Voltage Stability Enhancement Studies for Distribution Network with Installation of FACTS

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***Abstract*—Voltage stability studies and to maintain the flat voltage profile is quite important in order to maintain the healthy operation of electric power network as well as to provide the quality and cheap electric energy to the modern power users. Further with the advancement of power electronics technologies and its application to design flexible alternating current transmission devices (FACTS) have made it easier to alleviate the voltage stability problem in a quicker and cheaper way in the modern DNs. Hence, the present research work shows an attempt to investigate and solve the problem of voltage instability in distribution network (DN). All buses and lines are calculated in terms of voltage stability index (VSI) and to identify the optimal location of FACTS. The bus or line with minimum voltage profile in terms of VSI are more sensitive to the voltage collapse and it may further lead to blackouts. The FACTS are permanently installed at the weakest point to enhance voltage profile and improve the voltage stability in the DN. The present study is test on standard IEEE-15 bus DN and application results are shown to verify the feasibility of the present studies for DN.**

Keywords— Voltage profile, VSI, FACTS, power losses, distribution network.

I. Introduction

In vertically incorporated utility structure, all elements, including; generation, transmission and distribution of electrical power are within the aegis of electric power organization. Power generation is carried out in such a manner to accomplish the least operational expenses and the power distribution system is making the final delivery of electrical power to the modern consumers. Due to continuous advancements, the consumers' demands keep increasing exponentially. Consequently, the power system network facing many problems such as; voltage and frequency instability, line overloaded and power system blackouts. Voltage collapse is a process in which the appearance of sequential events together with the voltage instability in a huge area of system can lead to the case of unsuitable low voltage condition in the distribution network [1]. Load increasing can prompt unnecessary interest of reactive power; the system will indicate voltage instability and may further lead to black out of the system. In the event that there are not adequate reactive power assets and the further excessive demand of reactive power can prompt the voltage collapse of the network. To overcome voltage instability due to complex power system configuration, the topology can be modified by adding shunt capacitors and flexible alternating current transmission system (FACTS) device at the suitable locations in DNs [2]. This investigation addresses the static modelling of a Unified Power Flow Controller (UPFC), and their abilities to improve the voltage profile and bus power flow to which it is associated and evaluated. This technology of power electronic devices is termed as FACTS technology; it provides the ability to increase the controllability and to improve the transmission system operation in terms of power flow, stability limits with advanced control technologies in the existing power systems [3, 4]. Among different types of FACTS, UPFC has the ability to control active and reactive power flow of the network simultaneously in addition to controlling all the transmission parameters (voltage, impedance and phase angle) affecting the power flow in the network [5]. A placement and sizing strategy of shunt FACTS controller using Real Coded Genetic Algorithm is proposed in order to maintain voltage stability in [6]. Another approach of enhancing the voltage stability is by placing FACTS devices in the weakest buses or lines of the power system which are closest to the experience of voltage collapse. Different investigations such as methods like P-V curve, Q-V curve, index based methods etc. have been utilized to find the locations for FACTS devices [7-13]. P-V curve was used in [7, 8] to determine the weakest buses for FACTS devices allocation. In [9], the stability of load flow technique was study by the authors for the distribution system. The real-time contingency evaluation and ranking technique was discuss in [10] for DNs. In [11], the authors have presented the analysis and voltage stability solution of bulk power system. In the view of above discussion, this paper is set to:

(a.) To study the voltage stability issues of the distribution network (DN). The standard IEEE 15 bus system is used for the analysis and to study the voltage stability of the DN.
(b.) The models of voltage collapse point indicator and line stability factor is modelled and simulated to carry out the present studies. The various loading cases are considered in order to identify the exact bus which may bring the voltage instability in the DN.
(c.) Finally, the UPFC is install at the weak busses and the comparative analysis of voltage stability in terms of voltage profile, real and reactive power losses are measured and listed in terms of graphical and tabular results in order to validate the effectiveness of the present study.

