Voltage Control Settings to Increase Wind Power based on Probabilistic Load Flow

N.D. Hatziargyriou, *Senior Member, IEEE,* T.S. Karakatsanis, *Member, IEEE,* M.I. Lorentzou

***Abstract*— In this paper network constrained setting of voltage control variables based on probabilistic load flow techniques is presented. The method determines constraint violations for a whole planning period together with the probability of each violation and leads to the satisfaction of these constraints with a minimum number of control corrective actions in a desired order. The method is applied to define fixed positions of tap-changers and reactive compensation capacitors for voltage control of a realistic study case network with increased wind power penetration. Results show that the proposed method can be effectively applied within the available control means for the limitation of voltages within desired limits at all load buses for various degrees of wind power penetration.**

***Index Terms*— Distributed Generation, Probabilistic Load Flow, Constrained Load Flow, Sensitivity Analysis, Voltage Control**

I. INTRODUCTION

Connection rules and criteria applied nowadays to the penetration of Distributed Generation (DG) are based on deterministic steady state analysis. In general, the approach adopted is to ensure that any new generation does not reduce the quality of supply offered to other customers and to consider the generators as “negative load”. As the network operator has no control over the dispersed generator all decisions concerning the network are made considering the worst possible conditions of the generation for any set of network conditions. Hence at minimum load, maximum generation and at maximum load, minimum generation is assumed. Using deterministic load flow analysis however, it is not possible to assess objectively how often and where overvoltages or undervoltages occur in the network during a whole study period, since it is based on selected combinations of consumer loads and DG power production. As shown in [1] this can be achieved by applying probabilistic techniques like the probabilistic load flow (PLF) or the Monte Carlo simulation. PLF requires modeling of loads and power productions as probability density functions and provides the complete spectrum of all probable values of the bus voltages and power flows in the study period with their respective probabilities taking into account generation and load uncertainties and correlations and topological variations. The probabilistic load flow was analytically formulated since more than 25 years in [2, 3], and further developed and applied in [4-10]. This paper investigates the application of PLF techniques to the adjustment of voltage control settings in order to allow increased penetration of wind power in weak parts of a network. A method for network constrained setting of control variables based on PLF was presented in [11] and applied to distribution voltage control [11], voltage collapse analysis [12] and generator reactive power optimization [14]. Accordingly, once the probabilities of constraint violations are obtained from PLF, an iterative method is employed which provides adjustments of the control variables based on sensitivity analysis of the constrained variables with respect to the control variables, while maintaining constraints already satisfied within limits. The basic advantage of the method is that it provides increased flexibility in the selection of the control variables to be varied. Thus, application of the proposed method can lead to satisfaction of constraints with a minimum number of control variables adjusted or corrective actions on control devices in a desired order.

In this paper the above constrained probabilistic load flow (CPLF) method is applied to the setting of fixed positions of tap-changers and reactive compensation devices in order to increase wind power penetration in a weak part of the Hellenic power system that presents high interest for wind farm installations. The results show that the proposed method can be effectively applied within the available control means for the limitation of voltages within desired limits at all buses for the whole planning period considered even if high wind power penetration is allowed.

II. CONSTRAINED PROBABILISTIC LOAD FLOW

A. *Fundamentals of Probabilistic Load Flow*

The load flow problem can be expressed mathematically by two sets of non-linear equations:

Manuscript received February 23, 2004. (Write the date on which you submitted your paper for review.) This work was supported in part by the European Commission DG Research, DISPOWER project (ENK5-CT-2001-00522).

N. D. Hatziargyriou is Professor at the Electrical Engineering Department of NTUA, Greece, (e-mail: nh@power.ece.ntua.gr)

T. Karakatsanis is Ass. Professor at the Electrical Engineering Department of the University of Thrace

M. I .Lorentzou is with the Hellenic Transmission System, Operator, Athens 17122, GREECE (e-mail: mlorentzou@desmie.gr)

$$Y = g(X,U) \qquad Z = h(X,U) \tag{1}$$

Y the input, Z the output, X the state and U the control vector. The input vector Y comprises nodal power injections, the state vector X voltage magnitudes and angles, the output vector Z power flows, generation reactive injections, etc. and the control vector U the control means of the system like transformer taps, reactive compensation, voltages and active production at PV buses, etc. Probabilistic modelling of production takes into account generator outages and wind power uncertainties, while probabilistic distributions of demands are obtained from load time series analysis. Thus, PLF provides the complete spectrum of all probable values of state and output variables, each value with its respective probability taking into account generating unit unavailabilities, load uncertainties, dispatching criteria effects and topological variations.

