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Voltage Control Coordination of Distributed Generators in Cell-based Active Networks

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Abstract—This paper gives an introduction on the Cell-based Active Network (CBAN), a potential system concept for future distribution networks. One of its functions, to deal with limiting the network voltage changes, is focused on with a proposed control scheme. This is based on an appropriate dispatch of DG's active and reactive power which is implemented autonomously within cells (feeders) of the CBAN. The test results show that the voltage regulation in the CBAN can help to control and mitigate voltage deviations effectively. The simulations are performed with a detailed model of a Doubly Fed Induction Generator (DFIG).

Index Terms—Active Networks (AN), voltage regulation, multi-agent system (MAS), distributed generation (DG), power distribution.

I. INTRODUCTION

The increased penetration of distributed generation (DG) has considerable impacts on the distribution system such as voltage changes, fault level increase, protection functioning, power quality and stability. The existing distribution system infrastructure operating in a passive, conventional manner is insufficient to cope with these changes. The introduction of active elements in distribution networks can provide an efficient, flexible and intelligent solution.

This paper introduces the so-called Cell-Based Active Network (CBAN) concept. In order to deal with limiting the network voltage changes, a specific control scheme is proposed. Based on sensitive factors and weighting factors, DG's active and reactive power can be dispatched to regulate voltage autonomously within cells (feeders) of the CBAN.

The contribution of DGs on voltage control will be performed through their electronic interfaces and set by multi-agent system (MAS) technology. With a model of a Doubly Fed Induction Generator (DFIG) their dynamic behavior with the proposed method will be demonstrated.

II. CELL-BASED ACTIVE NETWORKS

A. Active Networks (AN)

The terms Active Networks (in Europe) and Distribution Automation (in US and Canada) have been mentioned recently for distribution systems having more control and communication means. While Distribution Automation is developed as the solution to improve system reliability, Active Networks focus mainly on facilitation of distributed and renewable generation [1]. Although the technologies in both concepts are essentially equivalent, AN is in some way more suitable to adapt with the sustainable focus of the future.

Under the framework of AN, Active Network Management (ANM) has been started in UK actually since 2002. Current activities of ANM are to solve technical issues of voltage control, power flows, and fault level [1]. More possible functionalities for ANM may also be included such as demand side management, network reconfiguration, and network restoration.

In another research, F. Van Overbeeke and V. Roberts have proposed a particular vision of Active Networks in [2]. This so-called Cell-Based Active Network (CBAN) concept has three main points: *interconnection*, *local control areas (cells)*, and *system services*. While the first point is to provide more than one power flow path, to manage congestion by re-routing power and to isolate faulted areas effectively, the third point organizes system services and how it should be charged to individual customers. However the most revolutionary part is proposed in the second point, the local control areas or "Cells". Each cell component can be used to manage and to control the power inside and across the cell boundaries. It can be deployed with different typical actuators such as voltage, active and reactive power controllers.

CBAN focuses mainly on control strategies and communication topologies for the distribution system. Therefore, the transition to the CBAN does not require an intensive physical change of the existing infrastructure.

B. Constructing CBAN

The transition from the existing distribution network to the CBAN can start from the traditional radial network concept. The radial network consists of separated sub networks (feeders). Hence, it is possible to establish a *local control area (Cell)* for each feeder. Within a Cell, each controllable component, i.e. controllable generators and loads will have an agent that can operate autonomously with local targets or cooperate with other agents to achieve area tasks. A superior agent is installed for each Cell as a *moderator* to manage autonomous actions as well as to communicate with other Cells. Communication requirements for the MAS can be a phone-based communication [3] or the internet-based communication. Fig.1 shows the structure of the Active Network with MAS control for the radial network.

