Coordinated Action of OLTC and D-GUPFC for Managing the Distribution System Voltage with DG units

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***Abstract*—This paper presents a new technique for the voltage regulation of a radial medium voltage (MV) distribution grid in presence of distributed generation (DG) units. The proposed technique consists of the coordinated action of on-load tap changer (OLTC) of transformer and hybrid power compensation by D-GUPFC. Managing the system voltage using the action of OLTC is one of the most common ways for voltage regulation of MV systems. However, OLTC cannot be used for voltage regulation of long radial distribution feeders as it changes the sending point voltage of the feeder. In this study, the problem of using OLTC for the voltage regulation of a radial distribution feeder will be solved by using reactive power compensation at the DG connected bus. Simulation results reveal that the proposed control method is capable of maintaining the system voltage within the permitted range in the worst scenarios of the test system.**

Keywords-component; FACTS; D-GUPFC; Distributed Generation; distribution systems.

I. INTRODUCTION

The proportion of renewable energies in power generation has increased significantly in recent years according to the political aims. Thus, the distribution networks have to meet hitherto unfamiliar technical challenges. A temporary reversal of the power flow can cause overvoltage problems. Traditional voltage regulation strategies cannot solve this problem. Consequently, regenerative sources need to be turned off temporarily or on the long term the network infrastructure has to be extended by the network operator. In some areas, the installed generation power is significantly higher than the consumption. Distributed generation (DG) causes altered power flow patterns. Thus, the power flow may even become bidirectional. The temporary reversal of the power flow can provoke voltage rises away from the substation, especially at remote feeder ends. If the voltage exceeds the tolerance of usually 10 % above nominal voltage, other devices and equipment might be damaged [1].

In recent years, several control strategies have been applied to maintain the voltage of distribution systems within the defined range. Theoretically, different methods can be applied for voltage regulation of distribution systems but the most applicable methods are curtailment of DG power, network reinforcement, OLTC action and reactive power compensation. Since the voltage rise problem is caused by the injected power of DG, curtailment of DG active power is one possible method but it does not allow to maximize the

benefits of integrating DG units. The voltage profile along the feeder is strictly dependent on the impedance of lines. Therefore, network reinforcement is another possible method but it is expensive, it needs long delays and DSOs normally consider it as the last possible option. Generally, OLTC action and reactive power compensation are the best possible methods but each of these methods has its own advantages and drawbacks which are explained in the following sections. In reference [2], a coordinated voltage control method has been proposed in order to manage the tap changer action of transformer and to control the reactive power of DG units and reactive power compensation in reference [3]. But the most of distributions network are constituted with several feeders which requires several controllers. A problem with more number of controllable parameters makes the system non-linear and discontinues. With the development in semi-conductor technology, the new convertible static compensators are developed using two or more series converters and coordinated with one shunt converter. The most popularly used Convertible Static compensator (CSC) devices are Generalized Unified Power Flow Controller (GUPFC) and Generalized Interline Power Flow Controller (GIPFC).

A simple modeling approach based on quadrature equation is proposed to analyze the effect of series connected multi-line VSC based FACTS controllers is presented in [3]. In the past, much effort has been made in the modeling of the Unified Power Flow Control (UPFC) for power flow analysis. UPFC compensate a single transmission line, whereas the GUPFC is used for the compensation and power flow control of multi-line transmission system. Mathematical models of GUPFC, IPFC and their implementation in Newton power flow are described in [8] to demonstrate the device performance. When the GUPFC is applied in distribution system is called D-GUPFC (Distribution-GUPFC) and its configuration is the same.

In this paper, in order to maximize the benefits of OLTC action and D-GUPFC response, a new voltage control method is proposed. The main idea is to concentrate the response of each controller in its most suited working ranges and to consequently use each controller in the defined voltage range which corresponds to its merits.

