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Using D-UPFC in Voltage Regulation of Future Distribution Systems

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Abstract- Among the important parameters for the control of electrical power systems is the voltage. Traditionally, the On-Load Tap Changer (OLTC) is the most popular and effective voltage control device in a distribution system. This paper presents an approach for the problem of using OLTC for the voltage regulation of a future distribution system. This problem will be solved by using reactive power compensation using Distribution Unified Power Flow Controllers (D-UPFC) at the DG connected bus. To perform multiple control functions, the D-UPFC may be equipped with several controllers. Simulation results reveal that in the worst scenarios of the test system, the proposed control method is able of maintaining the voltage of the system within the permitted range.

Keywords: Smart Grids; Distribution systems; Distributed Generation; D-UPFC; FACTS.

1. Introduction

Usually, Distributed Generations (DGs) are mentioned to the production of electricity using small generators located in the power load centers or in power distribution systems [1]. Distributed generation (DG) is cited to a small scale generation, generally between 1kW and 50MW electrical power generators they tied to an electric distribution system or that produce electricity at a site close to the customer [2]. DGs are from artificial and renewable models and are the energy resources which contain some artificial models like Gas turbines, Micro turbines, Fuel oil turbine, Stirling engines, Diesel engines, internal combustion reciprocating engines and Renewable Energy Resources such as Solar, Wind and Hydraulic [3].

It is well known that the interconnections of DG to an existing distribution network causes unfavorable technical problems, which include power quality problems such as slow/fast voltage changes. The traditional, voltage control On-Load Tap Changer (OLTC) is not designed for the connection of DG [5] Most existing distribution systems have been operated with uncontrolled DG units to maintain the power quality and reliability within admissible operation ranges.

The penetration level of DGs for a particular voltage level should be limited to maintain admissible power quality and reliability. Many regulatory committees and utilities have recommended DG interconnection procedures to guarantee a reasonable penetration level of DGs in distribution systems [4]. These limitations affect the full exploitation of the energy produced by the DG.

To enjoy existing voltage control and for exploit any energy produced by DG, a new voltage control method is proposed in this paper. The main idea is to use a device as UPFC to store the excess energy produced by DG and injected the minimum of the energy stored into the network when necessary with help of OLTC.

A device such as UPFC has the advantage of providing solution in fast response time. Thus, it providing in the systems an dynamic voltage control [7]. The UPFC is called D-UPFC (Distribution-UPFC) when is applied in distribution system and its configuration is the same [8].

2. Modeling of DGs in Load Flow Studies

The DG is noticed by two models when it is injected in networks [9]:

- Participating DGs (PV model).
- Non-participating DGs (PQ model).

2.1. DG Modeled as PV Node

Some types of DGs which can be modelled as PV nodes, like micro turbines, fuel cells and so on. It has to be dealt with separately because it does not match the back/forward sweep algorithm [11]. The model is Eq. (1).

$$\begin{cases} \mathrm{P} = -\mathrm{P_g} \\ \mathrm{U} = \mathrm{U_g} \end{cases} \quad (1)$$

2.2. DG Modeled as PQ Type

This type of DGs, a compared with PQ type load, has opposite power flows. Therefore, there is nothing to handle but invert the sign of power when dealing with PQ type DGs, as Eq. (2) shows. In the distribution power flow calculation, the vast majority of nodes are PQ nodes [10].

$$\begin{cases} \mathrm{P} = -\mathrm{P_g} \\ \mathrm{Q} = -\mathrm{Q_g} \end{cases} \quad (2)$$

3. Unified Power Flow Controllers

3.1. Operating principal of UPFC

The UPFC has complete dynamic control on the transmission parameters, line impedance, voltage and phase angle [12]. Practically, it is implemented by using two identical solid-state phase voltage source converters (series compensation block and shunt compensation block) which are connected via a common DC link capacitor as shown in Fig. 1 and each converter is coupled with a transformer. The basic operating of the UPFC is described in a number of publications In the literature of the last few years [13–15].