As one additional control level is installed for each cell component, the control architecture of the moderator of the cell is proposed to have two main parts: the Distributed State Estimation and the Local Control Scheduling. The DSE can work autonomously or together with other moderators to analyze the network topology, to compute the state estimation, and to detect bad data. Depending on the received information

from the DSE, the LCS will establish the control set points for different actuators such as voltage regulation or active and reactive power control of FACTS devices, remotely controllable loads and generators. This control architecture of *moderators* is depicted in Fig. 2.

As mentioned before, CBAN can perform different functions. Under scope of this study, voltage control will be investigated.

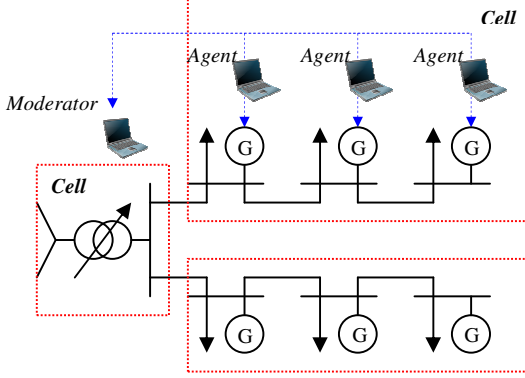


Fig. 1. Active Network managed by MAS

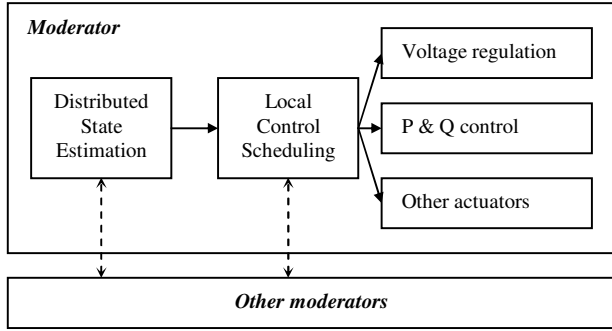


Fig. 2. Control architecture of the moderator

III. VOLTAGE CONTROL COORDINATION IN CBAN

A. Problems

Voltage variation is one of the barriers that hinder DGs penetration. Main solutions for voltage control problems in a distribution network are summarized as follows [4]

- Voltage control by the on-load tap changer of the HV/MV transformer (OLTC)
- Reactive power control with DGs and compensators
- DG active power control

Many works have been implemented to evaluate suitable solutions that facilitate connecting more DGs. Some works focus on intelligent control of the HV/MV transformer [5]-[6]. Alternative approaches concern local voltage control at DG's connecting point [7]-[9]. In [10], centralized and local voltage controls are compared in detail. Centralized voltage control is based on an active management scheme that first estimates the power system state by several measurement equipments, and then dispatches DGs according to the OPF. Local voltage control is deployed by combining automatic voltage regulation (AVR) and power factor control (PFC) of DGs.

Voltage control using reactive power generation has some disadvantages to regulate the bus voltage at the end of the feeder. It often requires generating great amounts of reactive power that might be out of generators' limits. The active power dispatch scheme can only cope with voltage changes if the active power output can be adjusted. The combination of active and reactive power dispatch schemes may be a good solution to deal with different kinds of voltage changes.

Based on this point of view, an approach to coordinate voltage regulation by appropriate dispatch of DG's active and reactive power is presented in this paper. The main idea is to reach the optimum for voltage regulation as follows:

$$\begin{aligned} \text{Min } f &= \sum_{j=1}^m (w_p \Delta P_{gj} + w_Q \Delta Q_{gj}) \\ \text{s.t. } \sum_{j=1}^m (\gamma_j \Delta P_{gj} + \beta_j \Delta Q_{gj} / V_{gj}^0) &= \Delta V_i \\ P_{gj}^{\min} &\leq P_{gj}^0 + \Delta P_{gj} \leq P_{gj}^{\max} \\ Q_{gj}^{\min} &\leq Q_{gj}^0 + \Delta Q_{gj} \leq Q_{gj}^{\max} \quad j = 1..m \end{aligned} \quad (1)$$

where m is the number of DGs in the feeder; Q_{gj} , Q_{gj}^{\min} , and Q_{gj}^{\max} are reactive power outputs and the limit for each DG; P_{gj} , P_{gj}^{\min} , and P_{gj}^{\max} are real power outputs and the limit for each DG.