II. ON LOAD TAP CHARGER ACTION OF TRANSFORMATEUR

Using OLTC action is the most popular method in voltage regulation of distribution systems because it is easy to implement and design. In this method, the turn ratio of the transformer winding is adjusted by the tap changer mechanism of the transformer when the voltage of the system exceeds the specified range. The tap changer action is normally adjusted by an automatic voltage control (AVC) relay which continuously monitors the system voltage and controls the action of tap changer. The AVC relay works based on the two controlling parameters which are the reference voltage of the regulated point and a defined dead band. This dead band is designed to limit the unnecessary actions of the tap changer. The tap changing operation is normally done with a time delay due to the dynamic response of the OLTC mechanism. The drawback of the OLTC method is that it cannot be used in voltage regulation of long radial distribution systems because it changes the voltage of the feeder sending point while the biggest voltage violation occurs at the end of line (ending point of the feeder). In this situation, in order to return the ending point voltage inside the permitted range, OLTC must change noticeably the sending point voltage and it can lead to voltage violation at this point of the feeder.

III. GENERALIZED UNIFIED POWER FLOW CONTROLLERS

A. *Basic Principles of GUPFC*

The basic configuration of GUPFC consist of two series converters connected in two transmission lines and are coordinated with shunt converter connected at sending common end of the considered transmission lines. This device has five/more degrees of freedom to control power system parameters. Such as it can control active and reactive power flows in series converter connected transmission lines and it can control voltage magnitude of the shunt converter connected bus. For control of GUPFC, proportional-integral (PI) loops are utilized. In this scheme the gains of controller parameters are being selected to provide stable operation of GUPFC under steady state and faulty conditions. GUPFC [6], also known as multi-line UPFC, can control bus voltage and power flows of more than one lines or even of sub-networks. The basic configuration of GUPFC is shown in “Fig. 1”. GUPFC series and shunt converters can be represented by an equivalent controllable voltage source in series with an equivalent reactance of converter transformers. Let us consider device is connected between buses i, j and k.

The equivalent voltage source model of simple GUPFC consisting of three converters is shown in “Fig. 2” . The two controllable voltage sources can be expressed as [7]

$$\begin{cases} \bar{V}_{s,ij} = V_{s,ij}\ e^{j\varphi_{s,ij}} \\ \bar{V}_{s,ik} = V_{s,ik}\ e^{j\varphi_{s,ik}} \end{cases} \quad (1)$$

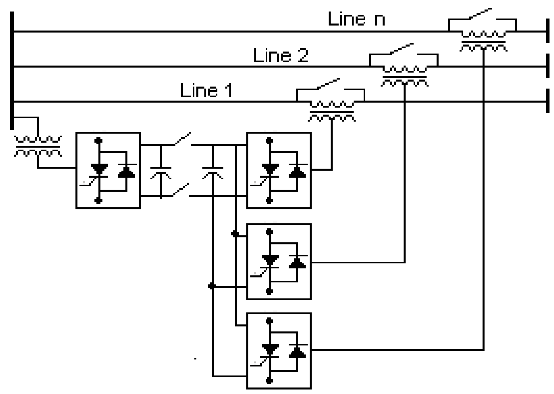


Figure 1. Generic representation of a GUPFC.

Where $V_{s,ij}$, $V_{s,ik}$ and $\varphi_{s,ij}$, $\varphi_{s,ik}$ are respective magnitude and phase angles of the series voltage sources operating within the limits $0 \leq V_{s,ij} \leq V_{s,ij\ max}$, $0 \leq V_{s,ik} \leq V_{s,ik\ max}$, and $-\pi \leq \varphi_{s,ij} \leq \pi$, $-\pi \leq \varphi_{s,ik} \leq \pi$.

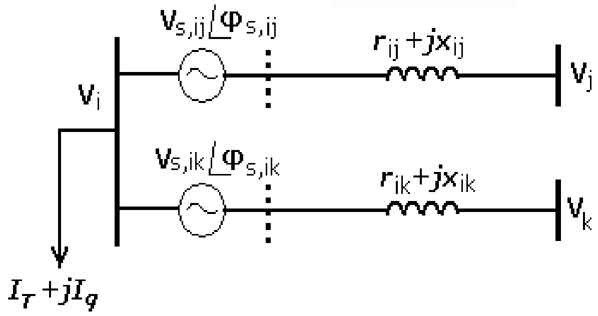


Figure 2. Equivalent circuit of GUPFC.