Most of the techniques developed for PLF are based on the linearization of (1) around an expected operating point defined by Xo, Uo.

$$X = X_o + J^{-1} Y \tag{2}$$

where $J = \dfrac{\vartheta g(X,U)}{\vartheta X}$ **(3)**

is the Jacobian of the system.

After linearization, the output vector elements are expressed as linear functions of the nodal active and reactive power injections, defined by probability density functions, as:

$$Z = Z_o + A^T Y \tag{4}$$

The weighting coefficients of these linear functions are the sensitivity coefficients obtained from matrix:

$$A^T = \left(\frac{\vartheta h(X,U)}{\vartheta X}\right)^T . \left(\frac{\vartheta g(X,U)}{\vartheta X}\right)^{-1} \tag{5}$$

Convolution techniques and the Fast Fourier Transform are used to deduce the unknown probability functions of the state and output variables.

The objective of constrained load flow is to maintain some or all the elements of X and Z within given operating limits. Such constraints are normally set to voltage magnitudes of load buses, active and reactive powers injected at generator buses, apparent power flows on lines, etc. Operation within constraints can be achieved by appropriate variation of the control variables U, which are also constrained, i.e. physical limits constrain the variation of transformer taps, shunt compensation devices, voltages at PV buses, etc.

In the general case, an unconstrained load flow solution would result in a number of variables in X and Z falling outside their permissible variation interval. In order to limit those variables, action on the control variables is required. This action can be based on the results of sensitivity analysis, i.e. calculation of the sensitivity factors of every variable which needs to be constrained with respect to the control variables.

B. *Sensitivity Analysis*

Consider a network of n buses and m control variables and

$$W = f(X,U) \tag{6}$$

the set of non-linear functions of the r variables to be constrained. f includes a selected number of the functions denoted by g and h in (1). Linearization of f at a given operating point defined by U=Uo and X=Xo gives:

$$f(X,U) = f(X_0, U_0) + \sum_{j=1}^{m} \frac{df(X,U)}{d\,u_j} \Delta u_j \tag{7}$$

Sensitivity analysis assuming $\Delta Y = 0$, provides:

$$\frac{df(X,U)}{du_j} = \frac{\vartheta f(X,U)}{\vartheta u_j} - \left[\frac{\vartheta f(X,U)}{\vartheta X}\right]^T \left[\frac{\vartheta g(X,U)}{\vartheta X}\right]^{-1} \left[\frac{\vartheta g(X,U)}{\vartheta u_j}\right] \tag{8}$$

or

$$C = D - A^T B \tag{9}$$

Matrix C has dimension r times m, where r the number of variables to be constrained and m the number of the control variables and consists of the elements:

$$c_{ij} = \frac{dw_i}{du_j} = \frac{df_i(X,U)}{du_j} \tag{10}$$

A^T is the sensitivity matrix (5) obtained during calculation of the probability density function of f and needs to be recalculated at each iteration based on the updated elements of the Jacobian. Thus, calculation of vector C requires only calculation of D which depends on function f and on the control variables u_j, and the calculation of B which is independent of f and depends only on control variables u_j. Suppose now that $f_{pi}(X,U)$ is the probability density function of the random variable w_i that has to be constrained and $fmin_i$, $fmax_i$ the extreme values of the probability density function obtained from PLF, as described above. Given the upper and lower limit of the interval where this variable is allowed to vary, $wmin_i$ and $wmax_i$ respectively, we call:

$$\begin{aligned}\Delta Wmax_i &= fmax_i - wmax_i \\ \Delta Wmin_i &= wmin_i - fmin_i\end{aligned} \qquad \textbf{(11)}$$