Reactive (active) power sensitive factors β_j (γ_j) are defined as the voltage sensitivity of bus i with reactive (active) power output change of generator j .

B. Mathematic equations

In order to find out those sensitive factors, the linearization of the power flow equations needs to be performed as follows:

$$\begin{bmatrix} \Delta P \\ \Delta Q / V^0 \end{bmatrix} = \begin{bmatrix} J_{p\theta} & J_{pv} \\ J_{q\theta} & J_{qv} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix} \quad (2)$$

In [3], these equations are decoupled with the assumptions that ΔP is more sensitive to the $\Delta \theta$, and ΔQ is more sensitive to the ΔV . Due to the fact that MV networks in the Netherlands include mainly cable lines with a relative high R/X ratio, this assumption is not suitable anymore.

However, the effect of active and reactive power generation change to bus voltages can be considered separately from (2) by the equations:

$$\Delta Q / V^0 = [J_{qv} - J_{q\theta} J_{p\theta}^{-1} J_{pv}] \Delta V = [B] \Delta V \quad (3)$$

and,

$$\Delta P = [J_{pv} - J_{p\theta} J_{q\theta}^{-1} J_{qv}] \Delta V = [A] \Delta V \quad (4)$$

With the assumption that the power load and active power output of the DGs will not change, (3) can be rewritten as:

$$\begin{bmatrix} 0 \\ \Delta Q_g / V_g^0 \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} \begin{bmatrix} \Delta V_L \\ \Delta V_g \end{bmatrix} \quad (5)$$

Hence,
$$\Delta V_g = [D] \Delta Q_g / V_g^0$$
 (6)

where
$$D = [C_{21} C_{11}^{-1} C_{12} - C_{22}]^{-1}$$
 (7)

Using (7), the reactive power sensitive factor β_j is determined as

$$\beta_j = D_{ij} / V_j^0 \quad (8)$$

Similarly, the relationship between the bus voltages and reactive power generation change can be established to find out active power sensitive factor γ_j .

The bus voltages therefore can be controlled by a reactive (active) power dispatch based on ranking of the sensitive factors β_j (γ_j).

However, in order to integrate active and reactive power dispatches, a comparative relationship between MW and MVar change needs to be considered. Thus, weighting factors w_p and w_Q are introduced as a proportion of cost for curtailing 1MW and generating (or absorbing) 1MVar.

IV. SIMULATIONS

The simulation of the electrical distribution network is done in Matlab/Simulink.

A. Generator model

The Doubly Fed Induction Generator, DFIG, based wind turbine was chosen for simulation as it allows the control of active and reactive power. The DFIG-based wind turbines use a wound rotor induction generator, where active and reactive powers are controlled via the AC/DC/AC converter connecting the rotor windings to the grid. Fig. 3 represents a typical configuration of a DFIG-based wind turbine.

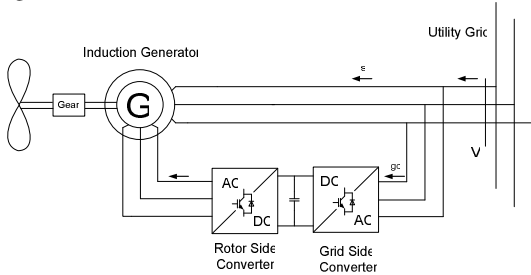


Fig.3. Doubly Fed Induction Generator based wind turbine.

In this paragraph, a brief description of the DFIG control strategy is given, the machine model is given in [12].