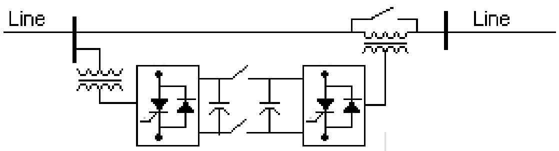

Fig. 1. Generic representation of the UPFC

The Fig. 2 shown the equivalent circuit of UPFC, which was used in the steady state model for load flow analysis. $\mathrm{Z_{sh}}$ and $\mathrm{Z_{se}}$ are the impedances of the two coupling transformer, one connected in shunt and other in series between the UPFC and the line [16].

The output of the series voltage source $\mathrm{V_{se}}$ and φ_{se} are controllable magnitude and angle between the limits $0 \leq \mathrm{V_{se}} \leq \mathrm{V_{se\ max}}$ and $-\pi \leq \varphi_{se} \leq \pi$ respectively and of the shunt voltage source is $\mathrm{V_{sh}}$ and φ_{sh} controllable between the limits $0 \leq \mathrm{V_{sh}} \leq \mathrm{V_{sh\ max}}$ and $-\pi \leq \varphi_{sh} \leq \pi$.

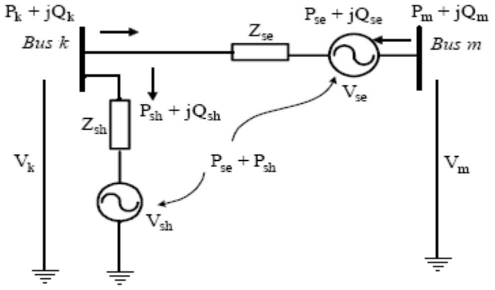

Fig. 2. Equivalent circuit of UPFC

3.2. Operating principal of UPFC

The two voltage sources of the UPFC mathematically are represented as:

$$\mathrm{V_{se}} = \mathrm{V_{se}}(\cos\varphi_{se} + \mathrm{j}\sin\varphi_{se}) \quad (3)$$

$$\mathrm{V_{sh}} = \mathrm{V_{sh}}(\cos\varphi_{sh} + \mathrm{j}\sin\varphi_{sh}) \quad (4)$$

Applying the voltage laws and kirchoff's current for the network in Fig. 2 gives:

$$\begin{bmatrix} \mathrm{I_k} \\ \mathrm{I_m} \end{bmatrix} = \begin{bmatrix} y_{se} + y_{sh} & -y_{se} & -y_{se} & -y_{sh} \\ -y_{se} & y_{se} & y_{se} & 0 \end{bmatrix} \begin{bmatrix} \mathrm{V_k} \\ \mathrm{V_m} \\ \mathrm{V_{se}} \\ \mathrm{V_{sh}} \end{bmatrix} \quad (5)$$

Where $y_{se} = \frac{1}{z_{se}}$ and $y_{sh} = \frac{1}{z_{sh}}$

The element of transfer admittance matrix can be put as

$$\begin{cases} \mathrm{Y_{kk}} = \mathrm{G_{kk}} + \mathrm{jB_{kk}} = y_{se} + y_{sh} \\ \mathrm{Y_{mm}} = \mathrm{G_{mm}} + \mathrm{jB_{mm}} = y_{se} \\ \mathrm{Y_{km}} = \mathrm{Y_{mk}} = \mathrm{G_{km}} + \mathrm{jB_{km}} = -y_{se} \\ \mathrm{Y_{sh}} = \mathrm{G_{sh}} + \mathrm{jB_{sh}} = -y_{sh} \end{cases} \quad (6)$$

Neglecting the losses of the associated coupling transformers and the converters in the steady-state operation it neither absorbs no injects real power in the system, the active power balance of the UPFC becomes

$$\mathrm{P_{se}} + \mathrm{P_{sh}} = 0 \quad (7)$$

From Fig. 2 and by Eq. (3), (4) and (5) for the shunt and series sources, the power equations of the UPFC are written

$$\begin{aligned} P_{se} &= V_{se}^2 G_{mm} \\ &+ V_{se}V_k(G_{km}\cos(\varphi_{se} - \delta_k) + B_{km}\sin(\varphi_{se} - \delta_k)) \quad (8) \\ &+ V_{se}V_m(G_{mm}\cos(\varphi_{se} - \delta_{mk}) + B_{mm}\sin(\varphi_{se} - \delta_m)) \end{aligned}$$

$$\begin{aligned} P_{sh} &= -V_{se}^2 G_{sh} \\ &+ V_{sh}V_k(G_{sh}\cos(\varphi_{sh} - \delta_k) + B_{sm}\sin(\varphi_{se} - \delta_k)) \quad (9) \end{aligned}$$