If $\Delta Wmax_i > 0$ or $\Delta Wmin_i > 0$, the upper or lower limit of w_i respectively, is not satisfied. In this case, one or more of the control variables must be modified by Δu_j, so that:

$$\Delta w_i \ge \sum_{j=1}^{m} c_{ij} \Delta u_j \qquad \textbf{(10)}$$

Change of any control variable u_j however, can be achieved only within predefined limits and in addition, it affects all variables including the ones which already are within limits. For changes around the linearisation point, this effect is proportional to the respective sensitivity factor and can result in violations of constraints that were previously satisfied. For this reason, the variation of each control variable is confined within limits updated at each iteration, in such a way that all constraints are taken into account. These include constraints already satisfied and control variable limits, as described in [11].

The basic advantage of the sensitivity analysis is that it provides great flexibility in the selection of the control variables to be used. Thus, one possible solution is to move the control variable which has the maximum effect on the worst violated constraint. If variation of one variable is not sufficient to alleviate the violation, bi-variate or multi-variate control in decreasing order of the appropriate sensitivity factors can be considered. This approach can be combined with corrective actions taking into account a predetermined priority order amongst the control variables, e.g. voltages at generator buses can be varied first followed by action on transformer taps, compensation devices, redistribution of active power and last by load shedding. In addition, continuous variation of the control variables or variation in discrete steps can be considered.

III. STUDY CASE

IV. The study case network represents the island of Evia near Attica interconnected to the mainland Hellenic System, as shown in Figure 1. This area presents excellent wind power potential and as a result a large number of applications by private investors corresponding to several GWs of installed wind power capacity have been submitted. The production system comprises 2x140 MW thermal stations modeled as conventional synchronous generators and 19 wind farms of total 200 MW located in 5 areas, represented by aggregate single machines. The transmission system comprises 150 kV transmission lines and 6 HV/MV substations. 2 aggregate local loads are also considered. Overall the system model comprises 58 buses, 30 transmission lines, 26 transformers, 2 generators and 19 wind turbine generators.

For PLF analysis, wind power production is modeled as a discrete distribution with 40 impulses corresponding to the Weibull distribution. For the loads normal, and for the thermal production binomial distributions respectively, are assumed. A fixed system topology is considered. It can be easily seen by deterministic load flow analysis that area 6 (Myrtia) is the weakest part of the system assuming very low voltage profiles. This is due to the large amount of wind power generation installed.

For the CPLF analysis voltages at all load buses (55 in total) are considered as the constrained variables with upper and lower limits equal to 0.85 p.u. and 1.15 p.u., respectively.

33 Control variables are considered:

- voltages at the 2 production buses in Aliveri with upper and lower limits 0.950 to 1.050 p.u.
- 27 transformer taps between 0.85 and 1.15 p.u., step 0.01,
- reactive power compensation at 4 buses (6, 9, 15 and 26), with upper limit 0.2 p.u. and step 0.050 p.u..

At a first priority, transformer taps and generator voltages are varied, at a second priority reactive compensation is used.

Three cases are examined next, corresponding to 50%, 75% and 100% of the total wind power installed in the Myrtia area. For each of the above cases, the effect of corrective control actions is shown. Results of corrective control actions for each case are used as initial conditions for application of control in the next case.