The equivalent circuit of GUPFC placed in line- *l* having impedance $r_{ij} + jx_{ij}$ $(= 1/(g_{ij} + jb_{ij}))$ connected between bus-*i* and bus-*j* and in line-*m* having impedance $r_{ik} + jx_{ik}$ $(= 1/(g_{ik} + jb_{ik}))$ connected between bus-*i* and bus-*k* is shown in Fig. 2. Let there be *p* (>2) numbers of lines connected at bus-*i* . GUPFC has five controllable parameters, namely the magnitude and the angle of inserted voltage (V_{s1}, $\varphi s1$) in line- *l* , the magnitude and the angle of inserted voltage (V_{s2} , φ_{s2}) in line- *m* and the magnitude of the current (I_q). The current in shunt converter can be delineated into two components viz. the current (I_T) in phase with the voltage at bus- *i* and current (I_q) in quadrature with the voltage at exciting substation.

Based on the principle of GUPFC operation and the circuit diagram, the basic mathematical relations can be written as

$$\bar{I}_{in} = (\bar{V}_i + \bar{V}_{s,in} - \bar{V}_n)\bar{y}_{in} \qquad \forall\, n = j\,, k \quad (2)$$

$$Arg(\bar{I}_q) = Arg(\bar{V}_i) \pm \pi/2\,, Arg(\bar{I}_T) = Arg(\bar{V}_i) \quad (3)$$

$$\bar{I}_T^* = \frac{Re\left[\bar{V}_{s,ij}\ \bar{I}_{ij}^* + \bar{V}_{s,ik}\bar{I}_{ik}^*\right]}{\bar{V}_i} \quad (4)$$

The power injection at bus- i can be written as

$$\bar{S}_i = P_i + jQ_i = \bar{V}_i \bar{I}_{ij}^* + \bar{V}_i \bar{I}_{ik}^* + \bar{V}_i (I_T + jI_q)^* + \sum_{\substack{i=1 \\ \neq j,k}}^{p} \bar{V}_i \bar{I}_{ip}^* + \bar{V}_i \bar{I}_{sh}^* \tag{5}$$

There $\bar{I}_{sh}$ is the shunt current due to line charging. All the bold quantities represent the complex variables.

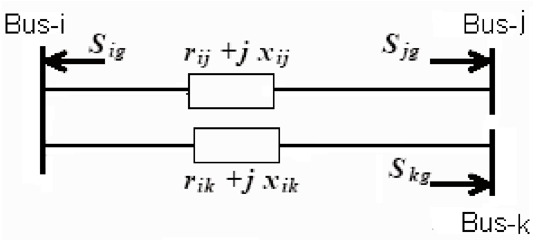


Figure 3. Injection model of GUPFC.

The effect of GUPFC can be represented as injected power with the network without GUPFC as shown in "Fig. 3". The injected complex powers $\bar{S}_{i,GUPFC}^* = (P_{i,GUPFC} + jQ_{i,GUPFC})$ at bus-*i* , $\bar{S}_{j,GUPFC}^* = (P_{j,GUPFC} + jQ_{j,GUPFC})$ at bus-*j* and $\bar{S}_{k,GUPFC}^* = (P_{k,GUPFC} + jQ_{k,GUPFC})$ at bus-*k* can be written as,

$$\bar{S}_{i,GUPFC} = \bar{S}_i^0 - \bar{S}_i = [\bar{V}_i \bar{V}_{sj}^* \bar{y}_{ij}^* + \bar{V}_i \bar{V}_{sk}^* \bar{y}_{ik}^* + \bar{V}_i (I_T + jI_q)^* \tag{6}$$

$$\bar{S}_{n,GUPFC} = \bar{S}_n^0 - \bar{S}_n = \bar{V}_n \bar{V}_{sn}^* \bar{y}_{in}^* \qquad \forall\, n = j\,, k \tag{7}$$

Where $\bar{S}^0$ is the complex power injection when there was no GUPFC.

