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VOLTAGE CONTROL IN DISTRIBUTION NETWORKS IN PRESENCE OF DISTRIBUTED GENERATORS BASED ON LOCAL AND COORDINATED CONTROL STRUCTURES

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Abstract. ***Nowadays, many factors lead to selection and utilization of distributed generations (DG) in distributed networks. But more penetration of DG's in network faced with problem due to existence of passive and inactive distribution networks. One of these essential issues is voltage rise due to injection of active power generated by DG's. That in this paper, control strategies for controlling of voltage profile of distribution network and adjustment of increase of DG's penetration is assessed and an optimal strategy for voltage rise with mathematical formulation is presented that will include both local and coordinated control approaches of reactive power generation. Finally, in this paper an implementation plan with smart control tools of DG's is suggested.***

Keywords: Voltage control, reactive power control, DG, Local and coordinated control, sensitivity matrix

1. INTRODUCTION

Nowadays, most of electrical energy is generated in large power plants that is transferred through transfer lines and is delivered to subscribers by inactive distribution networks. Number of network-connected DG's is increasing in last decade. Many factors lead to DG's increase:

- Continuous increase of electrical energy demand throughout the world cause to explore new energy resources.
- Limitation in fossil fuels storage leads to increase of interest to renewable energies.
- Progress in DG technologies such as concurrent generation of heat and electricity requires generate energy close to consumer.
- Freedomization of electricity market makes it possible to do business even with small power plants.

Distributed generations include a vast range of generators such as photovoltaic (PV), wind turbines, micro-turbines, fuel pills, CHP's, water units, which their generated power is in range of MW and KV that an example of these resources is shown in Figure 1. In distribution network, many researches have been made on DG effect on short circuit current, thermal limitation of conductors, voltage changes and fault protection. One of most effective concepts is permanent mode voltage rise due to coupling of DG resources that causes some challenges such as voltage level increase and power countdown. Uncertainty of photovoltaic (PV) and wind turbines in injection of active power into distribution networks with a small reactance to resistance ratio (X/R) better show voltage rise problem [1-2]. Two main approaches that are suggested for voltage control in DG's coupling are centralized and decentralized control strategies. Centralized approach has been assessed in papers so widely [3] to [5] but has some disadvantages that cause more interest to decentralized approach in last years. Important problem of centralized approaches is their need to invest for control tools and systems; so that all centralized approaches require a highly reliable telecommunication channel within distribution network [6]. On other side, one of main attributes of decentralized approaches is utilization of control operations in Point of Common Coupling (PCC). This approach deals with DG's capacity in order to support reactive power in network in a way that out of online network information only has access to voltage, active and reactive power of DG [7]. Phase approach is more efficient than other decentralized control approaches such as sensitivity analysis and has better control on voltage profile while lower reactive power consumption [7]. In paper [8], a novel algorithm for decentralized control based on sensitivity analysis is presented and the authors in [9] complete this approach and try to improve it via presenting of an adjustment technic so that to maximize generation capacity of active power based on curves of wind DG's capacity. In [10] an adjustment technic is presented with the goal of minimization of power loss and voltage divergence in distribution network with photovoltaic and based on decentralized approach. Decentralized control of voltage levels is being done by local regulation of active and reactive DG generated power in its coupling bus. In these methods, a voltage control strategy is being introduced in which we intend to regulate voltage initially by DG's reactive power change in order to keep DG active power generation still maximum and if voltage control by reactive power change was not enough then change generated active power, unavoidably. This strategy in this research is formulated by local and coordinated control method.

In section 2, voltage rise issue is explained. In section 3, a report of different methods of reactive power control is presented. In section 4, a control method for adjustment of voltage rise is presented and its mathematical equations are indicated.