1) Rotor side converter control system

The rotor side converter controls active and reactive power exchanged with the grid. The active power reference is determined from the power speed characteristic that gives the maximum power of the wind turbine as a function of the rotor speed. The direct power control is achieved by controlling the quadrature component of the rotor currents, I_{qr} . The reactive power or the stator voltage is controlled through the direct

component of the rotor currents, I_{dr} . Fig. 4 gives the control structure for the rotor side converter.

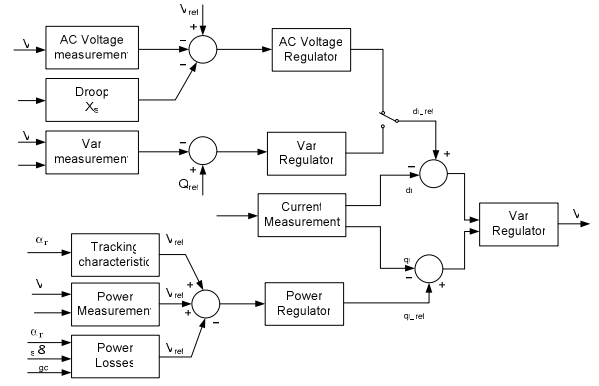


Fig.4 Rotor side converter control structure

2) Grid side converter control system

The grid side converter is responsible for keeping the DC link voltage constant. This is achieved through the control of the direct component of the grid side converter current, I_{gc} . Furthermore, this converter could also be used to control the reactive power exchanged with the grid, by controlling the quadrature component of I_{gc} . Fig. 5 gives the control system for the grid side converter.

The active power control has two modes, internal mode, where the power reference is given by the tracking characteristic, and external mode. The internal control mode is active when there is no active power curtailment command from the moderator. In the opposite case, the external control mode is engaged.

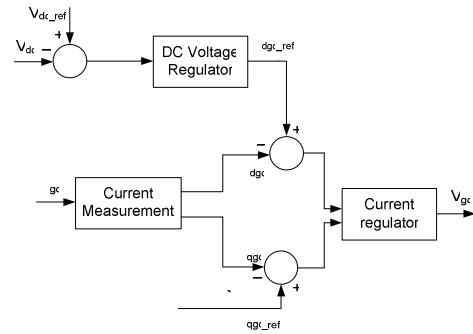


Fig.5. Grid side converter control system

B. Network model

The test system is a typical medium voltage grid in the Netherlands. It consists of a single feeder to which four DFIG-based wind turbines are connected.

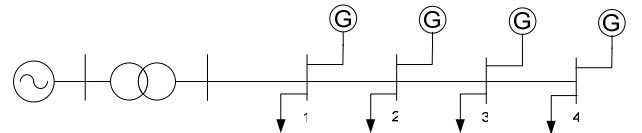


Fig.6. Test system

The test network consists of:

- 100 MVA voltage source (infinite bus).
- 150/10 kV, 66 MVA transformer

- Four, 5 km π -equivalent circuits line sections:
 $r = 0.125 \Omega/\text{km}$, $l = 0.2833 \text{ mH}/\text{km}$, $c = 0.53 \mu\text{F}/\text{km}$
- Constant three phase loads. Buses 1&2: 3 MW, 1.45 MVar (Ind.); Bus 3&4: 1 MW, 0.48 MVar (Ind.).
- Four generators: $S_{\text{nom}} = 10 \text{ MVA}$, $Q_{\text{min}} = -1 \text{ MVar}$, $Q_{\text{max}} = 1.5 \text{ MVar}$.

V. RESULTS

A. Voltage rise - Reactive power control for one generator

Suppose that due to a change of wind speed from 8km/h to 10km/h, more active power is produced by G4 from 1.87MW to 3.68MW that causes voltage rise up to 1.0545pu at bus 4, as shown in Fig. 7.

