Using DGUPFC to Control the Voltage of Multi-Feeder Smart Distribution System

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Abstract-This paper presents a new method for the voltage regulation of a medium voltage (MV) radial distribution network in the presence of the distributed generation units (DG). This method based of the coordinated between action of the on-load tap-changer (OLTC) in the transformer and of the static power compensator by DGUPFC. The DGUPFC is one of the FACTS devices and the latest generation of hybrid compensators (series and shunt compensators at the same time).The control of the system voltage with the OLTC action is one of the old most common ways in the regulate of MV systems voltage. However, the OLTC circuit cannot be used to regulate the voltage of several long distribution feeders with DG units. In this study, the OLTC problem of using for voltage regulation of a feeder distribution will be solved using the reactive power compensation at the connected DGUPFC bus. The results of the simulation show that the proposed control technic is able to maintaining the system voltage in the allowed band in the worst-case scenarios test.

Keywords-DGUPFC, Distributed Generation, Distribution systems, OLTC, Load flow.

List of abbreviations

DG	–	DistributedGeneration
DGUPFC	–	Distribution Generalized Unified Power Flow Controller
FACTS	–	Flexible Alternating Current Transmission Systems
HV	–	High Voltage
IPFC	–	Interline Power Flow Controller
MV	–	Medium Voltage
N-R	–	Newton-Raphson
OLTC	–	On LoadTap Changer
PI	–	ProportionalIntegral
SSSC	–	StaticSynchronousSeriesCompensator
STATCOM	–	StaticSynchronousCompensator
UPFC	–	Unified Power Flow Control

1. Introduction

The appearance of renewable energies and their participation in power generation has increased in recent years. The distribution networks should meet unfamiliar technical challenges [1]. The revers power flow caused by DG can cause overvoltage problems. This problem can't solved with traditional voltage regulation. Consequently, DG need to be temporarily turned off, or the network infrastructure must to be extended on the long term by the network operator. The generation power installed in some areas is higher than the consumption power. A voltage rises can be provoked away from the substation because of reversal temporary of the power flow, especially at feeder ends. Equipment and devices might be damaged if the voltage exceeds authorized usual tolerance [2].

With the connection of DG in distribution networks, a several control strategies to maintain the voltage within the defined range have been applied in recent years. Theoretically, for voltage regulation in distribution systems, different methods can be applied. Curtailment of DG power is the most applicable methods, reactive power compensation, OLTC action and network reinforcement. Since the problem of voltage rise is caused by DG injected power [3]. One of possible method is the reduction of DG active power, but it does not allow exploiting the maximum operation of the generators [4]. The voltage profile at along of the feeder is dependent on the impedance of lines. Therefore, the reinforcement of network is another possible method but it needs long delays, it is expensive and Distribution System Operators consider it as the last possible solution. Generally, reactive power compensation and OLTC action are the best possible option, but each of these solutions has its own drawbacks and advantages that will explained at the following sections. A coordinated voltage control method has been proposed in reference [5] in order to manage the transformer tap changer action and to control the DG reactive power, and reactive power with static compensation in reference [6]. However, in most, there are several feeders in distributions network that requires several controllers. With the development of the technology of semi conductors, and using two or more series converters which are coordinated with one shunt converter, a new static compensatorsare developed [7,8]. The most popularly convertible static compensator device is IPFC [9].

In reference [10], a simple modelling to analyze the effect of series connected multi-line is proposed based on quadrature equation. Much effort has been made in the past in the modelling of UPFC into the power flow analysis [11,12]. The UPFC can compensate a single line, whereas the DGUPFC can compensate and control the power flow of multi-line system. In [13], mathematical models of IPFC and their implementation in N-R power flow are described to show the device performance.

In this paper, a new voltage control technic is proposed in order to maximize the interest of OLTC action and DGUPFC response. The principal idea is to concentrate the action of each controller in its most adapt working ranges and to use consequently each controller in the specified voltage range that corresponds to its worth.