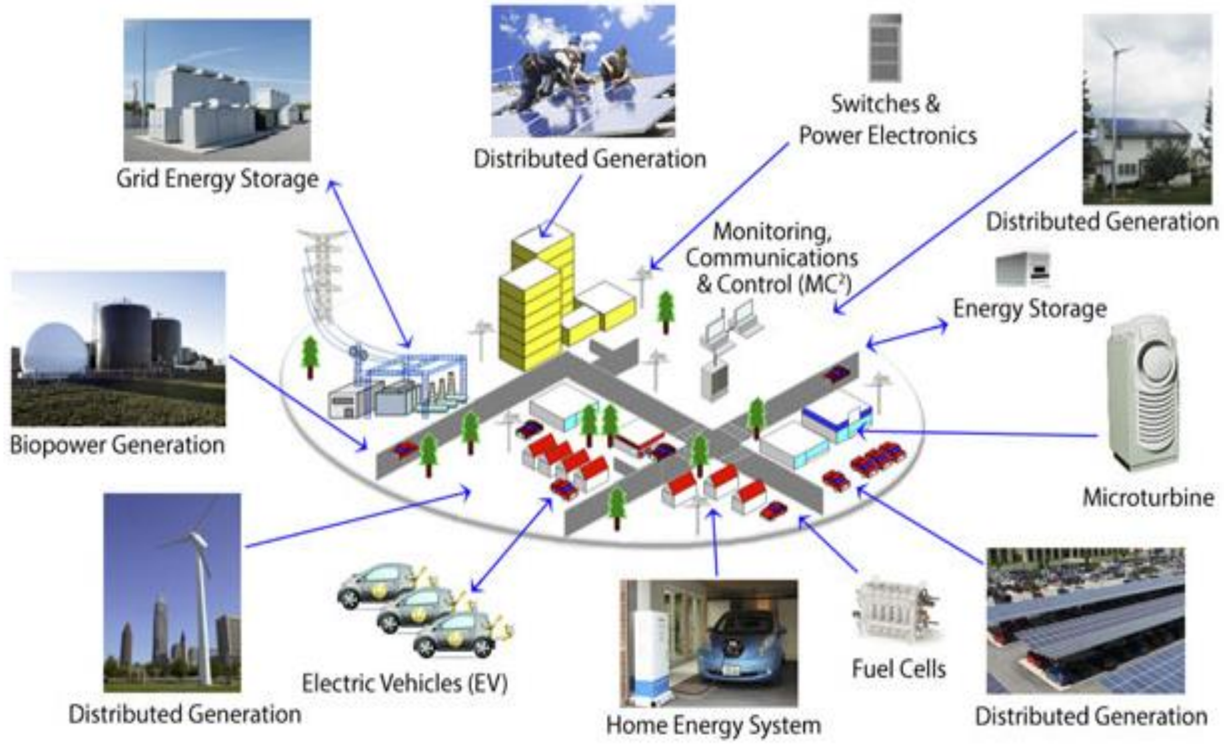

Figure 1. Types of distributed generations.

2. PERMANENT MODE VOLTAGE RISE

Real distribution networks are designed as inactive networks in which voltage drops within the line due to existence of conductors. In order to avoid voltage drop can keep voltage in primary substation higher than voltage of subscribers coupling point by power injection. To keep voltage in permitted range in coupling points, on load tap changers are used in distribution substations. Voltage drop between two nodes of 1 and 2 in which P_1 and Q_1 power is injected, are calculated based on Figure 2.

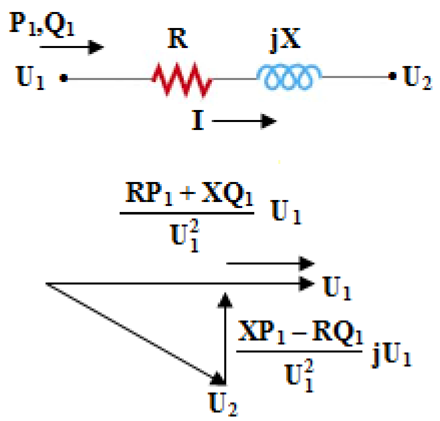

Figure 2. Voltage drop between two nodes.