Agent 4 has detected voltage rise and sends a message to the moderator that requires to keep the voltage of bus 4 at 1.05pu ($\Delta V_4 = -0.0045\text{pu}$). Based on the ranking of sensitive factors from the agents within the feeder, the moderator will decide a dispatch order for DGs.

In the first iteration, the list of sensitive factors that the moderator received from the agents are ($\beta_1-0.3830$; $\beta_2-1.0154$; $\beta_3-1.6573$; $\beta_4-2.2746$) and ($\gamma_1-0.0427$; $\gamma_2-0.1367$; $\gamma_3-0.2337$; $\gamma_4-0.3257$). Regarding the weighting factors w_P and w_Q , a ranking of sensitive factors will be determined by comparing w_P/γ_i and w_Q/β_i . The dispatch order is (β_4 ; β_3 ; β_2 ; γ_4 ; β_1 ; γ_3 ; γ_2 ; γ_1).

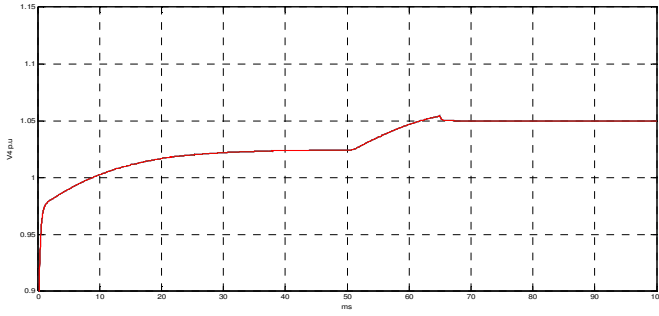


Fig.7. Case 1 - Voltage of controlled bus

As G4 has the largest value for the reactive power sensitive factor, it will be selected to dispatch first.

$$dQ_4 = \Delta V_4 \times V_4 / \beta_4 = -0.209 \text{ MVar} \quad (9)$$

This reactive power change is within capability of G4, hence only G4 is re-dispatched in this case.

After regulating, the voltage at bus 4 is 1.0501pu which is 0.0001pu above 1.05pu. The regulation procedure can be implemented again to reach more accurate results.

In this case, the simulation is converged after two iterations with the tolerance less than $10\text{e-}6$. Voltage at bus 4 reaches 1.05pu when G4 absorbs -0.217 MVar , see Fig.7 and Fig.8.

B. Voltage rise - Reactive power control for multi generators

Suppose that half of loads at bus 3 and bus 4 have been switched off and that the wind speed at G4 changes again from 8km/h to 12km/h, which causes voltage rise up to 1.063pu at bus 4.

In the first iteration of voltage regulation, the amount of voltage needed to change is $\Delta V_4 = -0.0130\text{pu}$. The sensitive factors are similar with the previous case. Due to the largest value of sensitive factors, G4 will be dispatched first:

$$dQ_4 = \Delta V_4 \times V_4 / \beta_4 = -0.614 \text{ MVar} \quad (8)$$

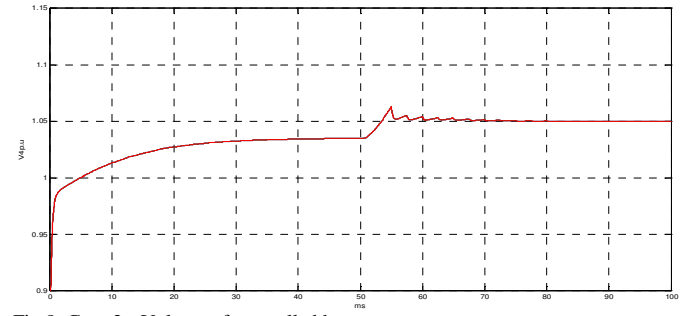


Fig.9. Case 2 - Voltage of controlled bus

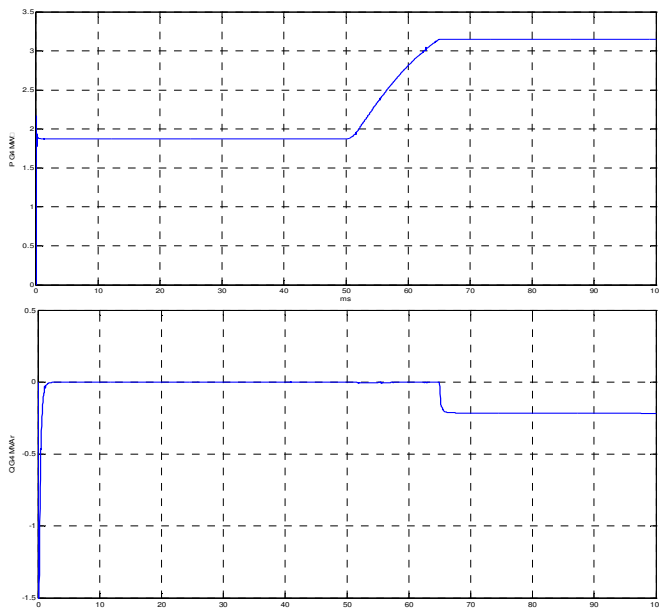


Fig.8. Case 1 - Active and reactive power changes of controlled generator G4

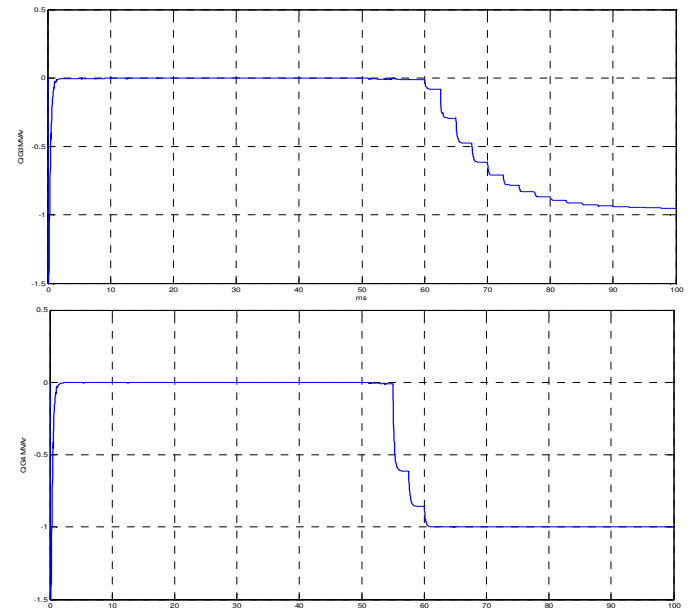


Fig.10. Case 2 - Reactive power changes of controlled generators G3, G4

However, the active power of G4 at this moment has not reached its reference value (6.38MW) due to the wind speed change yet. Thus, more active power is produced at G4 that increases the bus voltage. At the next iteration, the amount of voltage needed to change is $\Delta V_4 = -0.0053$ pu. The dispatch procedure is then implemented again.

Table 1 shows the dispatch order after several iterations of voltage regulation

Iteration	ΔV_4 pu	Q_4 MVar	Q_3 MVar
1	-0.0130	-0.614	0
2	-0.0053	-0.859	0
3	-0.0042	-1.000	-0.083
4	-0.0033	-1.000	-0.294

At the final stage, this controlled value is 1.05pu when G3 absorbs -0.9566MVar and G4 absorbs -1MVar, see Fig.9 and Fig.10.

C. Voltage rise – Active and reactive power control

In this case, the total load at bus 4 has been switched off. And suppose that with the change of wind speed from 8km/h to 12km/h, the active power output of G2, G3, and G4 change from 1.87MW to 6.38MW. Under this condition, voltage at bus 4 rises up to 1.0924pu dramatically.

Table 2 shows the dispatch order after several iterations of voltage regulation.