2. On Load Tap Charger Action

The adjustment of the voltage in the distribution networks is achieved by changing the tap of the transformers. The tap change can be carried out without disconnecting the transformer from the mains (setting under load). When switching from one socket to another, a resistor (more rarely an inductor) is inserted. The insertion of this resistor makes it possible to limit the current during the change of taps. During this change, a large current can flow in a part of the turns of the transformer and this is because at the time of the change of the plug there is a short circuit [14].

The tap change (whether to increase or decrease the voltage) occurs when the voltage measured at a point in the network exceeds either the minimum voltage or the maximum voltage and the voltage exceeds a minimum time.

Load adjusters typically have either 19, 21 or 25 outlets. They can compensate for a voltage variation of ± 12% of nominal voltage.

In long radial distribution systems, the OLTC can't be used in voltage regulation because it modifies the voltage of the feeder while the greater voltage violation occurs at ending point of the feeder. In order to return the voltage at the end of line inside the permitted range, the OLTC must change substantially the voltage of sending point and it can bring to voltage violation in this feeder point [15].

3. Distribution Generalized Unified Power Flow Controllers

3.1. *Topology of DGUPFC*

The DGUPFC is consist of two SSSC connected in two electric lines and are coordinated with a STATCOM connected at common node of the electric lines [16]. This dispositive has five more freedom degrees to control the power of the system. As it can control the active and the reactive power with the SSSC and it can control the voltage magnitude with the STATCOM, loops of PI are used to control of the DGUPFC.The DGUPFC is the equivalent of multi-UPFC, can control power flows and bus voltage of several lines [17-19]. The configuration of DGUPFC is presented in “Fig. 1”. DGUPFC series and shunt converters are represented bytransformersreactancein series with a voltage source. Let us consider that device is connected between bus i, bus j and bus k.

The DGUPFC is modelled as a voltage source consisting of three converters as in “Fig. 2”. The two of the controllable voltage sources are expressed as [20,21]

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

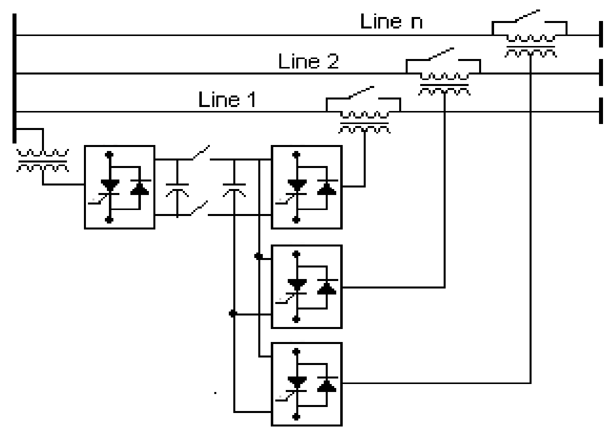

Fig. 1. Generic representation of a DGUPFC.

Where $V_{s,ij}$, $V_{s,ik}$ and $\varphi_{s,ij}$, $\varphi_{s,ik}$ are in respective the magnitude and the phase angles of series voltage sources where operating within his limits $0 \le V_{s,ij} \le V_{s,ijmax}$, $0 \le V_{s,ik} \le V_{s,ikmax}$, and $-\pi \le \varphi_{s,ij} \le \pi$, $-\pi \le \varphi_{s,ik} \le \pi$.

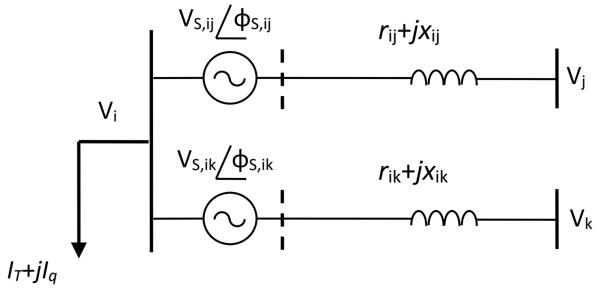

Fig. 2. Equivalent circuit of DGUPFC.