3.3. Implementation of UPFC in Newton Raphson power flow algorithm

The implementation of UPFC model into load flow solution required a modifications to the habitual load flow algorithm. into power mismatches calculation, the powers contributed by UPFC are included, the contributions of the voltage sources of the UPFC modifies the elements of the Jacobian matrix, change in the admittance matrix caused from series and shunt impedance, this increase the complexity of the program [17]. The network equations are combined with the UPFC power equations to give Eq. (10):

$$\mathrm{P_k} + \mathrm{jQ_k} = \sum_{j=1}^{n} \mathrm{V_k}\,\mathrm{V_m}\,\mathrm{Y_{km}}\angle(\theta_{km} - \delta_k + \delta_m) + \mathrm{P'_k} + \mathrm{jQ'_k} \quad (10)$$

Where

- P'_k , Q'_k : active, reactive power flow due to UPFC between the bus k and m.
- P'_m , Q'_m: active, reactive power flow due to UPFC between the bus m and k.

- $V_k\angle\delta_k$: the voltage ∠ angle of k[th] bus.
- $V_m\angle\delta_m$: the voltage ∠ angle of m[th] bus.
- Y_{km} : the admitance between the bus k and m.

Eq. (10) is linearised with respect to the variables of the UPFC and the network. The power flow constraint of the UPFC is included in the jacobian. The inclusion of these variables increases the dimension of the jacobian. The power equations are mismatched until convergence is achieved. A scalar multiplier is used to control the updating of variables to ensure that they converge in an optimal way to the solution point [18].

4. Simulation Results

Fig. 3 shown a distribution network considered in order to validate the presented voltage regulation scheme. The system under study consists of a D-UPFC which is installed at the end of the feeder where DG unit is located. The OLTC is installed on the secondary side of the 60/20 KV transformer [19].

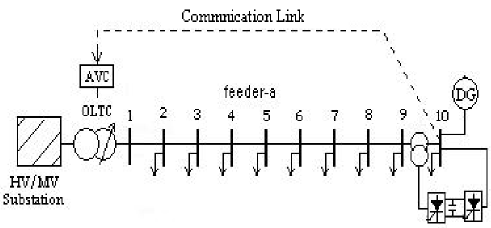

Fig. 3. The investigated system

Following, there are the parameters of the investigated system

- The bus and line data are for IEEE 10 bus distribution system.
- Total loads of the network are 12.368 MW and 4.186 MVAR.
- PDG= 4 MW is the Maximum power of DG unit.

In this paper, simulation of the voltage regulation of the system is given in a worst case. The simulations are carried out by using MATLAB to write the load flow program based on Newton Raphson algorithm.

Fig. 4 shows the voltage at the bus 10 as a function of power of DG unit and demand of the load.

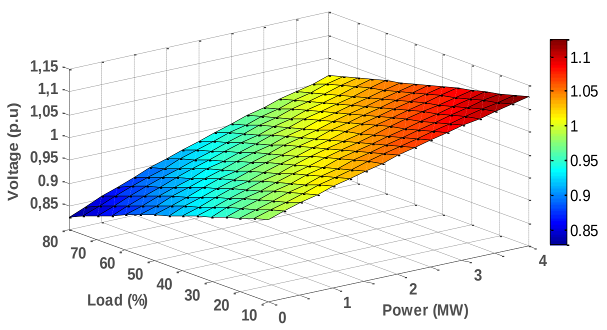

Fig. 4. Voltage at bus 10 with variations of load demand and DG power

We can see from Fig. 5 that the worst case of voltage drop is at 100% of the nominal load (demand of the load is maximal) and P_{DG}= 0 (DG generates its minimum power), and that the worst case of voltage rise is at 20% of the nominal load (demand of the load is minimal) and P_{DG}= 4 MW (DG generates its maximum power).