II. Mathematical Modelling of UPFC

UPFC is an advance power electronic device that is capable in controlling the power flow in a network without making any rescheduling in a power generation. A UPFC is a solid-

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state multi-functional FACTS controller with the aptitude to control three parameters that influence the power flow such as: bus voltage magnitude, phase angle between two buses and line reactance, either concurrently or independently. UPFC can control not only for controlling the power flow, but also for power system stabilizing control.

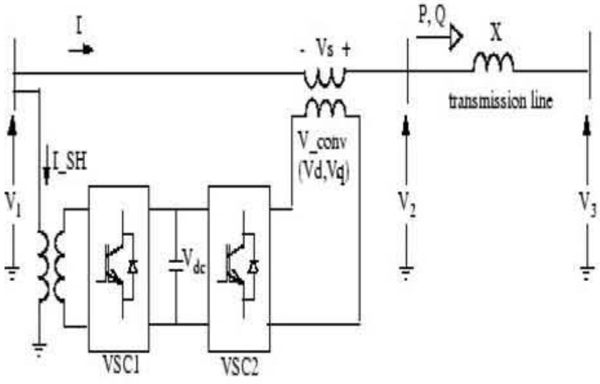

Figure 1. UPFC arrangement configuration [12]

In order to evaluate the impact of UPFC in the system network, formulation based on the circuit arrangement is essential, the schematic of UPFC is shown in Fig. 1 and the equivalent circuit of UPFC is shown in Fig. 2.

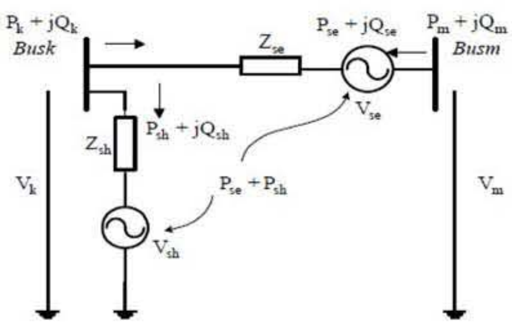

Figure 2. Equivalent circuit of UPFC [13]

Focusing on Fig. 2, as injected shunt voltage V_{Sh} and series voltage source V_{Se} are representing the equivalent. Z_{Sh} and Z_{Se} are coupled with UPFC transformers impedances, V_k and V_m are bus to bus voltages or sending and receiving end voltage. Series and shunt voltages can be written as:

$$V_{se} = V_{se}(\cos\theta_{se} + j\sin\theta_{se}) \quad (1)$$

$$V_{sh} = V_{sh}(\cos\theta_{sh} + j\sin\theta_{sh}) \quad (2)$$

Then UPFC active power and reactive power equation can be written as follows:

@ node k

$$\begin{aligned} P_k &= V^2{}_k G_{kk} + V_k V_m (G_{km}\cos(\theta_k - \theta_m) + B_{km}\sin(\theta_k - \theta_m)) \\ &+ V_k Vse(G_{km}\cos(\theta_k - \theta_{se}) + B_{km}\sin(\theta_k - \theta_{se})) \\ &+ V_k V_{sh}(G_{sh}\cos(\theta_k - \theta_{sh}) + B_{sh}\sin(\theta_k - \theta_{sh})) \end{aligned} \quad (3)$$

$$\begin{aligned} Q_k &= -V^2{}_k B_{kk} + V_k V_m (G_{km}\sin(\theta_k - \theta_m) - B_{km}\cos(\theta_k - \theta_m)) \\ &+ V_k V_{se}(G_{km}\sin(\theta_k - \theta_{se}) - B_{km}\cos(\theta_k - \theta_{se})) \\ &+ V_k V_{sh}(G_{sh}\sin(\theta_k - \theta_{sh}) - B_{sh}\cos(\theta_k - \theta_{sh})) \end{aligned} \quad (4)$$