The DGUPFC equivalent circuit when is placed in the line-l have impedance $r_{ij} + jx_{ij}$ $(= 1/(g_{ij} + jb_{ij}))$ connected between the bus-iand the bus-j and in the line-m have impedance $r_{ik} + jx_{ik}$ $(= 1/(g_{ik} + jb_{ik}))$ connected between the bus-iand the bus-k as showing in Fig. 2. In DGUPFC, there is five controllable parameters: the magnitude of insertedvoltage (V_{S1} ,V_{S2}) in line-1and line-2, the angle ofinserted voltage (φs1 , φs2) in line-1 and line-2and the magnitude of current in shunt converter (I_i), which can be decomposited into two components, the current (I_T) and the current (I_q) (current in phase with the voltage of bus-iand the current in quadrature with exciting substation voltage) [22,23].

Based on the circuit diagram of DGUPFC and the principle of it operation, the mathematical relations be written as

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

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

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

The injection of the power at bus-i be written as

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

Where $\bar{I}_{sh}$, is the shunt current of line charging.

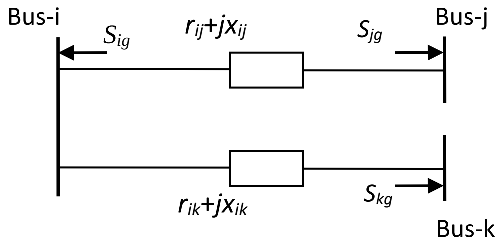

Fig. 3. DGUPFC injection model.

The DGUPFC effect is represented as an injected powers in the network as shown in"Fig. 3". The complex injected powers $\bar{S}_{i,DGUPFC}^* = (P_{i,DGUPFC} + jQ_{i,DGUPFC})$ at bus-*i* , $\bar{S}_{j,DGUPFC}^* = (P_{j,DGUPFC} + jQ_{j,DGUPFC})$ at bus-*j* and $\bar{S}_{k,DGUPFC}^* = (P_{k,DGUPFC} + jQ_{k,DGUPFC})$ at bus-*k* be written as

$$\begin{aligned} P_{i,GUPFC} = \; & -V_{s,ij}^2 g_{ij} - V_{s,ik}^2 g_{ik} - 2V_{s,ik}V_k g_{ik}\, cos(\varphi_{s,ik} - \delta_k) \\ & -2V_{s,ij}V_i g_{ij}\, cos(\varphi_{s,ij} - \delta_i) \\ & -V_{s,ij}V_j[g_{ij}\, cos(\varphi_{s,ij} - \delta_j + b_{ik}\, sin(\varphi_{s,ij} - \delta_j)] \\ & -V_{s,ik}V_k[g_{ik}\, cos(\varphi_{s,ik} - \delta_k) + b_{ik}\, sin(\varphi_{s,ik} - \delta_k)] \end{aligned} \tag{6}$$

$$\begin{aligned} Q_{i,GUPFC} = \; & V_i I_q \; + \; V_i V_{s,ij}[g_{ij}\, sin(\varphi_{s,ij} - \delta_i) + b_{ij}\, cos(\varphi_{s,ij} - \delta_i)] \\ & + V_i V_{s,ik}[g_{ik}\, sin(\varphi_{s,ik} - \delta_i) + [b_{ik}\, cos(\varphi_{s,ik} - \delta_i)] \end{aligned} \tag{7}$$

Similarly, the injection of active and reactive powers in the bus-j and bus-*k* be derived as

$$\begin{aligned} P_{n,GUPFC} = \; & V_n V_{s,in}[g_{in}\, cos(\varphi_{s,in} - \delta_n) \\ & -b_{in}\, sin(\varphi_{s,in} - \delta_n)] \qquad \forall n = j\,,k \end{aligned} \tag{8}$$

$$\begin{aligned} Q_{n,GUPFC} = \; & -V_n V_{s,in}[g_{in}\, sin(\varphi_{s,in} - \delta_n) \\ & +b_{in}\, cos(\varphi_{s,in} - \delta_n)] \qquad \forall n = j\,,k \end{aligned} \tag{9}$$

3.2. *Power Mismatches Equations of DGUPFC*

In Newton-Raphson method, the power mismatch equations be modified with using the equations in following.

