48237	0.831045	0.00894751	1100

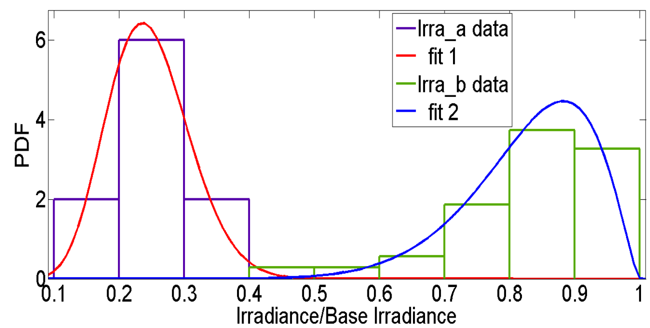

Figure 4. PDF of the Solar Irradiance

The accuracy of the proposed probabilistic power model is calculated by using average root mean square (ARMS) [1]

$$ARMS = \frac{\sqrt{\sum_{i=1}^{N}(F_{Mod,i}-F_{Ref,i})^2}}{N} \tag{10}$$

Where, $F_{Mod,i}$ and $F_{Ref,i}$ are the ith value on the CDF curves of the fitting model and the reference respectively and N is the selected number of points. The ARMS for this case is 0.242% showing the validity of the proposed probabilistic model.

IV. CASE STUDY

Fig. 5 shows the test system which has 16-machines and 5 areas and is a reduced order equivalent of the interconnected New England Test System (NETS) and New York power system (NYPS). The test system has three PV generators connected at buses 18, 41 and 42. The value of the parameter of PV farm is given in the appendix. All the PV Generators are operated at 0.83pu for both case A and B.

The test system has all Power system stabilizers (PSS) disabled and the excitation system is modeled as a simple fast acting static exciter whose value is given in appendix [13].

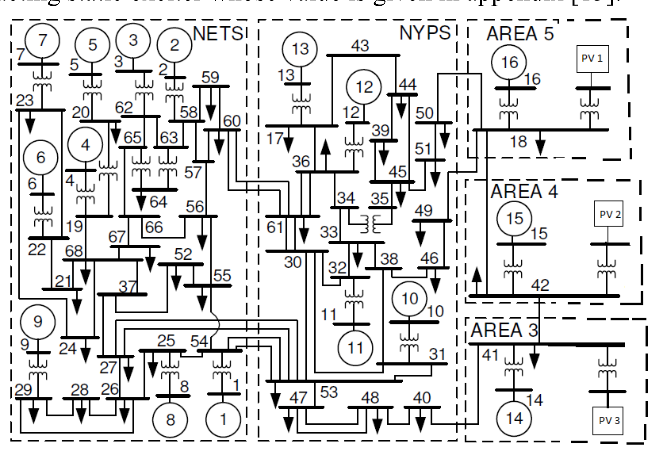

Figure 5. Modified IEEE 68 Bus System [14]

A. *PV penetration without POD*

In this first case, the deterministic small signal stability analysis was run and the critical eigen value was found to be -0.00915779+j*0.00429. The cumulant method was then used to obtain the CDF and PDF of real part of critical eigen value and damping factor.

The PDF of the real part of critical eigen value is shown in Fig.6. which clearly has some part of its area lying in the positive half suggesting the possibility of instability.

Fig.7 shows the CDF of the real part of the critical eigen value and can be used to calculate the following:

$$P(\sigma < 0) = F_{\sigma}(0) = \int_{-\infty}^{0} f_{\sigma}(x)dx = 80.94\%$$

This shows that the given system has 19.06% of being stochastically unstable due to PV fluctuations even though it was deterministically stable.

For comparison, the histogram of MCS is also shown. We can see that the histogram of MCS matches the Gram-Charlier expansion approximations.