The injected active and reactive powers at bus- i will be

$$P_{i,GUPFC} = -V_{s,ij}^2\, g_{ij} - V_{s,ik}^2\, g_{ik} - 2V_{s,ik} V_k g_{ik}\, cos(\varphi_{s,ik} - \delta_k) - 2V_{s,ij} V_i g_{ij}\, cos(\varphi_{s,ij} - \delta) - V_{s,ij} V_j [g_{ij}\, cos(\varphi_{s,ij} - \delta_j) + b_{ik}\, sin(\varphi_{s,ij} - \delta_j)] - V_{s,ik} V_k [g_{ik}\, cos(\varphi_{s,ik} - \delta_k) + b_{ik}\, sin(\varphi_{s,ik} - \delta_k)] \tag{8}$$

$$Q_{i,GUPFC} = V_i I_q + V_i V_{s,ij} [g_{ij}\, sin(\varphi_{s,ij} - \delta_i) + b_{ij}\, cos(\varphi_{s,ij} - \delta_i)] \; V_i V_{s,ik} [g_{ik}\, sin(\varphi_{s,ik} - \delta_i) + [b_{ik}\, cos(\varphi_{s,ik} - \delta_i)] \tag{9}$$

Similarly the real and reactive powers injections at bus- j and bus- k can be derived as

$$P_{n,GUPFC} = V_n V_{s,in} [g_{in}\, cos(\varphi_{s,in} - \delta_n) - b_{in}\, sin(\varphi_{s,in} - \delta_n)] \qquad \forall\, n = j\,, k \tag{10}$$

$$Q_{n,GUPFC} = -V_n V_{s,in} [g_{in}\, sin(\varphi_{s,in} - \delta_n) - b_{in}\, cos(\varphi_{s,in} - \delta_n)] \qquad \forall\, n = j\,, k \tag{11}$$

B. *GUPFC Power Mismatches Equations*

The power mismatch equations in NR method can be modified by using the following equations.

$$\Delta P_{i,new} = \Delta P_{i,old} + \Delta P_{i,GUPFC} \tag{12}$$

$$\Delta Q_{i,new} = \Delta Q_{i,old} + \Delta Q_{i,GUPFC} \tag{13}$$

Where, $\Delta P_{i,old}$ and $\Delta Q_{i,old}$ are the real and reactive power mismatches without FACTS device. Similar modifications can be obtained for the remaining GUPFC buses.

C. *GUPFC Jacobian elements*

The injected active power at buses ($P_{i,GUPFC}$, $P_{j,GUPFC}$ and $P_{k,GUPFC}$), and reactive powers ($Q_{i,GUPFC}$, $Q_{j,GUPFC}$ and $Q_{k,GUPFC}$) having a GUPFC are calculated using (8) to (13). Thus, the relationship are obtained for small variations in *V* and *δ*, by forming the total differentials,

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = J1 \begin{bmatrix} \Delta\delta \\ \Delta V/V \end{bmatrix} + J2 \begin{bmatrix} \Delta\delta \\ \Delta V/V \end{bmatrix} \tag{14}$$

$$J = J1 + J2 \tag{15}$$

where ***J***1 is the normal N-R power flow Jacobian matrix and ***J***2 is the partial derivative matrix of injected power with respect to the variables. The computation formulas of J2 are given below

$$\frac{\partial P_{i,GUPFC}}{\partial \delta_i} = -\sum_{n=j,k} 2V_{s,in} V_i\, g_{in}\, sin(\varphi_{s,in} - \delta_i) \tag{16}$$

$$\frac{\partial P_{i,GUPFC}}{\partial \delta_n} = V_{s,in} V_n\, [g_{in}\, sin(\varphi_{s,in} - \delta_n) - b_{in}\, cos(\varphi_{s,in} - \delta_n)] \qquad \forall\, n = j\,, k \tag{17}$$

$$\frac{\partial P_{n,GUPFC}}{\partial \delta_n} = V_{s,in} V_n\, [g_{in}\, sin(\varphi_{s,in} - \delta_n) + b_{in}\, cos(\varphi_{s,in} - \delta_n)] \qquad \forall\, n = j\,, k \tag{18}$$