$$\Delta P_{i,new} = \Delta P_{i,old} + \Delta P_{i,GUPFC} \tag{10}$$

$$\Delta Q_{i,new} = \Delta Q_{i,old} + \Delta Q_{i,GUPFC} \tag{11}$$

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

3.3. *Jacobian elements of DGUPFC*

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

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = J_1 \begin{bmatrix} \Delta\delta \\ \Delta V/V \end{bmatrix} + J_2 \begin{bmatrix} \Delta\delta \\ \Delta V/V \end{bmatrix} \tag{12}$$

$$J = J_1 + J_2 \tag{13}$$

Where *J₁* is the Newton-Raphson power flow Jacobian matrix without DGUPFC and *J₂* is the injected power partial derivative matrix with respect to the variables. The formulas of *J₂* are given as below

$\forall n = j\,,k$:

$$\frac{\partial P_{i,GUPFC}}{\partial \delta_i} = -\sum_{n=j,k} 2V_{s,in}V_i g_{in}\, sin(\varphi_{s,in} - \delta_i) \tag{1}$$

$$\frac{\partial P_{i,GUPFC}}{\partial \delta_n} = V_{s,in}V_n\, [g_{in}\, sin(\varphi_{s,in} - \delta_n) - b_{in}\, cos(\varphi_{s,in} - \delta_n)] \tag{2}$$

$$\frac{\partial P_{n,GUPFC}}{\partial \delta_n} = V_{s,in}V_n\, [g_{in}\, sin(\varphi_{s,in} - \delta_n) + b_{in}\, cos(\varphi_{s,in} - \delta_n)] \tag{3}$$

$$\frac{\partial P_{i,GUPFC}}{\partial V_i} = -\sum_{n=j,k} 2V_{s,in}g_{in}\, cos(\varphi_{s,in} - \delta_i) \tag{4}$$

$$\frac{\partial P_{i,GUPFC}}{\partial V_n} = V_{s,in}\, [g_{in}\, cos(\varphi_{s,in} - \delta_n) + b_{in}\, sin(\varphi_{s,in} - \delta_n)] \tag{5}$$

$$\frac{\partial P_{n,GUPFC}}{\partial V_n} = V_{s,in}\,[g_{in}\cos(\varphi_{s,in}-\delta_n)+b_{in}\sin(\varphi_{s,in}-\delta_n)] \qquad (6)$$

$$\frac{\partial Q_{i,GUPFC}}{\partial \delta_i} = \sum_{n=j,k}(V_{s,in}V_i[-g_{in}\cos(\varphi_{s,in}-\delta_i)+b_{in}\sin(\varphi_{s,in}-\delta_i)]) \qquad (20)$$

$$\frac{\partial Q_{n,GUPFC}}{\partial \delta_n} = -V_{s,in}V_n\,[-g_{in}\cos(\varphi_{s,in}-\delta_n)+b_{in}\sin(\varphi_{s,in}-\delta_n)] \qquad (7)$$

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

$$\frac{\partial Q_{n,GUPFC}}{\partial V_n} = -V_{s,in}\,[g_{in}\sin(\varphi_{s,in}-\delta_n)+b_{in}\cos(\varphi_{s,in}-\delta_n)] \qquad (23)$$

The Jacobian matrix of power flow can be modified and the equations of power flow can be solved with conventional N-R method using. (16) to (25).

4. Simulation results

In order to validate the program of the proposed voltage regulation, a radial distribution network composed of two lines which is shown in “Fig. 4”. Each line contain a DG unit which are located at the end of the distribution line. The OLTC is installed on the side of secondary of the HV/MV transformer (60/30 KV) [24-26].

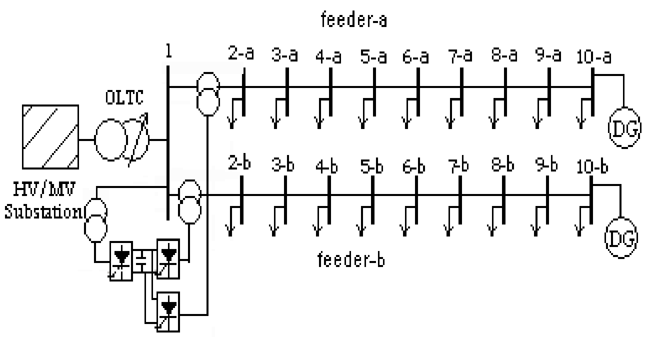

Fig. 4. The investigated system.