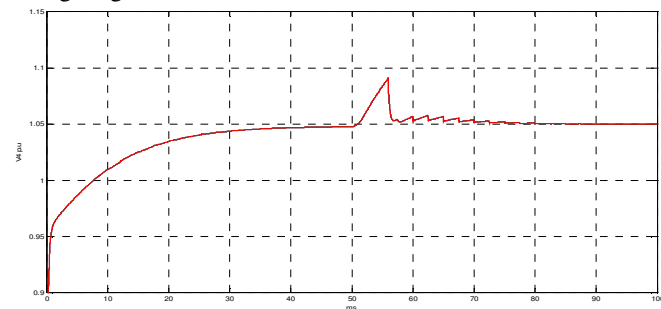


Fig.11. Case 3 - Voltage of controlled bus

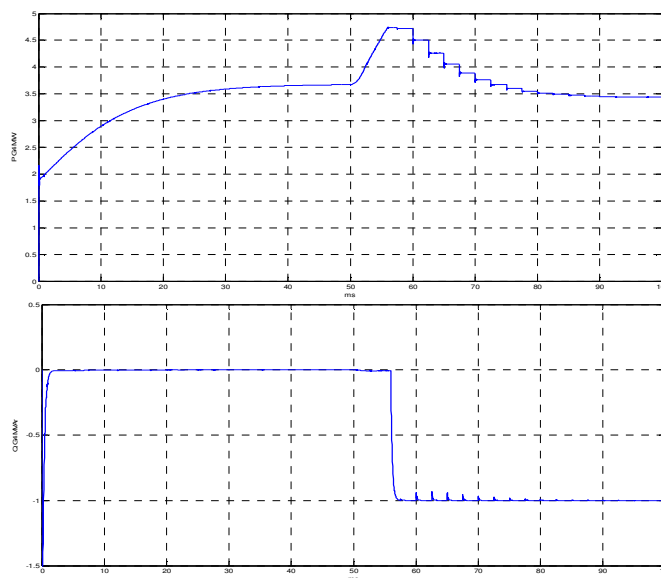


Fig.12. Case 3 – Active and reactive power changes of controlled generator G4

TABLE II
CASE 3 – POWER GENERATION DISPATCH

Iteration	ΔV_4 pu	Q_4 MVar	Q_3 MVar	Q_2 MVar	P_4 MW
1	-0.0424	-1.000	-1.000	-0.637	-
2	-0.0043	-1.000	-1.000	-1.000	4.739
3	-0.0068	-1.000	-1.000	-1.000	4.717
4	-0.0077	-1.000	-1.000	-1.000	4.505
5	-0.0068	-1.000	-1.000	-1.000	4.055

At the final stage, controlled voltage bus is 1.05pu when G4, G3, and G2 absorb -1MVar, and G4 generate 3.435MW (curtails -2.945MW), see Fig.11 and Fig.12.

D. Voltage drop

Voltage drop occurs when active power output of G4 changes from 1.87MW to 0MW (supposed that the wind speed changes from 8km/h to 4km/h) while the load at bus 4 is supposed to be doubled.

Similarly with voltage rise cases, in the first iteration of voltage regulation, dispatched values are $\Delta V_4 = 0.0268$ pu and $dQ_4 = 1.086$ MVar. Controlled voltage bus is 1.05pu when G4 generate 1.278MVar, see Fig.13 and Fig.14.