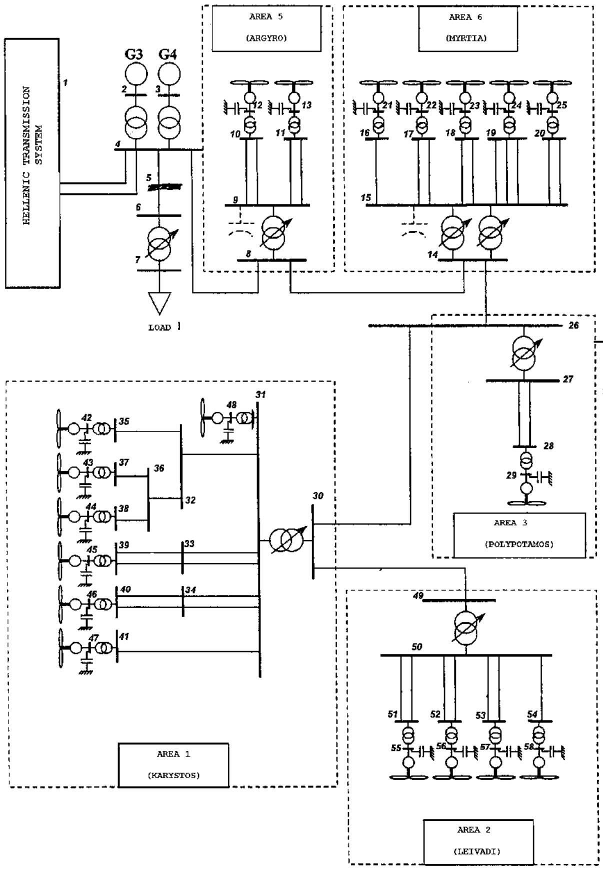

Fig. 1: Single-Line Diagram of the Evia study case network

A. *Case i: 50% of wind power generation in Myrtia*

PLF shows that the lower limits of the following three buses (7, 30 and 49) are mainly violated (figure 2), while there is a small probability 0.2% that three further bus voltages are lower than accepted. In particular the voltage at MHLAKI_L has an expected voltage of 0.779 p.u. with 6.79% standard deviation. The 99% min value is 0.668 p.u. and the 99% max value 0.891p.u. The cumulative probability of violating the lower limit of 0.85 p.u. is 90%. For the other two buses at LEIVADI_H2 and KARYSTOS_H1 the respective expected values are 0.866 p.u. and 0,862 p.u. and the cumulative probabilities of lower limit violations 25% and 31%, respectively.

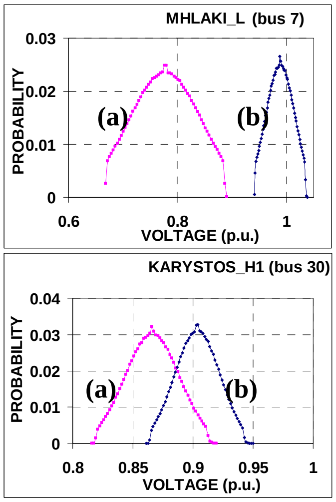

Fig. 2: 50% wind power penetration. Probability Density Function of the Voltage magnitude (a): without corrective control, and, (b) after corrective control

In this case the slack bus absorbs active power equal to 145.34MW and injects reactive power equal to 184.76MVAr. Application of CPLF provides the following corrective control actions:

- Tap at 6-7 transformer lowered from 1.013p.u. to 0.903p.u.
- Tap at 2-4 transformer lowered from 1.05p.u. to 0.99p.u.
- Voltages at buses 2 and 3 raised from 1.00 to 1.02 p.u.

Corrective control leads all bus voltages within acceptable limits, as shown in Figure 2. The expected absorption of active power at the slack does not change significantly (148.07MW) while the reactive generation is reduced to half (97.29MVAr).

B. *Case ii: 50% of wind power generation in Myrtia*

PLF shows that the lower bus voltage limits at 18 buses are now violated. One of the worst violations occurs again at bus 7 (MHLAKI_L) with expected voltage of 0.768 p.u., 7.81% standard deviation, 99% min value 0.639 p.u., 99% max value 0.901p.u. and cumulative probability of violating voltage lower limit 91%. The cumulative probabilities of lower voltage limit violations at the other buses ranges from 35% to 95%. It is obvious that the system is close to its voltage collapse limit. The expected slack bus power is -162.20MW (absorption) and 205.69MVAr (injection).

Application of the control settings defined in the previous case(i) improves significantly the voltage profiles. The number of buses where the lower limit of voltage is violated reduces to 8, with a lower probability. The expected value of the active power absorption at the slack bus becomes 165.63MW, while reactive power injected is reduced to half, 114.40MVAr.

Furthermore, the previous control settings are used as initial values of the CPLF algorithm. The following corrective control actions are obtained:

- Tap at one of the 14-15 transformer lowered from 0.992p.u. to 0.972 p.u.
- Tap at the other 14-15 transformer lowered from 0.925p.u. to 0.895 p.u.
- Reactive power compensation at bus 15 equal to 0.15 p.u.

