Probabilistic Power Quality Indices for an Electric Grid with Wind Energy Conversion System and STATCOM

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***Abstract*—The higher wind power penetration level there is, the more the power quality is affected in an electric grid. Thus, it is essntial to evaluate the power quality of the electric grid in presence of wind power generation. To examine the power quality, probabilistic indices must be defined to form a foundation for measuring negative effects of different disturbances on the electric grid. In this paper, the probabilistic power quality indices have been used to make an overall assesment of the power quality of the electric grid in prescene of wind power generation and static synchronous compensator. The purpose of the present study is to evaluate the probabilistic power quality indices for such an electric grid. Figures and Tables present the values of the probabilistic power quality indices and reveal that the static synchronous compensator positively affects some probabilistic power quality indices. Also, control parameters of the static synchronous compensator have been optimized in the form of an optmization problem so that the voltage sag index is minimized. The results show that the optimum values result in less voltage deviation.**

***Index Terms*—Markov model, power quality index, STATCOM, voltage sag, wind power**

I. Introduction

Electrical energy consumption is sharply increasing throughout the world. To satisfy the future energy demand, various renewable or green energy sources are being utilized. A modern electric grid prepares the way for renewable generation integration which improves energy security and brings great environmental benefits. To achieve this purpose, some technical studies must be carried out for the electric grid.

Intermittency or variability is defined as 'the state of a power source which is unintentionally stopped or unavailable'. The amount of the power produced by a wind power plant depends on wind speed, air density, turbine characteristics etc. Thus, it is obviously intermittent. On the other hand, the intermittency has a significant effect on the power quality of the electric grid. Therefore, it is essential to evaluate the power quality of the electric grid in presence of wind power generation.

The higher wind power penetration level there is, the more the power quality is affected [1], [2], [3], [4]. To examine the power quality, indices must be defined to form a foundation for measuring negative effects of different disturbances on the electric grid. In the majority of the recent research studies [5], [6], [7], power quality indices in the electric grid with wind power generation based on fixed wind speed have been proposed. Such indices give an instantaneous assessment and do not determine the overall power quality of the electric grid. In [8], [9], especially in [1], probabilistic power quality indices for the electric grid with wind power generation has been introduced. The conventional power quality indices have been combined with the probabilistic nature of wind speed using Markov model analysis [10] in order to provide an overall assessment. The power quality indices concern harmonics, flicker, and voltage sag.

In this paper, the probabilistic power quality indices proposed in [1] have been used to make an overall assessment of the power quality of the electric grid with a wind energy conversion system and a Static synchronous COMpensator (STATCOM). The difference between this paper and [1] is that one STATCOM has been added to the electric grid. The purpose of this paper is to evaluate the probabilistic power quality indices for such an electric grid. Finally, control parameters of the STATCOM have been optimized using an optimization problem in which the voltage sag index is minimized.

This paper is organized as follows: In section II, Markov model analysis for wind speed is explained. Then, in section III, the conventional power quality indices are combined with Markov model analysis to introduce the probabilistic power quality indices. Finally, the paper will end with the results and the optimzation problem in section IV.

II. Wind Speed Analysis Based on Markov Model

Assume that wind speed has variations. The wind speed variations have been shown in Fig. 1. To analyse the wind speed variations based on Markov model, it is necessary to pass through the following stages:

- The wind speed variations must be classified into N classes according to the speed range. The first and second

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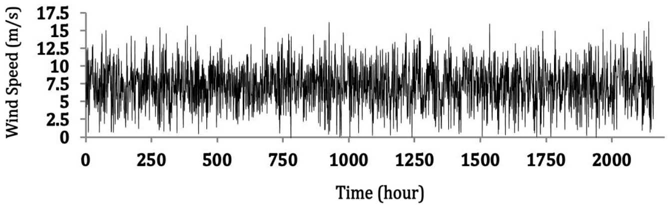

Fig. 1. Wind speed variations

Class	Wind Speed Range	M	P
1	$[0, 4] \cup [25, +\infty]$	313	0.1449
2	[4, 8]	952	0.4407
3	[8, 12]	768	0.3556
4	[12, 15]	118	0.0546
5	[15, 25]	9	0.0042

TABLE I
WIND SPEED CLASSIFICATION ACCORDING TO SPEED RANGE

R_{ij}	1	2	3	4	5
1	53	122	118	18	2
2	157	412	324	52	6
3	81	358	284	44	1
4	21	54	39	4	0
5	1	5	3	0	0

TABLE II
TRANSITION MATRIX

column of Table I suggest the wind speed classes. In this paper, five classes have been selected.