@ node m

$$\begin{aligned} P_m &= V^2{}_m G_{mm} + V_m V_k (G_{mk}\cos(\theta_m - \theta_k) + B_{mk}\sin(\theta_m - \theta_k)) \\ &+ V_m V_{se}(G_{mm}\cos(\theta_m - \theta_{se}) + B_{mm}\sin(\theta_m - \theta_{se})) \end{aligned} \quad (5)$$

$$\begin{aligned} Q_m &= -V^2{}_m B_{mm} + V_m V_k (G_{mk}\sin(\theta_m - \theta_k) - B_{mk}\cos(\theta_m - \theta_k)) \\ &+ V_m V_{sh}(G_{mm}\sin(\theta_m - \theta_{se}) - B_{mm}\cos(\theta_m - \theta_{se})) \end{aligned} \quad (6)$$

Series converter:

$$\begin{aligned} P_{se} &= V^2{}_{se} G_{mm} + V_{se} V_k (G_{km}\cos(\theta_{se} - \theta_k) + B_{km}\sin(\theta_{se} - \theta_k)) \\ &+ V_{se} V_m (G_{mm}\cos(\theta_{se} - \theta_k) + B_{mm}\sin(\theta_{se} - \theta_m) \end{aligned} \quad (7)$$

$$\begin{aligned} Q_{se} &= -V^2{}_{se} B_{mm} + V_{se} V_k (G_{km}\sin(\theta_{se} - \theta_k) - B_{km}\cos(\theta_{se} - \theta_k)) \\ &+ V_{se} V_m (G_{mm}\sin(\theta_{se} - \theta_m) - B_{mm}\cos(\theta_{se} - \theta_m)) \end{aligned} \quad (8)$$

Shunt converter:

$$P_{sh} = -V^2{}_{sh} G_{sh} + V_{sh} V_k (G_{sh}\cos(\theta_{sh} - \theta_k) + B_{sh}\sin(\theta_{sh} - \theta_k) \quad (9)$$

$$Q_{sh} = V^2{}_{sh} B_{sh} + V_{sh} V_k (G_{sh}\sin(\theta_{sh} - \theta_k) - B_{sh}\cos(\theta_{sh} - \theta_k) \quad (10)$$

Assuming that during the operation, the converter is lossless, their fore active power supplied to the shunt converter P_{sh} equals to the active power demanded by the series converter P_{se}, then;

$$P_{se} + P_{sh} = 0. \quad (11)$$

Also, if the coupling transformers resistances are negligible, then the active power at bus k equal to the active power at bus m, that can expressed as:

$$P_{sh} + P_{se} = P_k + P_m = 0 \quad (12)$$

The UPFC power equations linearized and combined with the equations of the AC transmission network for the cases when the UPFC control parameters. Equation (12) described that the active power exchange between shunt and series converters via DC link is balanced at any instant of operation.

III. FUNCTIONALITY OF INDICES

In power systems, the complex network is always represent in terms of single line diagram under the assumption that the system is balance under certain conditions. An interconnected network is illustrated in Fig. 3 where suffice V_s and V_r denotes the voltage at sending end and voltage at receiving end respectively.

(a). Voltage Collapse Point Indicator (VCPI)

The Voltage Collapse Point Indicator (VCPI) is well discuss in [10] and is base on the concept of maximum power transferred through the transmission line;

$$VCPI_{(p)} = \frac{P_r}{P_{r(\max)}} \leq 1 \tag{13}$$

P_r is the real power transferred to the receiving side while $P_{r(\max)}$ is the maximum power that can be transferred to the receiving end at a particular instant and is given as;

$$P_{r(\max)} = \frac{V_s^2}{Z} \cdot \frac{\cos\phi}{4\cos^2\left(\frac{\theta-\phi}{2}\right)} \tag{14}$$

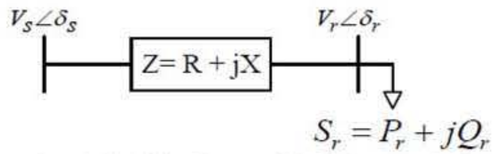

Figure 3. Single line diagram of distribution network [9].