As a result, none of the bus voltages violates its limits. The expected value of slack bus active absorption remains 167.20MW, while reactive power injection is reduced to 84.24MVAr. In figure 3, the probability density functions of the voltage magnitude before and after corrective control actions at three buses of the system, are shown.

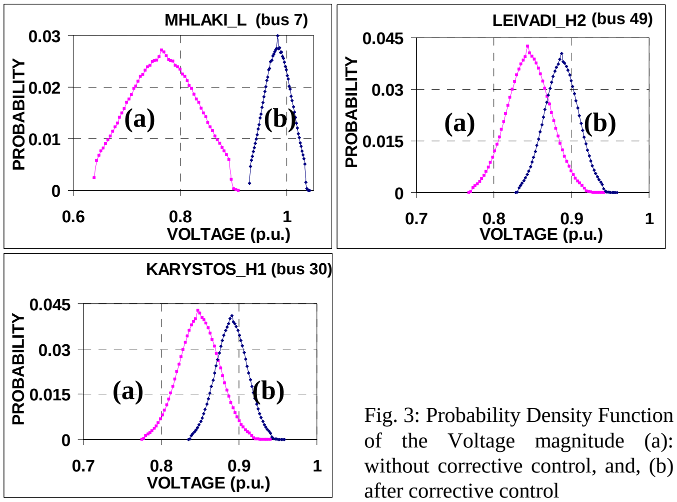

Fig. 3: Probability Density Function of the Voltage magnitude (a): without corrective control, and, (b) after corrective control

C. *Case iii: 100% of wind power generation at Myrtia*

In this case, PLF does not converge. Using the control settings obtained in Case ii leads to voltage limit violations at 13 buses (bus 15 with prob. 20%, buses 16-20 with prob. 20%, buses 21-25 with prob. 60%, bus 30 with prob. 4.4% and bus 49 with prob. 8%). The increase in the standard deviation of the pdfs and the effect of the Weibull distribution in the voltage pdf, as wind power penetration increases, is obvious. The slack bus active and reactive injections are -183.32MW and 124.37MVAr, correspondingly.

Application of the CPLF algorithm leads to the full use of reactive compensation at bus15 (0.20 p.u)., and reduction of the tap settings at Myrtia WP62 (bus 22) from 0.995p.u. to 0.985 p.u. and of the 6-7 transformer from 1.05p.u. to 1.02 p.u. These corrective control actions provide bus voltages that satisfy fully lower voltage limits, while there is a small 3% probability of violating the upper 1.150 p.u.limit at buses 55, 56, 57, 58. The expected values of power at the slack bus are -184.73MW for active and 93.40MVAr for reactive injection. In figure 4, the probability density functions of the voltage magnitudes with the initial control settings and after corrective control actions at three buses of the system, are shown.

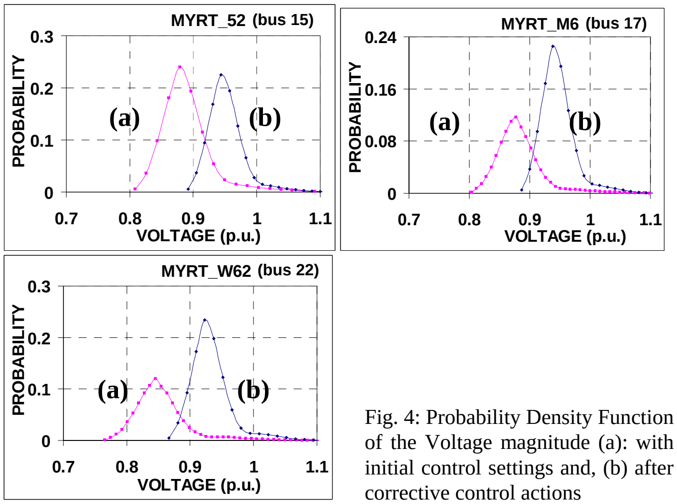

Fig. 4: Probability Density Function of the Voltage magnitude (a): with initial control settings and, (b) after corrective control actions

V. CONCLUSIONS

In this paper constrained setting of voltage control variables based on the results of probabilistic load flow and sensitivity analysis is applied in order to increase wind power penetration in a weak system. In particular, the method is applied to the setting of taps and reactive compensation devices, so that voltage limits at the load buses of a weak part of the Hellenic power system with various degrees of wind power penetration are satisfied. The results show that the proposed method can be effectively applied within the available control means for the limitation of voltages within desired limits for the whole planning period considered.