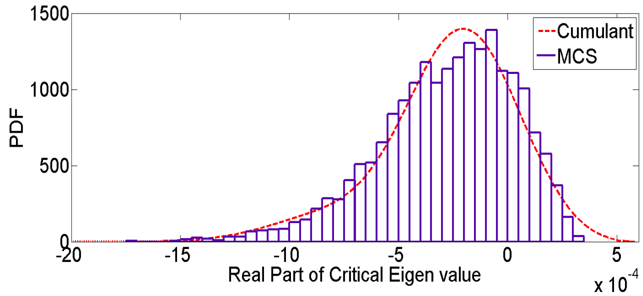

Figure 6. PDF of the Real part of the Critical Eigen Value

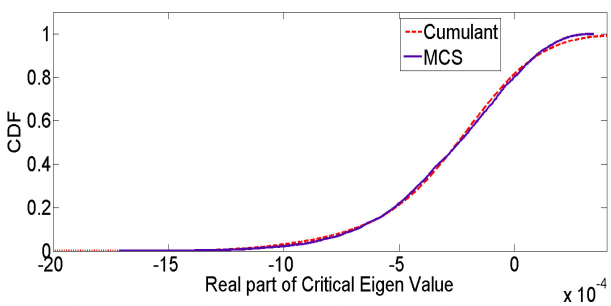

Figure 7. CDF of the Real part of the Critical Eigen Value

The PDF of the damping factor of critical eigen value is shown in Fig. 8 which has some part of its area lying on the negative left hand side suggesting possible instability. The CDF of the damping factor of critical eigen value is shown in Fig.9 and can be used to find:

$$P(\xi > 0) = F_{\xi}(0) = \int_{0}^{\infty} f_{\xi}(x)dx = 80.4\%$$

This result shows that there is a probability of 19.6% that the damping factor of critical eigen value can be negative which can lead the system to be oscillatory instability.

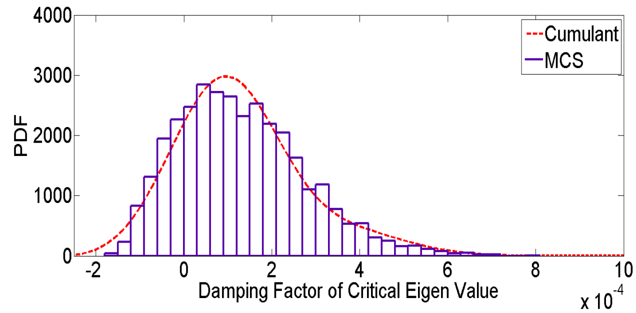

Figure 8. PDF of the damping factor of the Critical Eigen Value

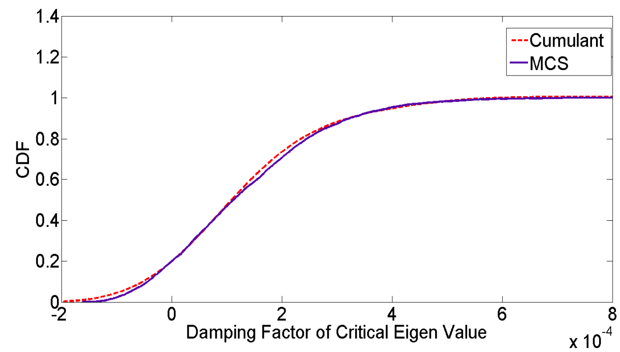

Figure 9. CDF of the Real part of the Critical Eigen Value

B. PV penetration with POD

The second case considers PV farms which have POD installed in it. The input signal for PODs of PV farm 1 and 2 is taken as current from Bus 18 to 42 and current from 41 to 42 for POD of PV farm 3. The main reason for selecting this signal was they are local and thus, more readily available. The POD parameters were tuned extensively to obtain the best possible values which are given in the appendix. Fig.10 shows the PDF of the critical eigen value. Unlike in the previous case, the whole area of PDF always lies in the negative plane suggesting the system to be small signal stable.