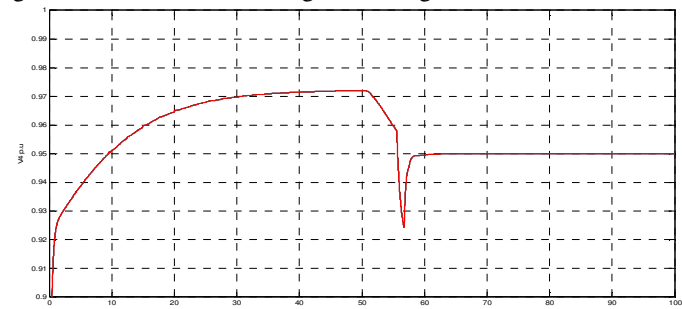


Fig.13. Case 4 - Voltage of controlled bus

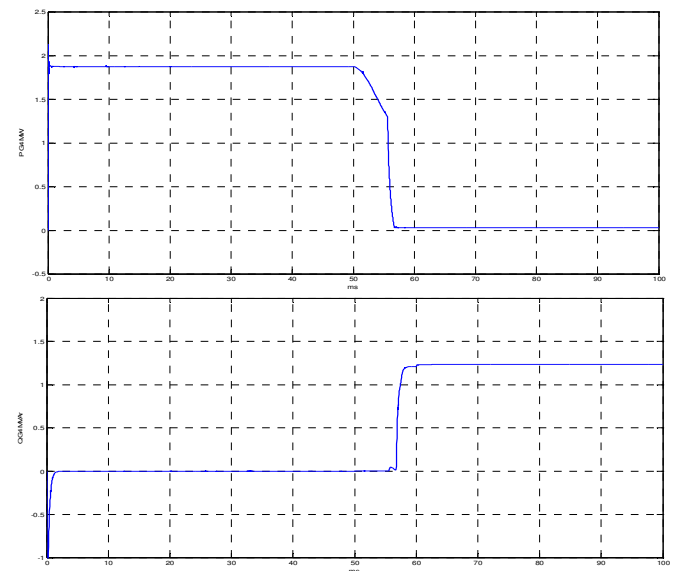


Fig.14. Case 4 – Active and reactive power changes of controlled generator G4

VI. CONCLUSION

It is shown from the results, that the control scheme presented in this paper can adapt effectively with different scenarios of voltage change. Voltage rise and drop cases are

controlled by coordinating of DG's active and reactive power output based on weighting factors and sensitive factors. This can alleviate limitations of conventional control schemes.

Under the frame work of constructing a CBAN, this voltage control method is an important application. MAS can be used as a technology to utilize this application in the distribution networks.

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VIII. BIOGRAPHIES

Phuong H. Nguyen was born in Hanoi, Vietnam in 1980. He received his MEng. in Electrical Engineering from the Asian Institute of Technology, Thailand in 2004. From October 2006, he joined the Electrical Power System Research group at Eindhoven University of Technology, the Netherlands as a Phd student.

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Johanna M.A. Myrzik was born in Darmstadt, Germany in 1966. She received her MSc. in Electrical Engineering from the Darmstadt University of Technology, Germany in 1992. From 1993 to 1995 she worked as a researcher at the Institute for Solar Energy Supply Technology (ISET e.V.) in Kassel, Germany. In 1995 Johanna joined to the Kassel University, where she finished her PhD thesis in the field of solar inverter topologies in 2000. Since 2000, Johanna is with the Eindhoven University of Technology, the Netherlands. In 2002, Johanna became an assistant professor in the field of distributed generation. Her fields of interests are: power electronics, renewable energy, distributed generation, electrical power supply.

Prof. W. L. Kling received his M.Sc. degree in electrical engineering from the Technical University of Eindhoven, The Netherlands, in 1978. Since 1993, he is a part-time Professor at the Electric Power Systems Laboratory, Delft University of Technology, Delft, The Netherlands. And since 2000, also at the Eindhoven University of Technology. Furthermore he is with TenneT, the Dutch Transmission System Operator, in the Asset Management Department responsible for network strategy. His experience is in the area of planning and operation of power systems. Prof. Kling is involved in scientific organizations such as Cigré and IEEE. He is the Dutch Representative in the Cigré Study Committee C6 Distribution Systems and Dispersed Generation and the Eurelectric/UCTE WG SYSTINT.