So have

$$\overline{U}_1 - \overline{U}_2 = \frac{(R+jX)\cdot(P_1 - jQ_1)}{U_1^2}\cdot \overline{U}_1 \qquad (1)$$

That change as following:

$$U_1 - U_2 \cong \frac{RP_1 + XQ_1}{U_1} \qquad (2)$$

Where:

- U_1 and U_2 are voltages of end of the line.
- R and X are resistance and reactance of the line.
- P_1 and Q_1 are active and reactive power that injected into node 1.

RP is not considered in transmission network due to low value of R/X, in contrast of distribution network. In distribution network both correlations should be considered. There for, voltage of nodes has a dependent relation with network structure, load conditions and active and reactive power that is generated in generators.

There are multiple methods for adjustment of voltage rise and voltage preserve in permitted range:

- Voltage reduction of distribution substation.
- Allow DG to convert reactive power in order to reduce RD + XQ.
- Utilization of OLTC (On Load Tap Changer).
- Increase of conductor's size (decrease of resistance).
- Limitation of DG's active power generation.
- A combination of above items.

3. REACTIVE POWER GENERATION CONTROL

Voltage profile in distribution network can effectively be controlled using transmitted reactive power between network and power plant. In this situation, generators do not work in a single power coefficient anymore. In most papers, suggested strategies for voltage control through reactive power generation as a controllable variable are categorized in two categories: Coordinated control and local control. Coordinated voltage control happens when a Power Control Unit (PCU) coordinates reactive power that is injected into feeder, by generator. In this situation, voltages of coupling points and DG's generated power are measured. Figure 3 shows an example of a 4-bus network.

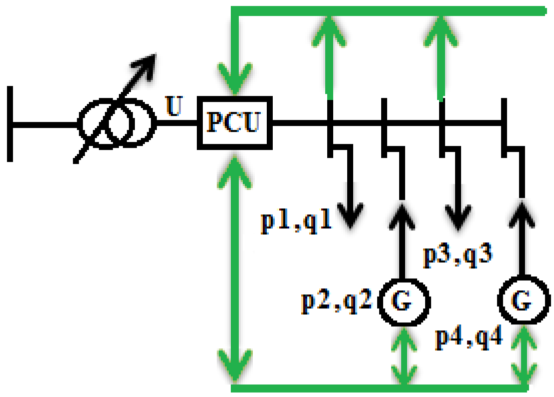

Figure 3. Coordinated reactive power control.

In local control, any generator just control its own generated reactive power based on local measurements that is shown in Figure 4.

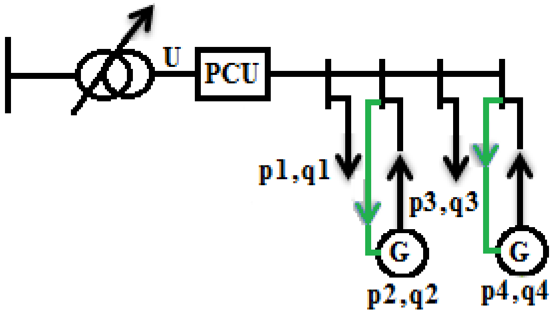

Figure 4. Local reactive power control.

In coordinated strategy, a communication system is implemented by feeder that has high reliability and resistance and has central Power Control Unit (PCU) that gather all required data for calculation of optimum method. For instance, coordinated controllers based on sensitivity theory are presented in [11-13] references. Other algorithms consider the presence of on load tap changers and try to optimize a cost function.

Reference [14] among researches that present local control, is based on sensitivity theory. Reference [15] presents an algorithm that minimizes reactive power that is required from transmission network. The other methods can be used both for centralized plans and also decentralized plans like reference [15-20].