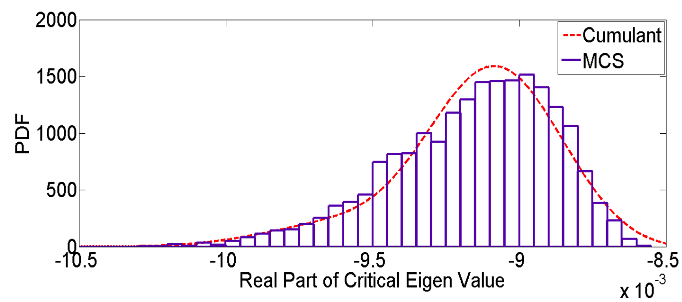

Figure 10. PDF of the Real part of the Critical Eigen Value with POD

Fig. 11 shows the CDF of the real part of the critical eigen value and can be used to find:

$$P(\sigma < 0) = F_{\sigma}(0) = \int_{-\infty}^{0} f_{\sigma}(x)dx = 100\%$$

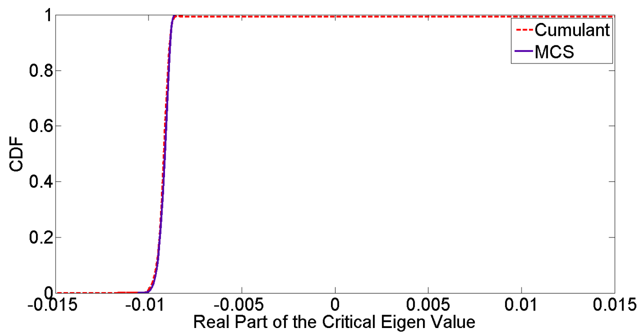

Figure 11. CDF of the Real part of the Critical Eigen Value with POD

This results shows that the system which has PV Generators with POD installed is always small signal stable.

C. PV penetration at different level

Finally, all PV generators without POD is varied from 10 to 100 percent (0.1 to 1 pu) of its value and the probability of damping factor of critical eigen value being less than zero was calculated. Fig. 12 shows that the probability of instability increases with the penetration level and is highest when all the PV farms operate at their rated value.

The probability of damping factor of critical eigen being less than zero is always nil percent for the case of PVG with POD installed and is thus, not shown for comparison.

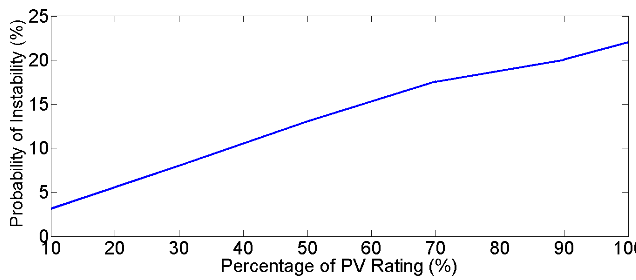

Figure 12. Probability of Instability in percentage for different penetration levels

V. CONCLUSION

In this paper, the cumulant method is used to analyze the effect of PV generation in small signal stability. The output of the cumulant method provides the important statistical parameters which are used with Gram Charlier Expansion to obtain the PDF and CDF of the real part of the critical eigen value and damping factor.

It was found that the system was stochastically unstable even though it was deterministically stable which showcase the effect of PV irradiance fluctuations. The paper also proposes one possible method to improve stability in such case by including a supplementary damping controller in PV control structure. It was found that it greatly enhances small signal stability. Finally, the effect of PV penetration on different levels was considered and was seen that it higher penetration leads to the deterioration of system stability.

APPENDIX

TABLE II

PARAMETERS OF THE PV CONTROLLER

PV Rating (MW)	Proportional gain	Integral gain	Converter time delay
100	0.1	0.05	0.015

TABLE III

POD PARAMETERS

K_W	T_w	T_1	T_2	T_3	T_4
1	10	2	0.2	0.3	0.2

TABLE IV

EXCITATION SYSTEM PARAMETERS

K	T_a	V_{max}	V_{min}
38	0.1	10	-10

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