The investigated system data are as follow:

- ➢ The feeder-a are the same as the feeder-b, they are same as the IEEE 10 bus distribution system.
- ➢ The maximum load of each feeder are 12.386 MW and 4.168 MVAR.
- ➢ DG unit are a maximum power of P_{DG}= 2.5 MW.

A worst case of voltage regulation is simulated in the investigated system. A program of load flow written in MATLAB based on N-R algorithm is used in the simulation.

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

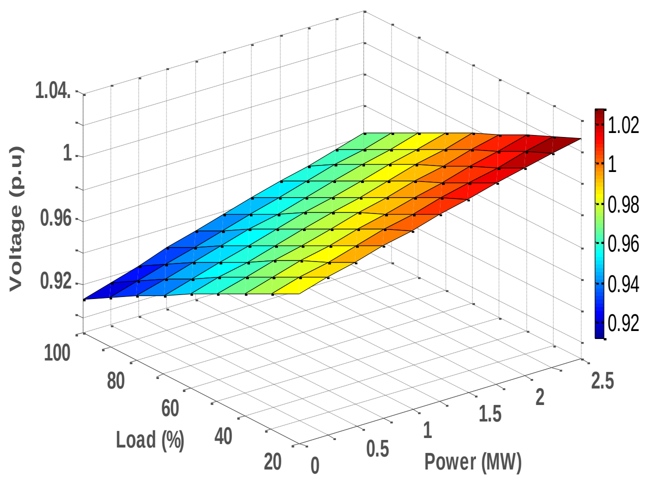

Fig. 5. Voltage at bus 10 with variations of power of DG and demand of the load.

We can see from the fig.5 that the worst case of voltage drop appear when the demand of the load is at maximal (100 % of the load of feeder) and DG do not generate any power (P_{DG}= 0). And that the worst case of voltage rise appear when the demand of the load is at minimal (20 % of the load of feeder) and DG generates the maximum power (P_{DG}= 2,5 MW).

4.1. *Case 1*

The first test case, is when the demand of the load at feeder-a is at minimal (20 % of the load of feeder) and the load at feeder-b is at maximal (100 % of the load of feeder). The two DGs units do not generate any power.

“Fig. 6” shows the voltage profile along the two feeders without any controller. At bus 7-b to bus 10-b, the voltage drop is less than the permitted range (- 5%). In this case, the OLTC is able to control the voltage within the predefined limits for all buses “Fig. 7” when it change his position from 0% to +4%.

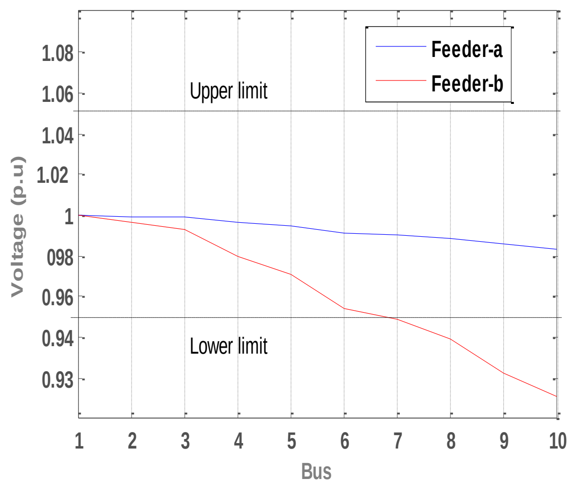

Fig. 6. Voltage profile without any controllerin case 1.