4. ADJUSTMENT OF VOLTAGE RISE

For a sample distribution network with multiple bus in network and one subcategory, where N_G numbers of them are connected to power plants, selection of subcategory of m numbers of network's buses, voltage difference vector in these m buses caused by DG's effect can be presented, for small changes, activation by below correlations in the range of working point where $q_i=p_i=0$ is considered (for instance for a situation that distribution network without DG's is utilized):

$$[\Delta U_b] = [B][\Delta p] + [C][\Delta q] \qquad (3)$$

Where $[\Delta U_b]$ is m×1 matrix of voltage difference in coupling points with consideration to voltage value in absence of DG, $[\Delta P]$ is (N_g×1) vector of injection active power difference by DG and $[\Delta Q]$ is (N_g×1) vector of DG injected reactive power difference.

Equation (3) in sensitivity matrix [B] and [C], describes ($m \times N_g$). In Equation (3), voltage difference is not considered due to load and turbulences of transmission network because suggested control approach just in decrease of DG resonance differences. The goal of voltage control is to minimize difference $[\Delta U_b]$ with control of generated reactive power. The law of reactive power control for N_G is presented in Equation (4).

$$[\Delta q] = [A][\Delta p] \qquad (4)$$

Where, A is a ($N_G \times N_G$) matrix that in this method solution convert to find a matrix [A] which minimized voltage differences. Voltage differences for selected buses m present some results related to active power differences.

$$[\Delta U_b] = ([B] + [C][A])[\Delta p] \qquad (5)$$

Two modes are considered in this paper $m=N_G-1$ and $m=N_G-2$ with diagonal matrix [A].

- First mode: $m=N_G$

Matrixes A and B and C are all square $N_G \times N_G$ matrix so analytical solution of voltage differences is as following:

$$[A] = -[C]^{-1}[B] \qquad (6)$$

Where, m points are selected and matrix C is not singular

- Second mode: m= N_G and diagonal matrix [A]

Solution can be written as below:

$$\min U_b = ([B] + [C][A])[\Delta p] \qquad (7)$$

Where, $A \in R^{Ng \times Ng}$ $B,C \in R^{M \times NG}$
With consideration of matrix [A] as diagonal, below functions of matrix elements are considered for minimization.

$$f(a_1, \dots, a_{N_G}) = [P]^T [B + CA]^T [B + CA][P] \quad (8)$$

Where

$$[A] = \begin{bmatrix} a_1 & 0 & \cdots & 0 \\ 0 & a_2 & & 0 \\ \vdots & \ddots & a_i & \ddots & \vdots \\ 0 & 0 & \cdots & a_{N_G} \end{bmatrix} \quad (9)$$

The minimum value of function $F_{(0)}$ by solving of below equation is obtained:

$$\frac{\partial f}{\partial a_i} = 0 \quad , \ i = 1, \dots, N_G \quad (10)$$

This solution requires solving of linear system with Q_1 to Q_n variables.

$$\begin{bmatrix} & L & \end{bmatrix} \begin{bmatrix} a_1 \\ \vdots \\ a_{N_G} \end{bmatrix} = \begin{bmatrix} m_1 \\ \vdots \\ m_{N_G} \end{bmatrix} \quad (11)$$

Where

$$L_{i,j} = p_j \sum_{r=1}^{M} c_{r,i} \cdot c_{r,j} \quad (12)$$

$$m_i = -\sum_{r=1}^{M} c_{r,i} \cdot \sum_{s=1}^{N_G} b_{r,s} \cdot p_s \quad (13)$$

N_G coefficients are including:

$$\begin{bmatrix} a_1 \\ \vdots \\ a_{N_G} \end{bmatrix} = \begin{bmatrix} & L & \end{bmatrix}^{-1} \begin{bmatrix} m_1 \\ \vdots \\ m_{N_G} \end{bmatrix} \quad (14)$$

If the point is based on topology of selected network matrix [L] will be nonsingular.

- Assessment of two modes

Considering above mentioned mathematical correlations, suggested strategy for adjustment of voltage rise is results in twin local and or coordinated control structures. Especially, m= N_G mode converts to zero vector of voltage difference but in general mode we need to control any reactive power using active power information of other generators. In another mode of m= N_G with diagonal matrix [A] voltage divergence does not reach to zero but become minimum so this issue for local controllers that does not need communications is quite appropriate.

