ADVANCED STOCHASTIC ANALYSIS OF MASSIVE DG PENETRATION —A VOLTAGE QUALITY CASE STUDY

Liang TAO
Siemens AG – Germany
liang.tao@siemens.com

Michael MUELLER
Siemens AG – Germany
michael.mlmr.mueller@siemens.com

Christine SCHWAEGERL
Siemens AG – Germany
christine.schwaegerl@siemens.com

ABSTRACT

This paper demonstrates why and how a stochastic load flow method based on sequential Monte Carlo simulation is applied to the voltage quality analysis of an existing medium voltage network with very high penetration of DG (distributed generation) units. Simulation results exhibit that oversized DG and large R/X ratio of distribution lines could lead to voltage quality issues that cannot be simply solved by traditional control measures such as on-load transformer tap changer (OLTC) or reactive power compensation techniques. Both preventive and remedial solutions to this problem are discussed in consequence.

INTRODUCTION

Due to rising environmental concerns and supporting regulatory and legislative conditions, an increasing number of dispersed generation (DG) units including renewable energy resources (RES) and combined heat and power plants (CHP) are connected to the power grid located at distribution level. Under a general lack of DG interconnection and operation guidelines, large shares of uncontrolled RES units could create various technical problems [1] beyond the capacity of traditional analysis and control routines.

In scope of this paper, stochastic simulations and analysis are performed to illustrate this issue via the voltage quality case study for a German 20kV distribution network with 18 feeders (Figure 1). All feeder couplings are assumed to be closed as it generally should lead to better voltage qualities in comparison with alternative open-ring configurations.

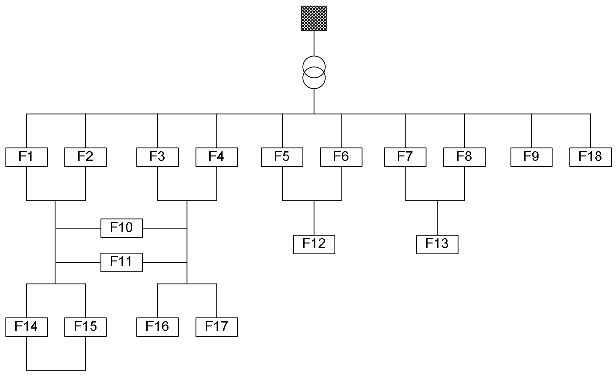

Figure 1: Feeder-wise Topology Definition of Test Network

Among the labelled feeders, F9, F12, F13, F16, and F17 are wind farms while other feeders normally consist of both loads and different RES units such as wind turbines (WT), photovoltaic units (PV), biomass generators (Bio) and small hydro plants (Hydro). The network is characterized by extremely high wind power infeed and limited PV and biomass penetration in comparison (hydro proportion is negligibly small) (Figure 2).

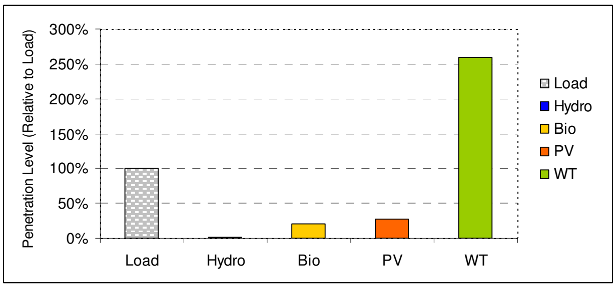

Figure 2: Penetration Levels of Different RES Units

STOCHASTIC ANALYSIS — WHY AND HOW

Traditional deterministic network analysis tries to evaluate DG impact by calculating worst case scenarios (maximum load and minimum generation and vice versa), which is supposed to be sufficient for covering all potential operating states to determine upper and lower boundaries of different network variables. However, in reality this approach often overestimates or underestimates boundary operating states as it ignores two important factors:

1) Simultaneity between loads and different DG units;
2) Inter-correlation caused by meshed feeder topologies.