The developed model of voltage collapse point indicator is shown in Figure 4.

(b). Line Stability Factor (LQP)

The LQP index is calculated as follows:

$$LQP = 4\left(\frac{V_s^2}{X}\right)\left(\frac{V_s^2}{X}.P_s^2 + Q_r\right) \leq 1 \tag{15}$$

The developed model of LQP is shown in Figure 5 and used for the analysis of the present work.

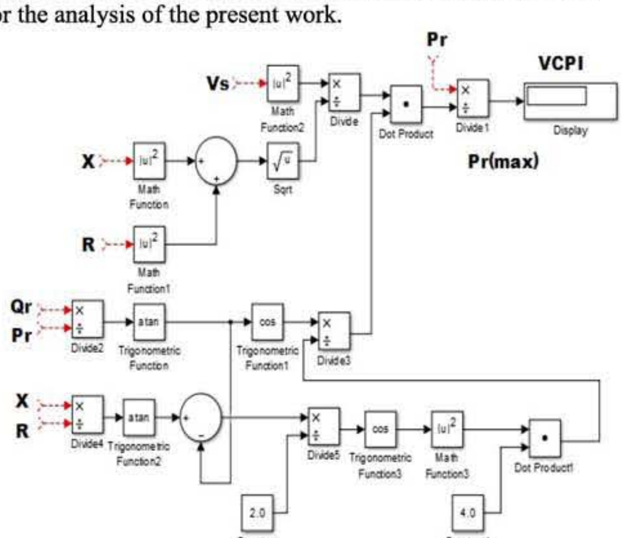

Figure 4. Develop model of VCPI

IV. METHODOLOGY USED FOR STUDY

Load flow analysis is quite significant for a system having multiple loads connected in the network. Power losses, real power, reactive power, phase angle and voltage impedance for all busses in a distribution feeder can be evaluated using this analysis and quite useful tool for future planning of the power system. In a three-phase balanced system, the complete system can be represented as single line equivalent diagram as given in Figure 1 for the complete analysis of the power network and the nodal analysis is used to derive two load equations namely:

- Gauss-Seidel [G-S] method.
- Newton-Raphson [N-R] method.

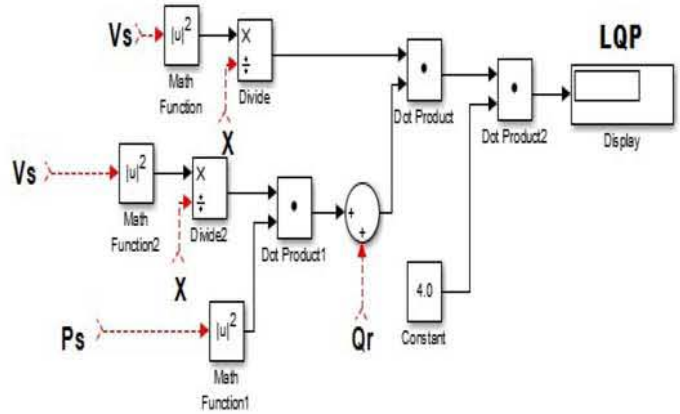

Figure 5. LQP development

In transmission line, the relationship between voltage (V) and current (I) in any bus is determined by:

$$I = Y.V \tag{16}$$

Y is the admittance from bus to bus given as: $Y_{i\,j}$, therefore equation (16) can be expanded in the form:

$$I = \sum_{i=1}^{n} Y_{i,j}.V_i \tag{17}$$

As complex power $S = V.I^*$, the equation (17) can be developed in terms of power as;

$$I = \frac{S^*}{V^*} \tag{18}$$

And

$$S_{ij} = P_i - Q_j \tag{19}$$

Therefore, Gauss-Seidel equation is obtained by substitute equation (17), (18) & (19) and make voltage as subject of the equation as follows;

$$V_i = \frac{1}{y_{i,i}}\left[\frac{P_i - jQ_i}{V_i^*} - \sum_{j=1, j\neq i}^{n} y_{i,j}V_j\right] \tag{20}$$