5. TEST NETWORK AND SCENARIOS

To test the used method a sample medium voltage network is used that its topology is shown in Figure 5.

Information of the lines presented in Table 1. All loads are considered equivalent to 400 kVA with power coefficient 0/85. Information of these generators indicated in Table 2.

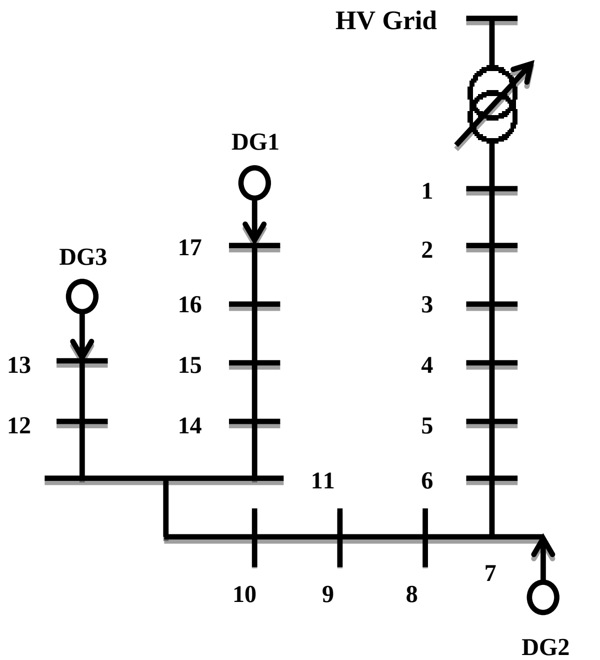

Figure 5. Medium voltage test network.

Table 1. Lines Information of Medium Voltage Test Network

From bus	To bus	L [km]	r [ohm/km]	l [mH/km]
1	2	0.942	0.125	0.493
2	3	0.810	0.125	0.493
3	4	0.266	0.125	0.493
4	5	0.642	0.125	0.493
5	6	0.809	0.206	0.608
6	7	0.266	0.206	0.608
7	8	1.000	0.125	0.493
8	9	1.200	0.125	0.493
9	10	1.126	0.206	0.608
10	11	0.378	0.125	0.493
11	12	0.935	0.519	1.957
12	13	0.595	0.519	1.957
11	14	0.640	0.206	0.608
14	15	0.400	0.206	0.608
15	16	1.500	0.519	1.957
16	17	2.000	0.519	1.957

Table 2. Information of Generators of Medium Voltage Test Network

DG unit	Node	Active power [MW]
DG1	17	5
DG2	7	2.2
DG3	13	2

5.1 Sensitivity Matrix Calculation

Voltages sensitivity of distribution buses relative to active or reactive power injection is obtained through keeping all network parameters constant and intermittent increase of active and reactive power of each DG and calculation of ratio between voltage difference and injected power. Matrixes B and C are including:

$$[B] = \begin{bmatrix} 0.152 & 0.169 & 0.162 \\ 0.303 & 0.171 & 0.324 \\ 0.874 & 0.171 & 0.325 \end{bmatrix}, \quad [C] = \begin{bmatrix} 0.372 & 0.392 & 0.382 \\ 0.743 & 0.395 & 0.764 \\ 2.078 & 0.397 & 0.767 \end{bmatrix} \tag{15}$$

5.2 Calculation of Matrix [A]

The applied algorithm on the explained network is done in mode of N_G=N=3. Three nodes that have voltage drop include V_b = (7,11,17).

Matrix [A] is obtained as below:

$$[A] = \begin{bmatrix} -0.428 & -0.001 & 0.000 \\ 0.020 & -0.430 & 0.000 \\ -0.020 & 0.003 & -0.424 \end{bmatrix} \tag{16}$$

Voltage profile of feeder is shown in Figure 6. Red line is voltage profile with presence of DG and no control. Blue line is voltage profile without DG and green line is voltage profile with DG with application of suggested control strategy. m=3 black circles are selected node.