$$\frac{\partial P_{i,GUPFC}}{\partial V_i} = -\sum_{n=j,k} 2V_{s,in}\, g_{in}\, cos(\varphi_{s,in} - \delta_i) \tag{19}$$

$$\frac{\partial P_{i,GUPFC}}{\partial V_n} = V_{s,in}\, [g_{in}\, cos(\varphi_{s,in} - \delta_n) + b_{in}\, sin(\varphi_{s,in} - \delta_n)] \qquad \forall\, n = j\,, k \tag{20}$$

$$\frac{\partial P_{n,GUPFC}}{\partial V_n} = V_{s,in}\, [g_{in}\, cos(\varphi_{s,in} - \delta_n) + b_{in}\, sin(\varphi_{s,in} - \delta_n)] \qquad \forall\, n = j\,, k \tag{21}$$

$$\frac{\partial Q_{i,GUPFC}}{\partial \delta_i} = \sum_{n=j,k} \begin{pmatrix} V_{s,in} V_i [-g_{in} \cos(\varphi_{s,in} - \delta_i) + \\ b_{in} \sin(\varphi_{s,in} - \delta_i)] \end{pmatrix} \quad (22)$$

$$\frac{\partial Q_{n,GUPFC}}{\partial \delta_n} = \begin{matrix} -V_{s,in} V_n [-g_{in} \cos(\varphi_{s,in} - \delta_n) + \\ b_{in} \sin(\varphi_{s,in} - \delta_n)] \end{matrix} \forall n = j, k \quad (23)$$

$$\frac{\partial Q_{i,GUPFC}}{\partial V_i} = I_q + \sum_{n=j,k} \begin{pmatrix} V_{s,in} [g_{in} \sin(\varphi_{s,in} - \delta_i) + \\ b_{in} \cos(\varphi_{s,in} - \delta_i)] \end{pmatrix} \quad (24)$$

$$\frac{\partial Q_{n,GUPFC}}{\partial V_n} = \begin{matrix} -V_{s,in} [g_{in} \sin(\varphi_{s,in} - \delta_n) + \\ b_{in} \cos(\varphi_{s,in} - \delta_n)] \end{matrix} \forall n = j, k \quad (25)$$

With help of (16) to (25) the power flow Jacobian matrix can be modified and power flow equations can be solved by conventional N-R method.

IV. Simulation Results

In order to validate the proposed voltage regulation scheme, a radial distribution system with two distribution lignes is considered which is shown in "Fig. 4". The system under study consists of two DG unit which are located at the end of the two distribution lines. The OLTC mechanism is installed on the secondary side of the HV/MV transformer (60/30 KV) [8] [9].

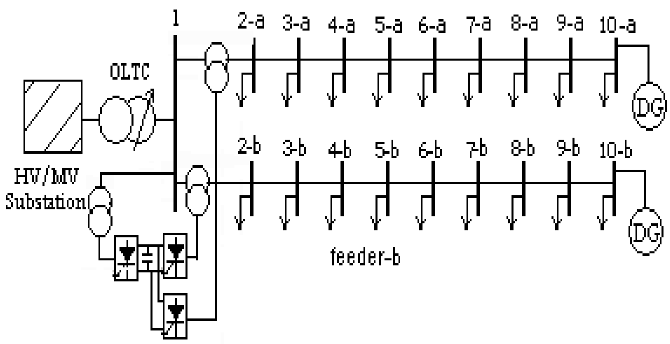


Figure 4. The investigated system.

The parameters of the investigated system are as follow:

- The line and bus data of feeder-a are same as feeder-b, and are same as IEEE 10 bus distribution system.
- Total load of each feeder are 12.368 MW and 4.186 MVAR.
- Maximum power of DG unit (P_{DG})= 2.5 MW.

In this paper, a worst case in the voltage regulation of the investigated system is simulated. The simulations are carried out by using a Newton–Raphson algorithm based load flow program written in MATLAB [8] [9].

"Fig. 5" shows the voltage at the bus 10 of one feeder as a function of demand of the load and power of DG unit.