4.1. Case 1

The first test case is when P_{DG}= 4 MW (DG generates its maximum power) and the demand of the load is 20% of the nominal load (load is minimal). In this situation, the voltage profile along the feeder is showed in Fig. 5.

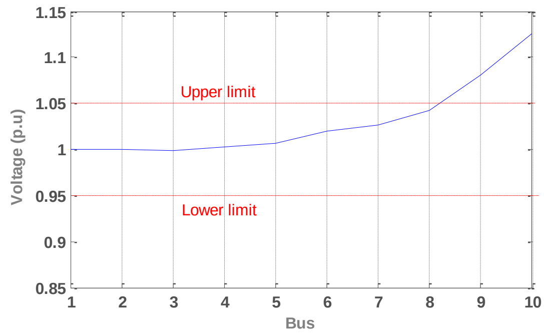

Fig. 5. Voltage profile in the case 1 without any controller

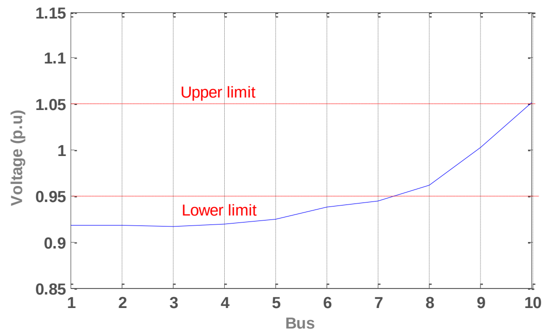

Fig. 6. Voltage profile in the case 1 with single action of OLTC

Voltage rise at bus 10 is exceeded the permitted range of the voltage (+5%), the single action of OLTC cannot manage the voltage rise along the feeder as shows Fig. 6. This action of OLTC causes a voltage drop at the near bus from sending point of the feeder (-5% between bus 1 and bus 7).

Fig. 7 show that the D-UPFC adapt the amount of absorbed reactive power to control the voltage of the regulated point. It can regulate the voltage at the target voltage value as long as we stay the exchanged reactive power within the maximal limits. Fig. 8 shows that the extreme voltage rise at bus 10 is managed by the proposed idea. As it can be seen, the voltage rise at bus 10 without any controller is about 12%. Based on the proposed idea, the OLTC action manage 5% of this voltage rise, and the D-UPFC response settle 7% of this voltage rise (the rest of the voltage rise) with absorption of 1.3 Mvar of reactive power (inductive mode).

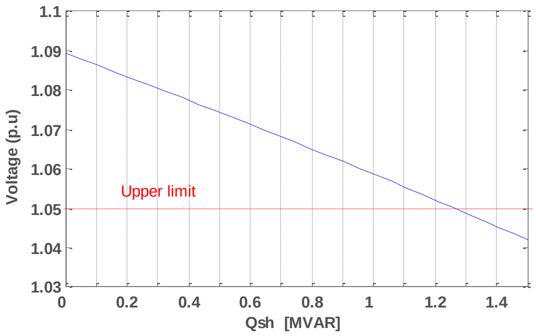

Fig. 7. Voltage at bus 10 in the case 1 with the variation of D-UPFC reactive power