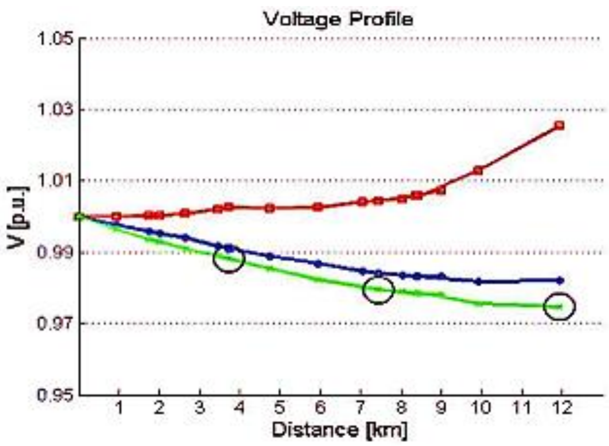

Figure 6. Voltage profile with complete matrix A.

Using partial algorithm in mode of m=N_G with diagonal matrix [A] it is possible to find a solution with reactive power of each generator that is dependent just to active power of that generator. As an example, a solution with diagonal matrix [A] is obtained as below:

$$[A] = \begin{bmatrix} -0.427 & 0.000 & 0.000 \\ 0.000 & -0.433 & 0.000 \\ 0.000 & 0.000 & -0.377 \end{bmatrix} \tag{17}$$

Voltage profile of feeder with diagonal matrix [A] is shown in Figure 7. Same as before, Red line is voltage profile with presence of DG and no control. Blue line is voltage profile without DG and green line is voltage profile with DG with application of suggested control strategy. m=3 black circles are selected node. Obtained reactive powers for three given active powers of DG's are indicated in Table 3.

Table 3. Active and Reactive Powers of Generators

DG unit	Active power [MW]	Reactive power [MVAR]	Reactive power [MVAR]
DG 1	5	-2.134	-2.137
DG 2	2.2	-0.948	-0.952
DG 3	2	-0.813	-0.753

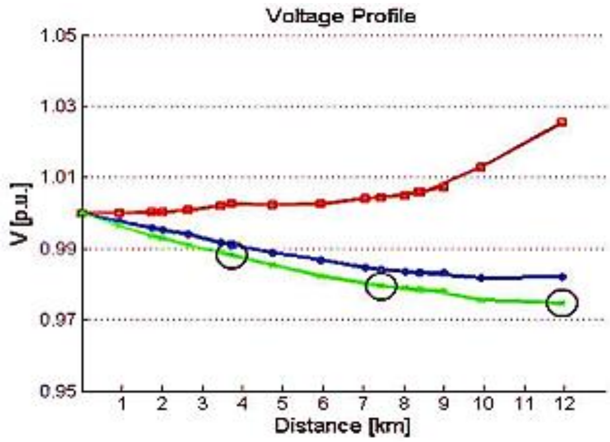

Figure 7. Voltage profile with diagonal matrix A.

Diagonal matrix [A] is used in situations that there is no connection between generators. Buses that voltage control should be done on them are selected based on network topology. For instance, selection of buses 2, 3, 4 results in creation of singular matrix C that is similar to dependence of bus voltage to injected reactive power of generators: Also all simulations are done in PSAT environment.

6. SMART CONTROL EQUIPMENT

DG smart control equipment with their communication ability can be utilized as IED's and be considered as basis of future smart networks. Voltage control systems include 2 categories that can be used for implementation of implied control strategies:

Stimulation Control Systems (ECS) for synchronous generators or voltage controllers of electronic power inverters for inverter-based generators.

6.1 Smart VCS's

For synchronous generators, combination of smart ECS's with traditional voltage regulators is used as VCS's. Smart ECS's can be implemented as software modules that their performance is shown in Figure 8.