Then, by splitting equation (17) in to two equations as follows as to get the real and imaginary values, Newton-Raphson is obtained;

$$P_i = \sum_{j=1}^{n} |V_i||y_{i,j}||V_j|\cos\left(\theta_{i,j} + \delta_i - \delta_j\right) \tag{21}$$

$$Q_i = -\sum_{j=1}^{n} |V_i||y_{i,j}||V_j|\sin\left(\theta_{i,j} + \delta_i - \delta_j\right) \tag{22}$$

Equations (21) and (22) represent Newton-Raphson method and one of the most powerful method for analysing load flow studies. In the present study, this method is used in order to achieve accurate and faster solution in terms of converging iterations and to obtain more reliable solution for DN.

V. MODELLING AND ANALYSIS OF DN

The IEEE-15 bus distribution feeder model represented in the form of single line diagram and shown in Figure 6 is simulated using standard MATLAB software. The IEEE-15 bus distribution feeder is consisting of the following data:

- Number of buses=15
- Slack bus=01
- Number of lines=14
- Base voltage=11KV
- Base power=100KVA
- Tolerance limit=0.001

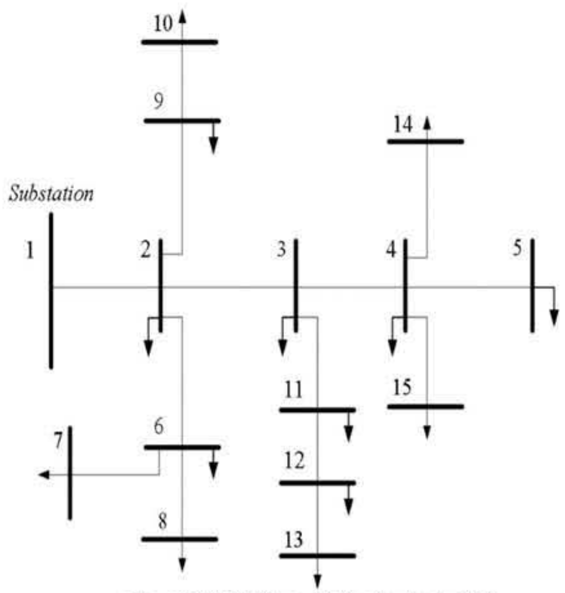

Figure 6. IEEE-15 bus distribution feeder [11]

Further, Table 1 and 2 shows the line data as well as load data for simulated IEEE 15 bus system and Table 3 shows the converge voltage, phase angle and stability index at 40% increase in system loading.

TABLE 1: LINE DATA FOR 15-BUS SYSTEM

From bus	To bus	R(ohms)	X(ohms)
1	2	0.0005	0.0012
2	3	0.0304	0.0355
3	4	0.0015	0.0036
4	5	0.0005	0.0012
2	9	0.0251	0.0294
9	10	0.366	0.1864
2	6	0.3811	0.1941
6	7	0.0922	0.047
6	8	0.0493	0.0251
3	11	0.819	0.2707
11	12	0.1872	0.0619
12	13	0.7114	0.2351
4	14	1.03	0.34
4	15	1.044	0.345

TABLE 2: LOAD DATA OF 15-BUS SYSTEM

Bus No	Real power (KW)	Reactive power (KVAr)
3	37.233	21
4	4.067	1.54
5	69.3	37.8
6	27.72	15.4
7	7.392	3.5
8	131.04	72.8
9	38.22	21
10	55.44	24.5
11	4.62	2.45
12	24.024	12.985
13	12.936	7
14	8.778	9.8
15	5.544	2.8