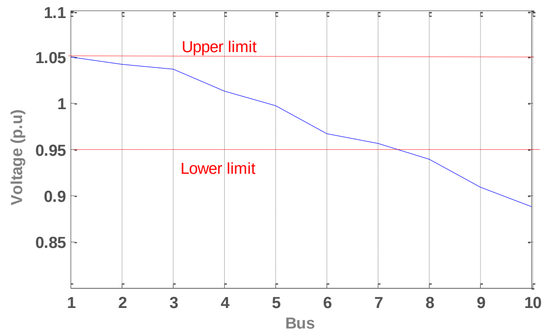

Fig. 10. Voltage profile in the case 2 with single action of OLTC

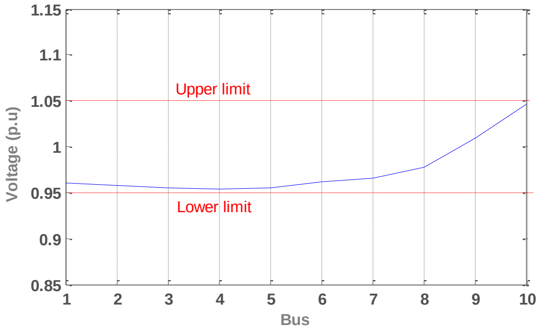

Fig. 8. Voltage profile in the case 1 with the proposed idea

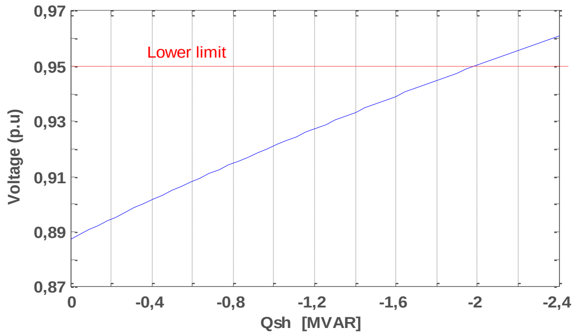

Fig. 11. Voltage at bus 10 in the case 2 with the variation of D-UPFC reactive power

4.2. Case 2

The second worst test case is considered when P_{DG}= 0 MW (DG generates its minimum power) and the demand of the load is 100% of the nominal load (load is maximal). In this situation, the voltage profile along the feeder is showed in Fig. 9. The voltage drop at bus 10 is exceeded the permitted range of the voltage (-5%). Like the 1st case, the single action of OLTC cannot effectively manage the voltage drop along the feeder (more than 6%) as shows in Fig. 10.

Fig. 11 show that the D-UPFC adapt the amount of injected reactive power to control the voltage of the regulated point. It can regulate the voltage at the target voltage value as long as we stay the exchanged reactive power within the minimal limits. As it can be seen in Fig. 12, that the proposed idea with the combination of D-UPFC response and OLTC action is able to keep the voltage within the predefined limits of all buses. In this case, the D-UPFC injects 2.1 Mvar of reactive power (capacitive mode).

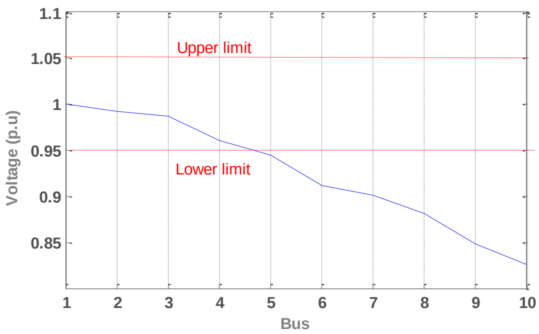

Fig. 9. Voltage profile in the case 2 without any controller

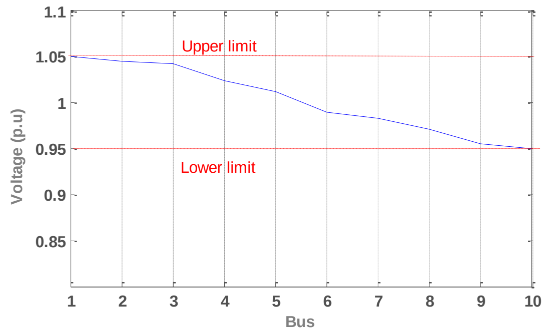

Fig. 12. Voltage profile in the case 2 with the proposed idea

It can be concluded based on the simulation results, that the proposed method is able to keep the voltage within the limits of all system buses and exploit any energy produced by DG, by absorbing and storing the excess energy produced (case 1). The proposed method is able too to keep the voltage within the limits of all system buses when there is a voltage drop by injecting the minimum of the energy stored into the network with help of OLTC (case 2).

5. Conclusion

The concept of future distribution system has influence for many potential opportunities for the control schemes of the OLTC. The OLTC transformer control relationship with reactive control has been illustrated. When system have problem such as voltage violations, the FACTS device as D-UPFC is an instrumental for support in the power system. The proposed method was to allow D-UPFC to manage the rest of the voltage violations during use the OLTC action in the predefined range based on the permitted range of voltage. And simulation results have verified this method. A practical evaluation and the cost of implementation of the proposed method will be investigated in future research.

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