- The vertical vector M must be calculated. M_i is the number of the samples which belong to the ith class. The third column of Table I shows this vertical vector.
- The vertical vector P must be calculated. P_i is the probability of the ith class and is equal to the number of the samples of the ith class divided by the number of all the samples. The last column of Table I shows this vertical vector.
- The matrix R must be calculated. This matrix is called the transition matrix [1], [10]. The size of the transition matrix is $N \times N$. R_{ij} is equal to the number of the samples belonging to the class i whose next samples belong to the class j. Table II illustrates the transition matrix for the wind speed variations shown in Fig. 1.
- The matrix ϕ must be calculated. This matrix is called the transition rate matrix [1], [10]. The size of the transition rate matrix is $N \times N$. ϕ_{ij} is given by:

$$\phi_{ij} = \frac{R_{ij}}{M_i} \tag{1}$$

Table III shows the transition rate matrix for the wind speed variations shown in Fig. 1.

ϕ_{ij}	1	2	3	4	5
1	0.1693	0.3898	0.3770	0.0575	0.0064
2	0.1651	0.4332	0.3407	0.0547	0.0063
3	0.1055	0.4661	0.3698	0.0573	0.0013
4	0.1780	0.4576	0.3305	0.0339	0
5	0.1111	0.5556	0.3333	0	0

TABLE III
TRANSITION RATE MATRIX

State	α	f	d
1	0.1450	0.1204	1.2038
2	0.4405	0.2497	1.7644
3	0.3557	0.2242	1.5868
4	0.0547	0.0528	1.0351
5	0.0042	0.0042	1

TABLE IV
PROBABILITY, FREQUENCY, AND DURATION FOR EACH STATE

- The simultaneous equations (2) to (5) must be solved to find the steady-state probability for each state, α_i.

$$\alpha_1 . \sum_{\substack{j=1 \\ j \neq 1}}^{N} \phi_{1j} = \sum_{\substack{j=1 \\ j \neq 1}}^{N} \alpha_j . \phi_{j1} \tag{2}$$

$$\alpha_2 . \sum_{\substack{j=1 \\ j \neq 2}}^{N} \phi_{2j} = \sum_{\substack{j=2 \\ j \neq 2}}^{N} \alpha_j . \phi_{j2} \tag{3}$$

$$\vdots$$

$$\alpha_N . \sum_{\substack{j=1 \\ j \neq N}}^{N} \phi_{Nj} = \sum_{\substack{j=N \\ j \neq N}}^{N} \alpha_j . \phi_{jN} \tag{4}$$

$$\sum_{i=1}^{N} \alpha_i = 1 \tag{5}$$

- The frequency of each state, f_i, and the duration of each state, d_i, must be calculated as follows:

$$f_i = \alpha_i . \sum_{\substack{j=1 \\ j \neq i}}^{N} \phi_{ij} \tag{6}$$

$$d_i = 1 \Big/ \sum_{\substack{j=1 \\ j \neq i}}^{N} \phi_{ij} \tag{7}$$

Table IV shows the steady-state probability, frequency, and duration of each state. These variables will be used to calculate the probabilistic power quality indices.

The parameters are the same as the parameters given in [1] unless otherwise mentioned.

III. Probabilistic Power Quality Indices

This section introduces the probabilistic power quality indices concerning harmonic, flicker, and voltage sag based on Markov model.