ACKNOWLEDGEMENT

The financial contribution of the European Commission, DG Research of the DISPOWER project (ENK5-CT-2001-00522) is gratefully acknowledged.

REFERENCES

[1] N. Hatziargyriou, T. Karakatsanis, G. Strbac, “Connection Criteria for Renewable Generation Based on Probabilistic Analysis”, 6th PMAPS’2000, Sept. 25-28 2000, Funchal, Madeira, Portugal.

[2] B. Borkowska, "Probabilistic Loadflow", IEEE Trans. on PAS, Vol. PAS-93, No. 3, May/June 1974, pp. 752-759.

[3] R.N. Allan, B. Borkowska, C.H. Grigg, "Probabilistic Analysis of Power Flows", Proc. IEE, Vol. 121, No. 12, pp. 1551-1555, Dec. 1974.

[4] R.N. Allan, C.H. Grigg, D.A. Newey, R.F. Simmons, "Probabilistic Load Flow Techniques Extended and Applied to Operational Decision Making", IEE Proc., Vol. 123, No. 12, Dec. 1976, pp. 1317-1324.

[5] R.N. Allan, M.R.G. Al-Shakarchi, "Linear Dependence between Nodal Powers in Probabilistic AC Load Flow", Proc. IEE, Vol. 124, No. 6, June 1977.

[6] R.N. Allan, A.M. Leite da Silva, R.C. Burchett, "Evaluation Methods and Accuracy in Probabilistic Load Flow Solutions", IEEE Trans on PAS, Vol. PAS 100, No. 5, May 1981, pp. 2539-2546.

[7] R.N. Allan, A.M. Leite da Silva, "Probabilistic Load Flow Using Multilinearisations", IEE Proc., Vol. 128, Pt. C, No. 5, September 1981, pp. 280-287.

[8] A.M. Leite da Silva, R.N. Allan, S.M. Soares, V.L. Arienti, "Probabilistic Load Flow Considering Network Outages",IEE Proc., Pt C, Vol.123, May 1985, pp.139-145.

[9] A.M. Leite da Silva, V.L. Arienti, "Probabilistic Load Flow by a Multilinear Simulation Algorithm", IEEE Proc., Vol. 137, Pt. C, No. 4, July 1990, pp. 276-282.

[10] A.M. Leite da Silva, S.M.P. Ribeiro, V.L. Arienti, R.N. Allan, M.B. Do Coutto Filho, "Probabilistic Load Flow Techniques Applied to Power System Expansion Planning", IEEE Trans. on Power Systems, Vol. 5, Nr. 4, Nov. 1990, pp. 1047-1053.

[11] T.S. Karakatsanis, N.D. Hatziargyriou, "Probabilistic Constrained Load Flow Based on Sensitivity Analysis", IEEE Trans. on Power Systems, Vol. 9, Nr. 4, Nov. 1994.

[12] N.D. Hatziargyriou, T.S. Karakatsanis, “Distribution System Voltage and Reactive Power Control Based on Probabilistic Load Flow Analysis”, IEE Proc. Generation, Transmission and Distribution, Vol. 144, No. 4, July 1997, pp. 363-369.

[13] N.D. Hatziargyriou, T.S. Karakatsanis, “Probabilistic Load Flow for Assessment of Voltage Instability”, IEE Proc. Generation, Transmission and Distribution, Vol. 145, No. 2, March 1998, pp. 196-202.

[14] “Probabilistic Constrained Load Flow for Optimizing Generator Reactive Power Resources”, N.D. Hatziargyriou, T.S. Karakatsanis, IEEE Trans. on Power Systems, Vol. 15, Nr. 2, May 2000, pp. 687-693.