TABLE 3: CONVERGED VOLTAGE, PHASE ANGLE AND STABILITY INDEX AT 40% LOAD INCREASE WITHOUT UPFC PLACEMENT

Bus No	V_LF (pu)	V angle (deg)	Stability index
1	1	0	0.5
2	1.0543	-32.73	0.527
3	1.4869	-57.49	0.743
4	0.6569	-113.00	0.328
5	0.5750	-125.56	0.288
6	1.0512	-34.48	0.526
7	1.0666	-34.82	0.533
8	0.9895	-41.48	0.495
9	1.0760	-40.26	0.538
10	1.0717	-43.91	0.536
11	1.7405	-58.89	0.870
12	1.9544	-60.15	0.977
13	2.0140	-60.47	1.007
14	0.6534	-115.06	0.327
15	0.6654	-113.68	0.333

The load data were exponentially increased in stairs steps of 10% up to 40% with and without UPFC placement. Simulation studies were done for different scenarios in IEEE-15 bus distribution feeder network. Five different scenarios are considered for the present study which are as follows:

- Scenario 1: The network is running on a normal load condition.
- Scenario 2: 10% load increase with and without UPFC.
- Scenario 3: 20% load increase with and without UPFC.
- Scenario 4: 30% load increase with and without UPFC.
- Scenario 5: 40% load increase with and without UPFC.

The real and reactive power plots with increase in system loading is given in Figure 7 for MW and MVAr increase. The voltage profile of all busses is given in Figure 8 without considering the UPFC placement as well as it is also observe that when system loading is increase to 40% the bus 5 is highly affected in terms of voltage profile and may lead to the voltage instability of the complete network. Hence UPFC should be placed at this bus to improve the voltage profile of the DN. The UPFC has the ability to increase the voltage profile at the weakest bus and further results in power losses reduction simultaneously. Under the stress condition described in Figure 8, after UPFC placement at bus 5 the load flow was run again and the obtain results are listed in Table 4.

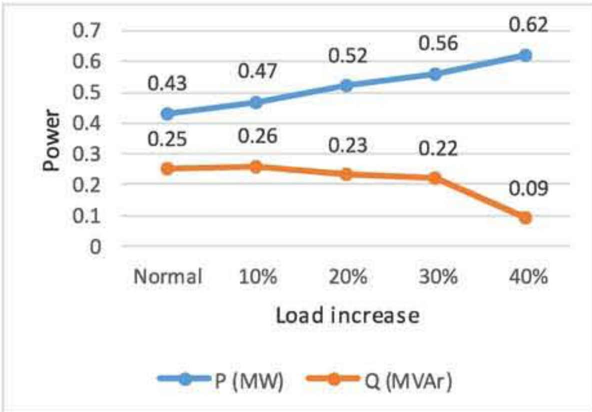

Figure 7. Active and reactive power load increases

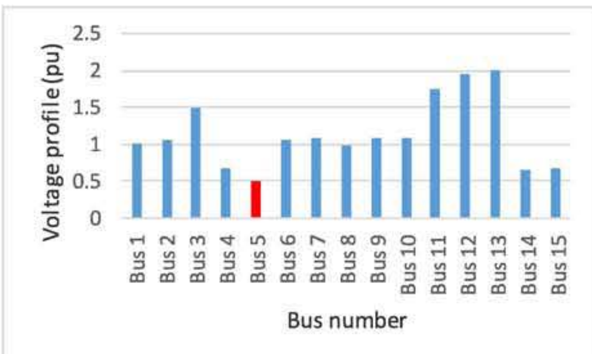

Figure 8. Voltage profile for all buses before UPFC placement at 40% load increase