A. Harmonic

The Total Harmonic Distortion (THD) of voltage is expressed as follows: [5]

$$\mathrm{THD}_V = \left[\sum_{h=2}^{40} (U_h)^2 \right]^{0.5} \tag{8}$$

where U_h is calculated according to the following equation:

$$U_h = \frac{V_h}{V_n}. \tag{9}$$

The THD of current is expressed as follows: [5]

$$\mathrm{THD}_I = \left[\sum_{h=2}^{40} (I_h)^2 \right]^{0.5} \tag{10}$$

where U_h is calculated according to the following equation:

$$I_h = \frac{I_h}{I_n}. \tag{11}$$

h denotes the harmonic order and is an integer multiple of the nominal frequency, 60 Hz or 50 Hz. V_h is the amplitude of the harmonic voltage whose order is equal to h. I_h is the amplitude of the harmonic current whose order is equal to h. The probabilistic harmonic voltages are given by: [1]

$$PU_h = \sum_{i=1}^{N} \alpha_i \, U_h. \tag{12}$$

The probabilistic harmonic currents are given by: [1]

$$PI_h = \sum_{i=1}^{N} \alpha_i \, I_h. \tag{13}$$

The probabilistic THD of voltage and the probabilistic THD of current are calculated as follows, respectively: [1]

$$\mathrm{PTHD}_V = \sum_{i=1}^{N} \alpha_i \, \mathrm{THD}_V \tag{14}$$

$$\mathrm{PTHD}_I = \sum_{i=1}^{N} \alpha_i \, \mathrm{THD}_I. \tag{15}$$

B. Voltage Sag

The probabilistic voltage sag is expressed as follows: [1]

$$PV_{\mathrm{sag}} = \sum_{i=1}^{N} \alpha_i \, V_{\mathrm{sag}}. \tag{16}$$

C. Flicker

In [1], [11], the block diagram of the flicker meter has been explained in detail. The instantaneous flicker level is the output of the flicker meter. The simulation time is equal to τ and thus, a useful index in terms of the instantaneous flicker level, IFL, is defined as: [1]

$$IFL_t = \int_0^{\tau} IFL \, dt. \tag{17}$$

The probabilistic flicker level is expressed as follows: [1]

$$\mathrm{PIFL} = \sum_{i=1}^{N} \alpha_i \, IFL_t. \tag{18}$$

IV. Results

Fig. 2 depicts the electric grid studied in this paper which has been implemented and simulated using MATLAB