A good illustration of this problem can be found in Figure 3.

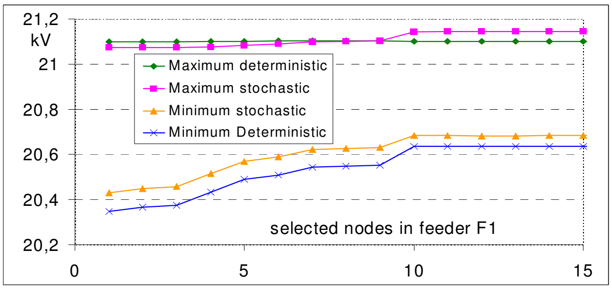

Figure 3: Comparison of Selected Nodal Voltage Bands in F1 Calculated with Deterministic and Stochastic Methods

Figure 3 shows that the deterministic approach could easily lead to pessimistic or optimistic estimation of voltage and other network variables, which, in terms of network planning and operation, will eventually translate into costly device over-dimensioning or dangerous underestimation of extreme operating states. Therefore stochastic analysis turns out to be a comparatively more accurate model of reality for distribution networks with heavy DG penetration.

In scope of this paper, the study focuses on steady state voltage variations; network performance is evaluated with stochastic load flow (sequential Monte Carlo simulation). A considerable amount of work (e.g. [2], [3], [4]) has already been done on probabilistic load flow with RES units, most of which adopt analytical methods to minimize computation requirement. However, analytical solutions to the stochastic load flow problem have not yet been able to fully decouple interdependencies between varied time series data [5], thus a stochastic load flow method based on sequential Monte Carlo simulation is applied in this paper.

Based on field measurement data, time-series generation profiles of loads, wind turbines, small hydro plants, photovoltaic units and biomass generators can be simulated from varied stochastic models (e.g. Markov chain for wind turbine etc.) for stochastic load flow. A collection of sample weekly curves is shown in Figure 4.

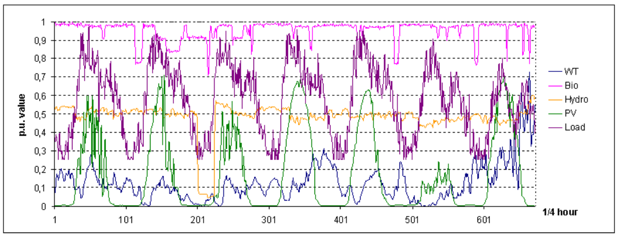

Figure 4: Sample Weekly Load and Generation Curves

Simulations with uncontrolled DG (zero reactive power output) have shown that voltage bands at many remote nodes expand significantly when compared to the original network with no DG penetration. To facilitate illustration, a worst supply point (WSP) with highest voltage variation is chosen to examine this effect, which is shown by probabilistic voltage density functions in Figure 5.

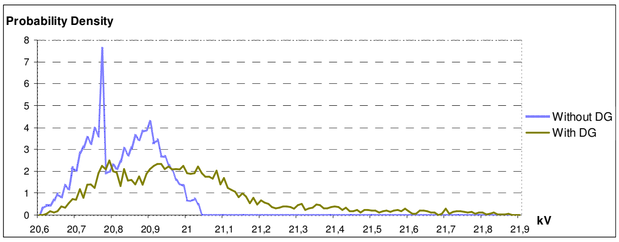

Figure 5: Influence of Uncontrolled DG on WSP Voltage

IMPACT OF ON-LOAD TAP CHANGER

Voltage peaks at WSP (and similar nodes) occur mainly during high wind production, which is obviously a direct consequence of disproportional WT penetration (shown in Figure 2). This unconventional voltage quality issue poses a serious challenge to existing control measures such as on-load tap changer (OLTC).