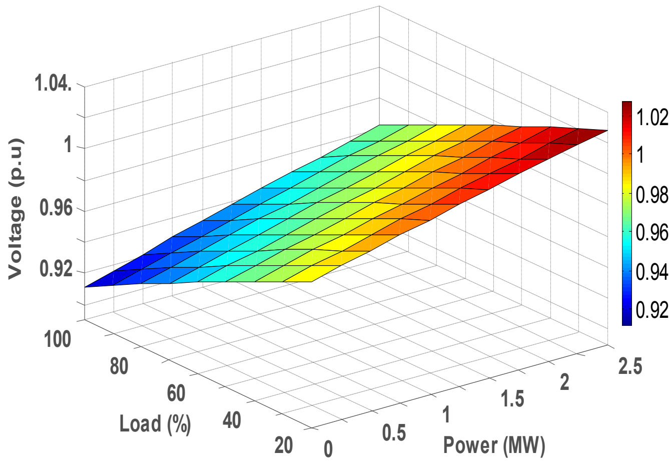


Figure 5. Voltage at bus 10 with variations of demand of the load and power of DG.

We can see that the worst case of voltage rise is when DG generates its maximum power (P_{DG}= 2.5 MW) and the demand of the load is minimal (20% of the nominal load) and that the worst case of voltage drop is when DG generates its minimum power (P_{DG}= 0) and the demand of the load is maximal (100% of the nominal load).

A. *Case 1*

The first test case is when the two DGs units are at its minimum power, the demand of the load at *feeder-a* is minimal (20% of the nominal load) and load at *feeder-b* is maximal (100% of the nominal load).

"Fig. 6" shows the profile of the voltage along the *feeder-a* and *feeder-b* without any controller. As the voltage drop at bus 7-b to bus 10-b is more than the permitted range of the voltage (± 5%), while OLTC is able to keep the voltage of all buses within the predefined limits "Fig. 7".

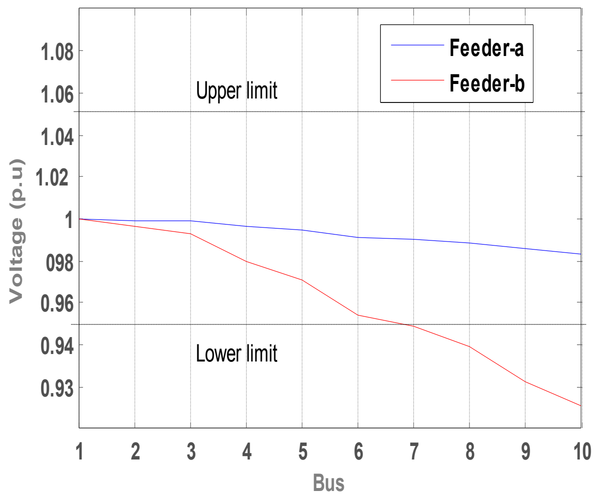


Figure 6. Voltage profile of the system buses in the case 1 without any controller.

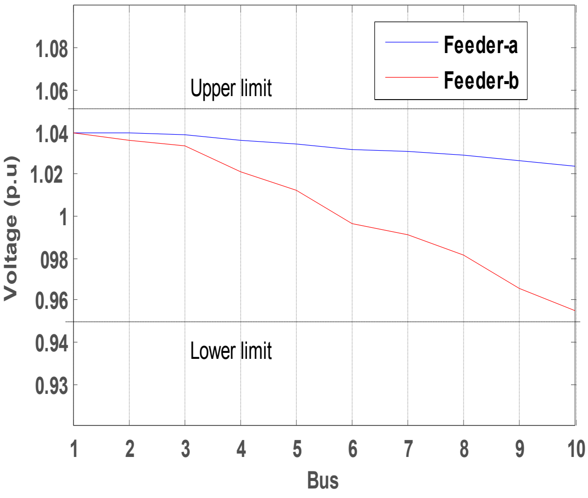
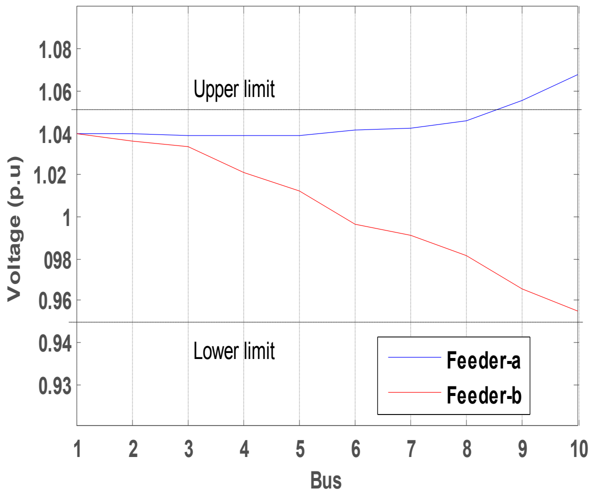