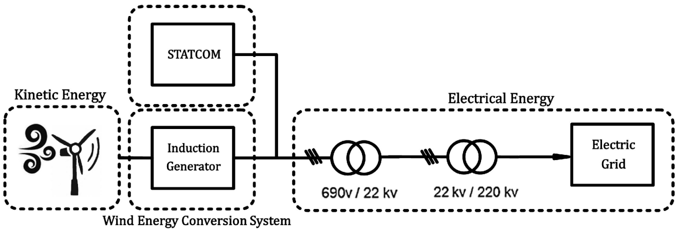

Fig. 2. Electric grid studied in this paper

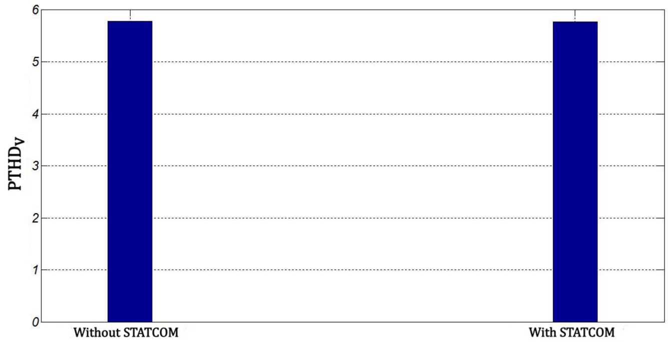

Fig. 3. Probabilistic THD of voltage

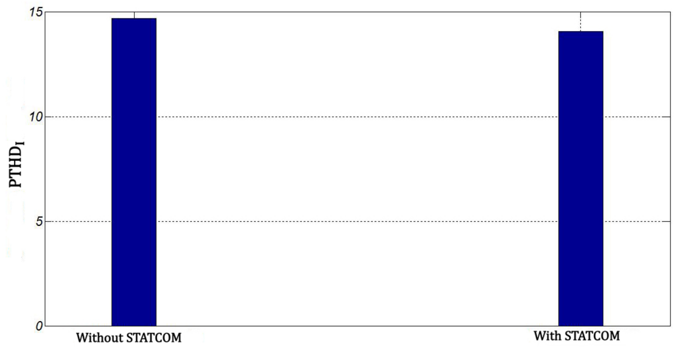

Fig. 4. Probabilistic THD of current

Class		1	2	3	4	5	Probabilistic Index
THD_V		5.7284	5.7413	5.8328	5.9345	6.3455	5.7850
Harmonic voltage order	2nd	9×10^{-4}	1.1×10^{-3}	1.7×10^{-3}	9×10^{-4}	9×10^{-4}	1.3×10^{-3}
	3rd	1.2×10^{-3}	4.2×10^{-3}	1.6×10^{-3}	3.6×10^{-4}	3.2×10^{-4}	2.8×10^{-3}
	4th	2.4×10^{-3}	2.9×10^{-3}	2×10^{-3}	1.9×10^{-3}	2.8×10^{-3}	2.5×10^{-3}
	5th	6.1×10^{-3}	8×10^{-4}	7.6×10^{-3}	1.31×10^{-2}	1.22×10^{-2}	4.7×10^{-3}
THD_I		19.3385	17.5132	10.6705	6.3694	6.3540	14.6881
Harmonic current order	2nd	8.2×10^{-3}	1.39×10^{-2}	7.7×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	1.02×10^{-2}
	3rd	9.1×10^{-3}	2.11×10^{-2}	9.3×10^{-3}	9.1×10^{-3}	6.9×10^{-3}	1.44×10^{-2}
	4th	8.2×10^{-3}	1.39×10^{-2}	7.7×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	7.2×10^{-3}
	5th	1.01×10^{-2}	7.4×10^{-3}	6.7×10^{-3}	2.2×10^{-3}	2×10^{-3}	8.4×10^{-3}
IFL_t		529.57	529.87	515.36	500.96	566.08	523.23
V_{sag}		0.0302	0.0308	0.0352	0.0389	0.0397	0.0328

TABLE V
POWER QUALITY INDICES WHEN STATCOM IS DISCONNECTED.

Class		1	2	3	4	5	Probabilistic Index
THD_V		5.5678	5.5479	6.0794	5.9782	5.5379	5.7633
Harmonic voltage order	2nd	6×10^{-4}	2×10^{-3}	2×10^{-3}	1.1×10^{-3}	1.9×10^{-3}	1.7×10^{-3}
	3rd	2.9×10^{-3}	3.5×10^{-3}	7.8×10^{-3}	3.3×10^{-3}	3×10^{-3}	4.9×10^{-3}
	4th	4×10^{-3}	5.8×10^{-3}	2×10^{-3}	2.9×10^{-3}	3.9×10^{-3}	4×10^{-3}
	5th	3.9×10^{-3}	5.3×10^{-3}	5.5×10^{-3}	1.15×10^{-2}	7.6×10^{-3}	5.5×10^{-3}
THD_I		18.5047	16.7910	10.1540	6.1411	5.3791	14.0489
Harmonic current order	2nd	1.07×10^{-2}	4.8×10^{-3}	3.9×10^{-3}	2.5×10^{-3}	4×10^{-3}	5.2×10^{-3}
	3rd	1.83×10^{-2}	5.1×10^{-3}	1.22×10^{-2}	5.4×10^{-3}	1.1×10^{-3}	9.5×10^{-3}
	4th	1.53×10^{-2}	2.15×10^{-2}	3.5×10^{-3}	3×10^{-3}	3.1×10^{-3}	1.31×10^{-2}
	5th	1.18×10^{-2}	1.65×10^{-2}	1.88×10^{-2}	1.38×10^{-2}	1.15×10^{-2}	1.65×10^{-2}
IFL_t		22.93	26.12	28.23	33.92	37.81	26.88
V_{sag}		0.0163	0.0163	0.0169	0.0175	0.0175	1.66×10^{-2}