The network is dominated by urban loads and a considerable proportion of cables (65%), which makes shunt capacitors or other remote voltage support measures unnecessary even in the absence of DG units. This means OLTC for infeed transformer is the only existing voltage control measure. No line drop compensation is assumed to be in effect, thus the OLTC will attempt to regulate secondary voltage (relative value) of infeed transformer around 104% with ±1% error — this set point is not lowered (as suggested by [6]) after DG penetration so as to facilitate comparison.

In order to illustrate the effect of OLTC on the network, a simplified network with equivalents of single transformer, line, load, and DG elements shown by Figure 6 can be used.

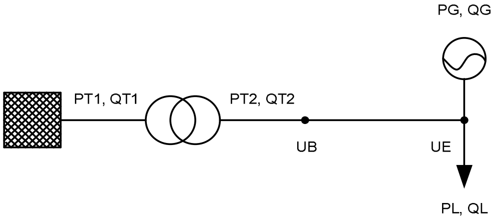

Figure 6: Simplified Single-Element Network

Voltage drop or rise in a line can be estimated by the equation $dU \cong (RP + XQ)/U$; similarly the same equation can be applied to the series R/X components of a transformer by ignoring parallel impedances (note that the obtained voltage difference should apply to secondary side of transformer). Considering the fact that average series R/X ratios of lines and transformers in test network are respectively around 1.5 and 0.03, voltage differences across a line can be seen as influenced by both active and reactive power flow, while output voltage of infeed transformer is almost solely determined by reactive power flow.

Now consider a moment of peak wind production with active power output 3 times larger than load demand, the reversed active power flow will cause voltage rise across the line even under heavy reactive power compensation (due to large R/X ratio). Transformer response to this phenomenon will be highly dependent on reactive power flow while largely ignoring active power. This means in the simplified network, reactive power from DG could partially change voltage rise in the line and almost totally determine voltage rise or drop magnitude at secondary side of transformer.

In Figure 7, network voltages (UB and UE) under off-load and on-load tap changer (TC) operations are compared for three levels of DG reactive power output: maximum consumption, zero output, and maximum generation. The comparison of UE value after OLTC operation indicates that using DG units to consume reactive power during peak active power production helps to relieve voltage stresses.

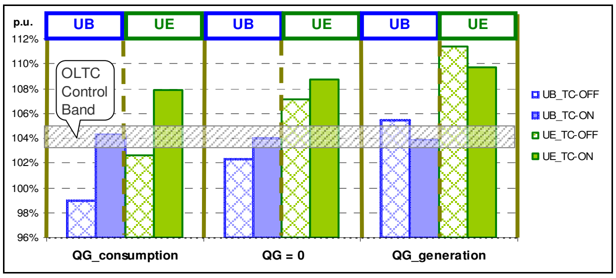

Figure 7: UB and UE Values under Varied Control Modes

However, one important fact must be observed from Figure 7: the use of OLTC does not influence voltage rise in the line. Thus by adjusting UB voltage within control band via OLTC, voltages of remote nodes (such as UE) could deteriorate in consequence if DG units are not controlled properly. This means OLTC itself is no longer a sufficient measure for regulating DG-penetrated network.

CONTROL OF DG REACTIVE POWER

Active control of DG units' reactive power output is needed in addition to OLTC to cope with voltage quality issues caused by high RES penetration. With the application of power electronic interfaces, DG units based on both conventional [6] and new RES [7] technologies can be approximately seen as fully controllable in terms of reactive power output.

Due to high intermittency of RES active power output, the task of adjusting DG reactive power to reduce voltage fluctuation requires real-time control implementation. Two applicable control options exist so far: centralized control based on optimal load flow calculation and distributed control of individual DG units [8]. The later option is applied for the simulations of the network as it tends to be comparatively easier and cheaper to implement in reality.