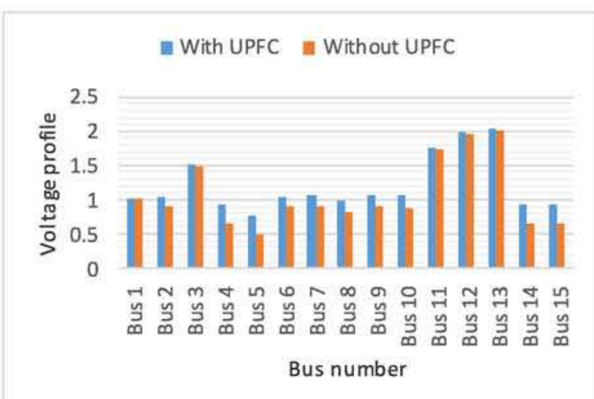

Figure 9. Comparison of voltage profile for all buses after UPFC placement at 40% load increase

The comparative analysis of voltage profile of IEEE 15 bus DN is shown in Figure 9 for 40% load increase with and without UPFC placement. It is observe that all busses voltages increase significantly after placing the UPFC on bus 5. At bus 5, the voltage has jump from 0.5 p.u. to 0.7735 p.u. lead to the voltage stability of the network. Busses 11-13 are the strongest busses in terms of enhancement in voltage profile of this network. Further, the graphical analysis of Bus 5 is also carried out in terms of real and reactive power improvement and it is evident from the results of Figure 10 that there is an significant decrement in real power loses of the network which reduces from 620kW to 610kW and reactive power from 90kVAr to 330kVAr and this is an significant enhancement with respect to voltage stability and network losses reduction.

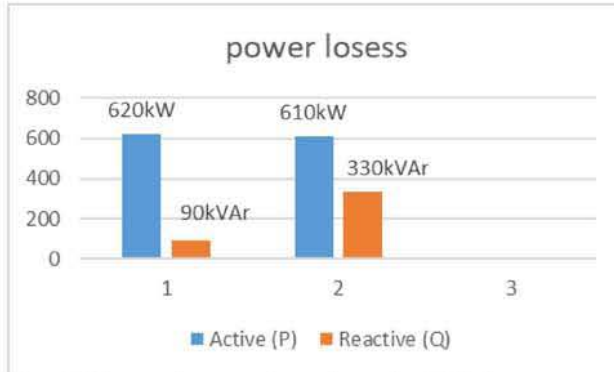

Figure 10. Shows a decrement of power loses after UPFC placement

TABLE 4: LOAD FLOW OF BUS VOLTAGE AFTER UPFC PLACEMENT

Bus No.	With UPFC	Without UPFC
Bus 1	1	1
Bus 2	1,0543	0,9154
Bus 3	1,5079	1,4869
Bus 4	0,928	0,6569
Bus 5	0,7735	0,5
Bus 6	1,0512	0,9024
Bus 7	1,0666	0,9147
Bus 8	0,9898	0,818
Bus 9	1,076	0,894
Bus 10	1,0717	0,8759
Bus 11	1,7659	1,7405
Bus 12	1,9835	1,9544
Bus 13	2,0442	2,014
Bus 14	0,9434	0,6534
Bus 15	0,943	0,6654

VI. CONCLUSION

The present research work shows an enhance performance of a UPFC and its future promising technology to improve the voltage profile and power loses mitigation for DN. The feasibility studies of UPFC is tested on standard IEEE-15 bus test system. The investigation was carried out using standard MATLAB software. The system was firstly simulated by running a load flow tool with Newton-Raphson method in order to observe the bus voltage magnitude, the power that is being generated, power that is consumed, and the power that is lost (power loses) through the network. The weakest bus was determined at the 40% increase in system loading and may lead to voltage instability of the system. However, after UPFC placement there is an significant enhancement of voltages of all busses as well as Bus 5 voltage jump from 0.5 to 0.7735 p.u. and shifting the bus 5 from voltage instability to stable zone. It is also observe that the active and reactive power loses were decrease by 98.3% and 27.27% that fulfil the beauty of the UPFC installation in the DNs and its promise to mitigate the voltage instability problem of the modern DNs. These different aspects give scope for the future research work as P-Q load increases up to 40%. Incidentally, P-Q load is almost balanced in residential areas but in industrials Q is very high, hence in future research work the Q load will be increased separately and observe the results.

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