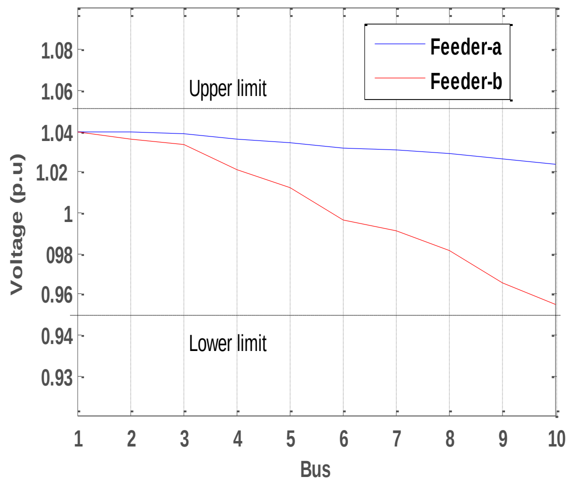

Fig. 7. Voltage profile with single action of OLTC in case 1.

4.2. *Case 2*

The second test case, is when the demand of the load at the two feeders and DG unit which is connected at feeder-a are the same as case 1, and the other DG generates the maximum power.

"Fig. 8" shows the voltage profile along the two feeders without any controller (OLTC position at 0%). At *bus 7-b* to *bus 10-b*, the voltage drop is less than the permitted range (-5%). In this case, the OLTC is not able to control the voltage within the predefined limits for all buses, it leads to a voltage rise at some buses of feeder-a (*bus 9-a* and *bus 10-a*) when it change his position to +4%. "Fig. 9".

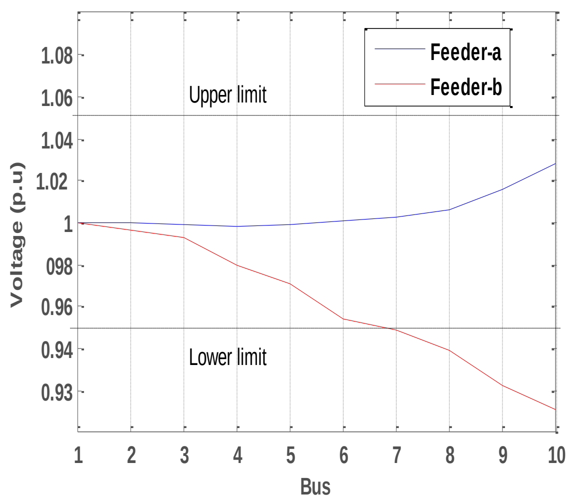

Fig. 8. Voltage profile without any controller in case 2.

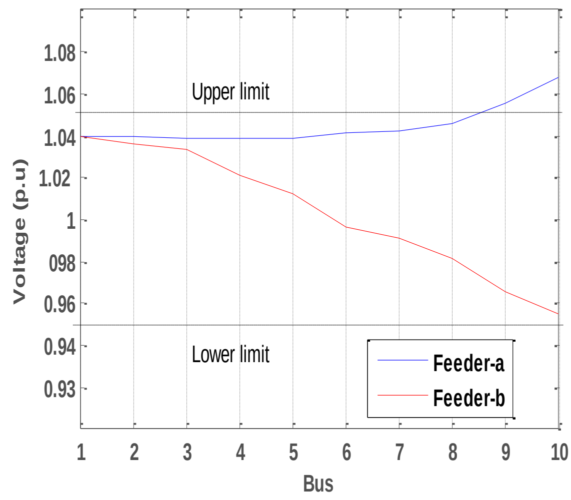

Fig. 9. Voltage profile with single action of OLTC in case 2.

"Fig. 10" show the voltage of *bus 10-a* according to the variation of magnitude and voltage phase angle of series injection of DGUPFC in the feeder-a.

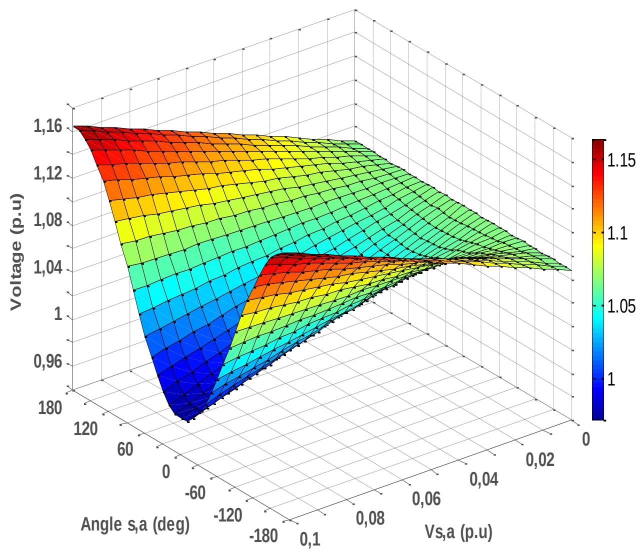

Fig. 10. The voltage of bus 10-a according to the variation of magnitude and voltage phase angle of series injection.