Stochastic load flow calculations are performed for three potential scenarios (first two scenarios proposed by [9]):

(1) Constant instantaneous reactive power:

$$Q(t)/Q_N = -1$$

(2) Constant instantaneous power factor:

$$Q(t)/Q_N = -P(t)/P_N$$

(3) Hybrid reactive power control:

$$Q(t)/Q_N = 1 - 2 * P(t)/P_N$$

These three control scenarios are illustrated by Figure 8, in which the capability region of a DG is simplified into a square for convenience of calculation (i.e. ignore apparent power limit). Obviously all three scenarios are based on linear P-Q correlations and they all force DG to consume maximum reactive power during maximum active power production so as to minimize instantaneous voltage rise effect across lines. Their difference lies in the slope rate of P-Q curve.

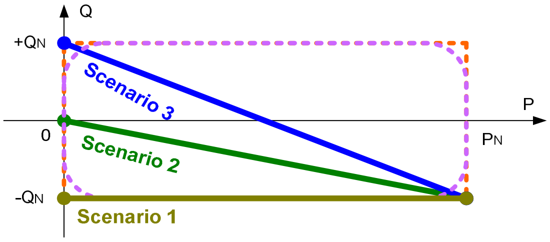

Figure 8: Three Potential Reactive Power Control Scenarios

By assuming reactive power output of all DG units in the network to be controllable between leading power factor of 0.95 and lagging power of 0.95, stochastic load flows are performed for all three scenarios. The probability density curves of WSP voltage are drawn in Figure 9. Scenario 3 enables minimum voltage fluctuation at WSP (smaller voltage band), but it also leads to a higher average voltage.

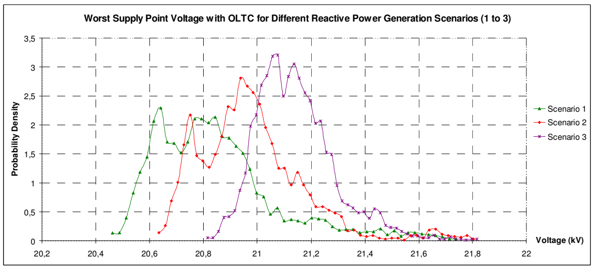

Figure 9: WSP Voltage Curves under 3 Different Scenarios

Performance by scenario 2 is drastically improved under high DG reactive power output capacity (Figure 10). However, such high reactive powers lead to massive overloading of devices.

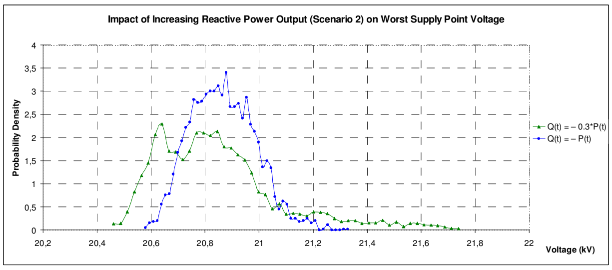

Figure 10: Expanded Scenario 2 with Higher Q/P Ratio

CONCLUSION AND FURTHER OPTIONS

In this paper the voltage quality problem of a test network with high RES penetration is examined under a stochastic modelling environment. Simulations indicate that control of DG reactive power output is needed in addition to OLTC for alleviating voltage fluctuations. One major obstacle encountered in this study is the large amount of reversed active power flow in the network during peak RES production, which contributes significantly to voltage rises along various feeders and cannot be sufficiently mitigated via reactive power compensation.

In comparison with reactive power control schemes discussed so far, a much more effective measure of reducing voltage fluctuation in networks with high (line) R/X ratios is direct manipulation of active power flow. Possible solutions include dispatching of DG (including RES) units [10][11] as well as utilization of storage components [12]. However, both approaches rely heavily on effective forecasting of intermittent RES output, which is widely recognized as a difficult task already by itself.

Another implication of this study is the source of voltage fluctuation problem in test network—oversized RES penetration in a lighted-loaded medium voltage network. With a more coordinated planning of DG interconnection, similar problems can be easily avoided by allocating DG units in a more dispersed and balanced fashion among loaded substations. In such attempts of optimizing technical and economic performances of DG-penetrated networks, stochastic analysis will undoubtedly play a more and more vital role in the coming future.