Figure 7. Voltage profile of the system buses in the case 1 with single action of OLTC.



Fgure 9. Voltage profile of the system buses in the case 2 with single action of OLTC.

B. *Case 2*

The second test case is when the DG unit connected at feeder-a is at its maximum power, the other DG unit is at its minimum power, a demand of the load at feeder-a is minimal (20% of the nominal load) and a load at feeder-b is maximal (100% of the nominal load).

"Fig. 8" shows the profile of the voltage along the feeder-a and feeder-b without any controller. As the voltage drop at bus 10-b is more than the permitted range of the voltage (± 5%), The single action of the OLTC leads to a voltage rise at feeder-a (bus 9-a to bus 10-a) "Fig. 9".

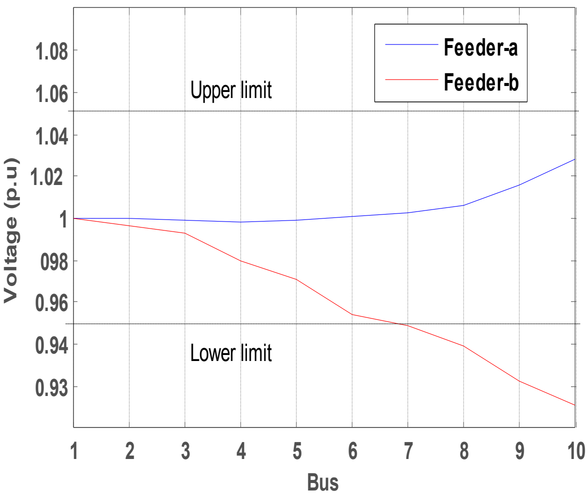


Figure 8. Voltage profile of the system buses in the case 2 without any controller.

"Fig. 10" show the voltage at bus 10-a with the variation of magnitude and phase angle of serie injected voltage of GUPFC in the feeder-a, The voltage at bus 10-a varies in the range 0.92 to 1.12 pu.

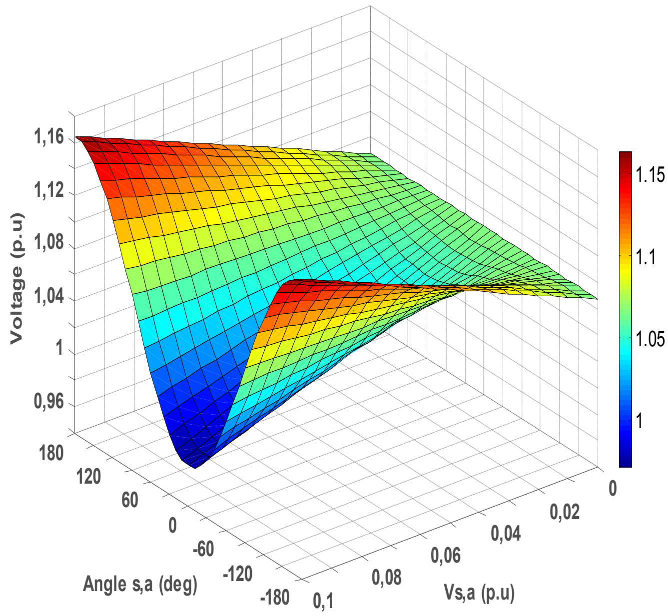


Figure 10. voltage at bus 10-a with the variation of magnitude and phase angle of serie injected voltage.