TABLE VI
POWER QUALITY INDICES WHEN STATCOM IS CONNECTED.

software. It consists of one STATCOM and one wind energy conversion system equipped with an induction generator. Table V and Table VI show the values of the power quality indices for the electric grid when the STATCOM is disconnceted and connected, respectively. The wind speed has variations according to the variations shown in Fig. 1. Table IV has been used to calculate the probabilistic power quality indices in Table V and Table VI. The results have been also presented by Fig. 3 to Fig. 6 which are in agreement with the values given in Table V and Table VI. As shown in Fig. 3 to Fig. 6, there is no considerable difference in PTHD when the STATCOM is connected and when it is disconnected, while the probabilistic flicker level and the probabilistic voltage sag are significantly improved when it is connected to the electric grid.

Fig. 5. Probabilistic flicker level

Table VII shows the parameter values of the controllers of the STATCOM. They have been optimized using an optimization problem in which the voltage sag index is minimized. Fig. 7 indicates that the voltage deviation has decreased when the optimum values of the parameters are used. In fact, the best values for the parameters have been found by the optimization algorithm so that the voltage sag or the voltage deviation gets the minimum value.

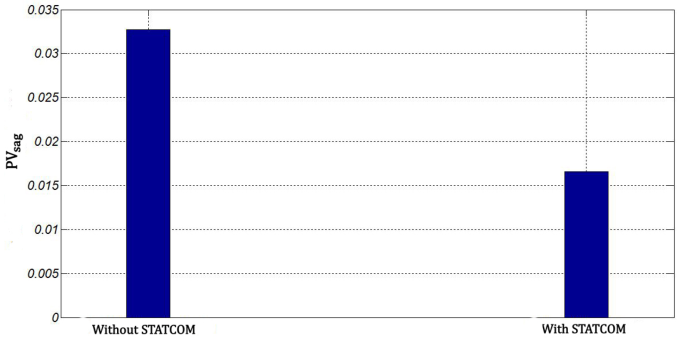

Fig. 6. Probabilistic voltage sag

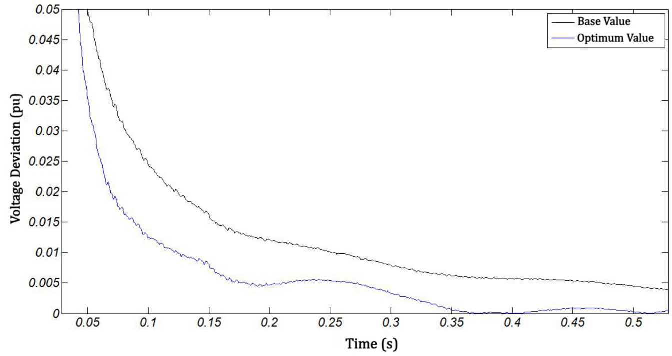

Fig. 7. Voltage deviation for two different parameter values of the controllers of the STATCOM

V. Conclusion

The conventional power quality indices were combined with the probabilistic nature of the wind speed using Markov model analysis in order to make an overall assessment of the power quality of the electric grid in presence of the wind energy conversion system and the STATCOM. The purpose of this paper was to evaluate the probabilistic power quality indices for such an electric grid. Figures and Tables presented the values of the probabilistic power quality indices and revealed that there is no considerable difference in PTHD when the STATCOM is connected and when it is not connected, while the probabilistic flicker level and the probabilistic voltage sag are significantly improved when it is connected to the electric grid. Finally, control parameters of the STATCOM have been optimized using an optimization problem in which the voltage sag index is minimized. The results revealed that the optimum values result in less voltage deviation.

	$k_{i_{var}}$	$k_{i_{vol}}$	k_p	k_i	V_{sag}
Base Value	0.05	20	0.55	2500	0.0169
Optimum Value	0.8636	47.0149	0.5396	730.87	0.0127

TABLE VII
Parameter Values of the Controllers of the STATCOM

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