We can see various values of magnitude and voltage phase angle of series injection which can maintain the voltage of bus 10-a within the permitted band. We can takes among these values, the values (0.04 pu, 0 rad) (magnitude, phase angle)

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

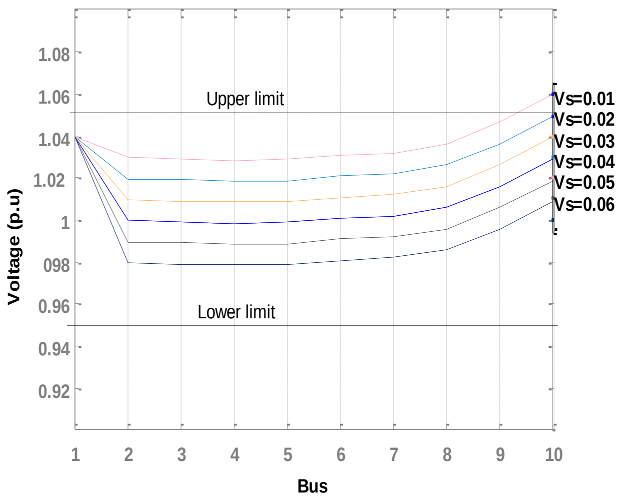

Fig. 11. Voltage profile of the Feder-a with variation of Vs in case 2.

"Fig. 12" shows the profile of the voltage along the two feeders with the proposed method.

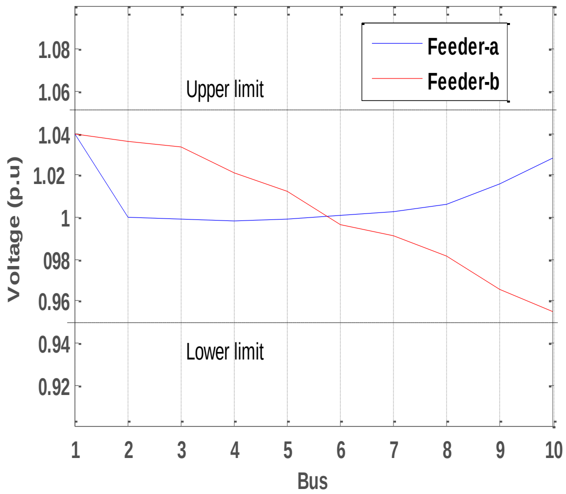

Fig. 12. Voltage profile with the proposemethod in case 2.

The proposed method is capable to managing the voltage rise in bus 9-a and bus 10-a. It can be seen, that there is a voltage drop at feeder-b if there is no controller "Fig. 8", this voltage drop was seen by OLTC that caused a voltage rise at feeder-a by his action of management "Fig. 9", based on the proposed method, latter was compensated by DGUPFC response "Fig. 12".

It can be concluded based on the simulation results, that the proposed idea is able to maintain the voltage at all buses in the limits values.

5. Conclusion

This paper has restituted the insufficiency of the OLTC action which is one of the most popular method using in voltage regulation of distribution networks because it is easy to design and implement, but it can't to manage the voltage violations in distribution networks with many of lengthy feeder. The idea was to use the OLTC action within the predefined range (depending on the allowed voltage range) and allow the a new FACTS device (The DGUPFC) to handle the remaining voltage violations. The results of the simulation revealed that the proposed idea allows us to control the voltage problem of a medium-voltage distribution system with multiple feeders in the worst working conditions. In addition, because the DGUPFC is used under extreme voltage conditions (when the OLTC system is no longer working) according to the variation of magnitude and voltage phase angle of series injection.

In future, research, the cost of investment in different models of distribution network and a practical's tests of the proposed idea will be studied.

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