ACKNOWLEDGMENTS

This paper is inspired by the technical consulting service performed for a real-life medium voltage network of E.ON. Mitte AG (Germany), to which the authors are grateful for its consent of publication. The idea as well as the method for analysis applied in this study was developed within the EU research project ‘EU-DEEP’ (FP6 Project: SES6-CT-2003-503516), which provides partial funding support that the authors kindly acknowledge.

REFERENCES

[1] Philip P. Barker, Robert W. de Mello, 2000, *”Determining the Impact of Distributed Generation on Power Systems: Part 1 – Radial Distribution Systems”*, Power Engineering Society Summer Meeting, IEEE Volume 3, Issue, 2000, 1645 – 1656

[2] N.D. Hatziargyriou, T.S. Karakatsanis, 1997, *“Distribution System Voltage and Reactive Power Control Based on Probabilistic Load Flow Analysis”*, Generation, Transmission and Distribution, IEE Proceeding, vol. 144, Issue 4, 363 – 369

[3] N.D. Hatziargyriou, T.S. Karakatsanis, 1998, *“Probabilistic Load Flow for Assessment of Voltage Instability”,* Generation, Transmission and Distribution, IEE Proceedings, vol. 145, Issue 2, 196 – 202

[4] N.D. Hatziargyriou, T.S. Karakatsanis, M.I. Lorentzou, 2004, *“Voltage Control Settings to Increase Wind Power Based on Probabilistic Load Flow”,* Probabilistic Methods Applied to Power Systems, 2004 International Conference, volume, issue, 12 – 16, 737 – 741

[5] G.Papaefthymiou, P.H.Schavemaker, L. van der Sluis et al, 2005, “*Integration of Stochastic Generation in Power Systems”*, 15th PSCC, Liege, 22-26 August 2005, Session 42, Paper 1, Page 1

[6] Ferry A. Viawan, Daniel Karlsson, 2007, “*Combined Local and Remote Voltage and Reactive Power Control in the Presence of Induction Machine Distributed Generation“,* IEEE Transactions on Power Systems, vol. 22, NO. 4, 2003 – 2012

[7] Hee-Sang Ko, Gi-Gab Yoon, Won-Pyo Hong, 2007, *“Active Use of DFIG-Based Variable-Speed Wind-Turbine for Voltage Regulation at A Remote Location”,* IEEE Transactions on Power Systems, vol. 22, NO. 4, 1916 – 1925

[8] Panagis N. Vovos, Aristides E. Kiprakis, A. Robin Wallace, Gareth P. Harrson, 2007, *“Centralized and Distributed Voltage Control: Impact on Distributed Generation Penetration”,* IEEE Transactions on Power Systems, vol. 22, NO. 1, 476 – 483

[9] Raymond O’Gorman, Miles Redfern, 2005, “*The Impact of Distributed Generation on Voltage Control in Distribution Systems*”, CIRED 18th International Conference on Electricity Distribution, Turin 6-9 June 2005, Session No 4

[10] Domenico Villacci, Gianluca Bontempi, Alfredo Vaccaro, 2006, *“An Adaptive Local Learning-Based Methodology for Voltage Regulation in Distribution Networks with Dispersed Generation”*, IEEE Transactions on Power Systems, vol. 21, NO. 3, 1131 – 1140

[11] Mesut E. Baran, Ismail M. El-Markabi, 2007, “*A Multiagent-Based Dispatching Scheme for Distributed Generators for Voltage Support on Distribution Feeders”,* IEEE Transactions on Power Systems, vol. 22, NO. 1, 52 – 59

[12] A. G. Tsikalakis, N. L. Soultanis, N. D. Hatziargyriou, 2006, *“On-line Storage Management to Avoid Voltage Limit Violations”*, Probabilistic Methods Applied to Power Systems, 2006. PMAPS 2006. International Conference, 1 - 7