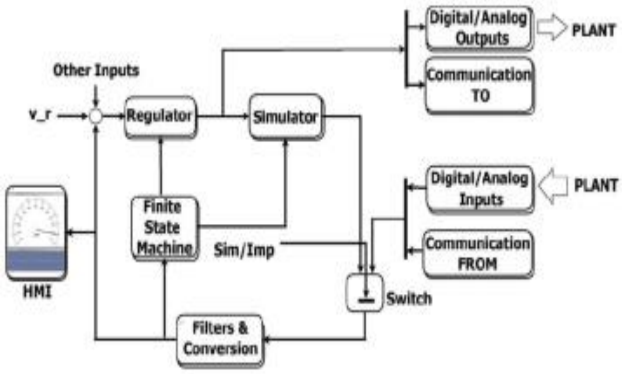

Figure 8. Function plan for smart ECS.

In this section, a physical system simulator (network generator) is developed for automatic control generation and assessment using high level software's (such as Simulink/Matlab or Scilab/scicos) that includes below items:

- Finite mode machine that identifies all logic and safety function.
- In regulator mode and finite mode machine, all conventional applications of ECS such as: voltage control, reactive power control, compensation of line voltage drop, compensation of reactive power, PSS (Power System Stabilizer), additional functions as automatic synchronizing equipment, virtual equipment for immediate monitoring and Datagram (stability) can properly be combined as software modules.
- HMI (Human-Machine Interface).

Input and output activities that is include some drivers for digital-analogue input-output signals and also include PCU (Power Control Unit) communications, DCS (Distribution Control System) and SCADA. These input-output channels are implemented using digital-analogue input-output boards (for wired communication) or by using different networks (for wireless communication). For their importance, utilization of communicational compound functions is described in next section.

All already presented performances regarding smart ECS can properly be implemented as an inverter-based generator with a smart control tool.

6.2 Communications

Development of some systems and concepts such as DG, smart network, sub-network, virtual power plant, requires to design energy management systems and distribution management systems to achieve all ICT advantages. Telecommunication is one of most important tasks that should be identified which for suggested smart VCS's, all communications by SCADA or DCS system using TCP and UDP-based software protocols through IP can be implemented. Network protocols such as TCP/IP are using properly and successfully for applications that were not imagined so far. Smart VCS's can obtain advantages of these protocols completely and not only be used for communication with EMS (Energy Management System) or DMS (Distribution Management System) but also be used for identification of two other important performances:

- By doubling the structure of Figure 8 and copying from Figure 8 as an additional two-unit structure, one can increase the security of the loss of intelligent control equipment.
- Telecommunication can be used for exchange of control signals (such as reactive power increase/decrease orders) and measurement data's of controllers like PCU of Figure 3. In this case, AVR (Automatic Voltage Regulation) module and VCS (Voltage Control System) would be compatible with higher level controllers naturally and no side equipment is required for voltage control algorithms, anymore.

Aforementioned H/W and S/W patterns can completely be derived for implementation of voltage control algorithms as well as voltage rise adjustment technics. This issue shows that smart VCS's should be used as effective essential principals of voltage control systems in future networks.

7. CONCLUSION

From presented mathematical results in this paper and its studied issues below items can be concluded:

- The presented algorithm is simple and can be used for different communication structures: In coordinated control, each generator obtain active power information from other DG's. For synchronous generator, this algorithm is implemented using smart ECS control and communication capabilities.
- An easier and proper application for calculation of diagonal matrix [A] is to keep it constant.
- Presented strategy for adjustment of voltage rise does not consider the limitations that are resulted from capacity and capability limits of generator (This issue can be used in future for more development).
- Matrix [A] is highly dependent to R/X value of line's cables. Very high R/X value creates very high values in matrix [A] coefficients. In this case for adjustment of voltage rise we need to strengthen network (for instance, increase of conductor's size for loss reduction).

It is seen that input reactive power from transmission system increases by suggested algorithm and therefor will have current rise in transmission lines that results in higher losses. Future development of this study can minimize reactive power demand from transmission network.

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