We can see several values of magnitude and phase angle of serie injected voltage can keeps the voltage at bus 10-a within the permitted range. Among these values, we takes the value 0.04 pu for the magnitude and 0 rad for the phase angle.

"Fig. 11" shows the profile of the voltage along the feeder-a in the case 2 with different values of Vs (series voltage amplitude).

"Fig. 12" shows the profile of the voltage along the feeder-a and feeder-b with the proposed idea.

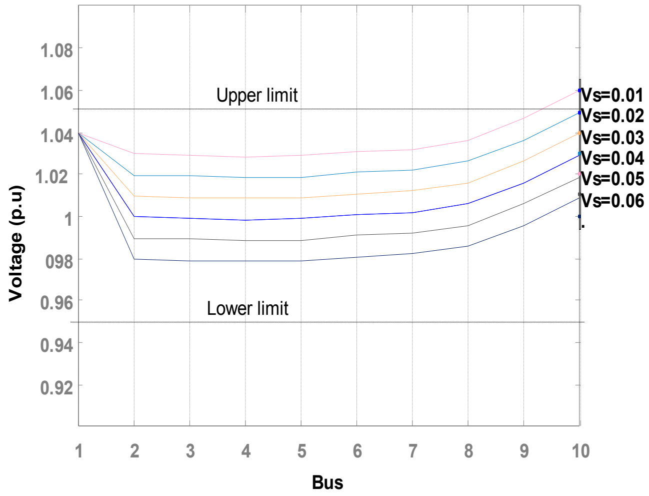


Figure 11. Voltage profile of the Feder-a in the case 2 with variation of Vs.

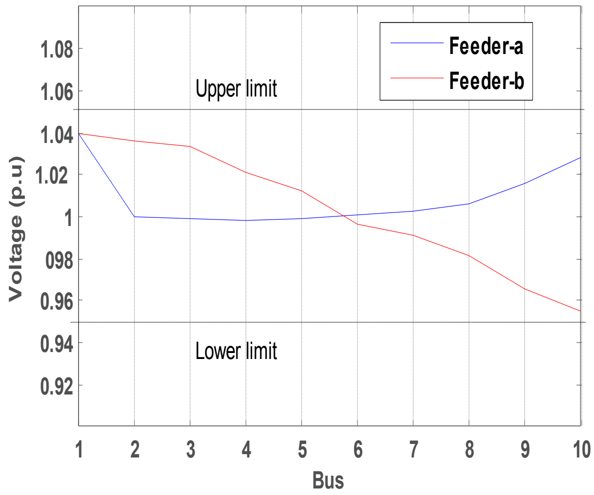


Figure 12. Voltage profile of the system buses in the case 2 with the proposed idea.

The proposed idea is capable of managing the extreme voltage rise at bus 9-a to bus 10-a caused by OLTC action. As it can be seen, without any controller "Fig. 8", there is a voltage drop at feeder-b and based on the proposed idea, this voltage drop was managed by OLTC action that caused the voltage rise at feeder-a"Fig. 9" , latter was compensated by D-GUPFC response as shown in "Fig. 12".

Based on the simulation results, it can be concluded that the proposed method is able to keep the voltage of the all buses within the limits.

V. Conclusion

A new idea was presented in this paper for the voltage regulation of multiple feeders radial distribution systems with Distributed Generation connected at the systems bus. The proposed method was principally based on the combination of the two different control methods which are static compensator and OLTC action. The idea was to use (based on the permitted range of voltage) the OLTC action in the predefined range and allow the D-GUPFC to manage the rest of the voltage violations. Simulation results revealed that proposed idea enables us to control the voltage problem of a radial medium voltage distribution system with multiple feeders in the worst working conditions. Moreover, as the D-GUPFC is used in the extreme voltage conditions (when OLTC cannot work anymore), it doesn't considerably increase network losses. In the future research, the cost of implementation and a practical evaluation of the proposed method will be investigated.

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