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Control of UPFC for Voltage Stability constrained Available Transfer Capability (VSATC)

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Abstract

In the present situation of the power business, the interest for power is expanding constantly, which can be met by setting up the new era plants, transmission lines and substations which includes overwhelming expense. Along these lines, it is proposed that the current accessible exchange capacity of the power framework be improved by utilizing the Flexible Alternating Current Transmission Systems (FACTS) gadgets, for example, Static Synchronous Series Compensator (SSSC), Static Synchronous Compensator (STATCOM) and Unified Power Flow Controller (UPFC) and so forth. UPFC has been considered in lieu of its adaptability to analyze its impact in improving the power framework Available Transfer Capability (ATC). The most extreme Voltage Stability obliged Available Transfer Capability (VSATC) is accomplished by differing the parameters of UPFC by considering its energy infusion display in conjunction with Distributed Slack Bus (DSB) idea. The actualized procedure hosts Newton Raphson (NR) method to suit the UPFC and DSB idea, while minding the end goal of solving basic 5 bus power transmission Hale system.

Keywords: FACTS, SSSC, STATCOM, UPFC, VSATC, DSB and NR.

INTRODUCTION

In view of the enormous size, it is a major challenge to keep up the voltage size and responsive power at the evaluated levels while taking care of the power requests. Additionally, in the present electricity market, it is possible to freeload upon the transmission system for consumers to access the power. This may result in un-stabilization of the system due to overload and / or voltage drop. One probable solution to tackle such problems, is building Available Transfer Capability (ATC) of the power framework subjected to voltage security, requirements. [1] Illustrates ATC as a measure of transference ability remnant in the transmission network to further commercial activity that is deemed surplus.

FACTS device (Flexible Alternating Current Transmission Systems) that provides voltage and reactive support can be seen as a viable solution in this pertinence. These devices are the combinations of different power electronics devices which controls the flow of power and other parameters of the power system [2].

Of these devices, one of the most versatile and unique featured instrument is UPFC (Unified Power Flow Controller). Its parameters **r, γ** and **Xse** (pu magnitude phase angle and series voltage source impedance) can be changed irrespective of their associations with power losses, voltage profiles, etc., [3]. The UPFC has been treated as the combination of the Static Synchronous Compensator (STATCOM –shunt compensator) and the Static Synchronous Series Compensator (SSSC-series compensator) [4].

UPFC provides the functional flexibility in power flow control by combining the control of phase angle along with controlled shunt and series reactive compensation. This paper considers a power injection variant of it, which will be helpful to estimate the UPFC impact on power system and it is incorporated as the steady state power model in the Newton-Raphson method based power flow program [5]. The experiments were performed in MATLAB programming environment.

Available Transfer Capability is the ability of the coupled electrical power systems to move the power robustly and steadfastly from one place to other place through all the power transmission lines. For the safe operation of the power system and to achieve optimal power transfers, the transfer capability is computed and the power system is supervised, to make the power transfers within the specified transfer capability. It is trivial that highly loaded buses or circuits with fewer voltages will limit the ATC significantly. Thus, line flow is redistributed and bus voltages are regulated with the FACTS technology and ATC is enhanced effectively [6].

The ability of the transmission framework will constrain the mass power move in an interconnected power framework. The transfer capability is the maximum power that can be transferred. The total transfer capability (TTC) without thermal over loads and voltage limit deviations is the highest power flow through the selected interface [7-8].

This paper investigates, the dictating factors **r, γ** and **Xse** effect on the system to monitor the enhancement of the system's Voltage Stability constrained Available Transfer Capability (VSATC) in conjunction with Distributed Slack Bus (DSB) concept.

This paper is organized in the following manner. After the introduction (section-1), in Section –2, the distributed slack bus concept and voltage stability constrained available transfer capability concept are explained. Section-3 explains the steady state model of UPFC. The UPFC model implementation along with modifications in the NR method is given in the Section - 4.A simple 5- bus Hale network is taken for the case study, conclusions and results are presented in Section –5.

DISTRIBUTED SLACK BUS CONCEPT

In the present scenario, the slack bus serves two purposes: 1) It acts as a virtual reference for the system and 2) as a plunk for the unaccounted reactive and active powers. To address this problem, distributed slack bus concept has been proposed where the extra load is distributed among the other generator buses based on their respective Generation Participation Factors (GPFs) which leads to more robustness, reduction of voltage drops and losses.

The Generation Participation Factor (active power) (GPFp) is defined as the ratio of the maximum generation active power limit of a particular bus to the total plant installed maximum active power capacity [9], i.e., formulates it as the addition of all the generators' maximum power capacities. Mathematically, it is represented as:

GPFp of **i** $^{\text{th}}$ generator bus is,

$$GPF_{p,i} = \frac{P_{g,i}^{\max}}{\sum_{i=1}^{NG} P_{g,i}^{\max}} \tag{1}$$

(NG = no. of generator buses, $P_{g,i}^{\max}$ = maximum power of the **i** $^{\text{th}}$ generator bus).

1) The energy balance condition

$$P_G = P_D + \text{losses} \tag{2}$$

$$P_G = \sum_{i=1}^{NG} P_{g,i} \;\; \text{(total generation)} \tag{3}$$

$$P_D = \sum_{i=1}^{NB} P_{d,i} \;\; \text{(total demand)} \tag{4}$$

(NB = no. of buses)

2) Load Up-gradation

$$P_{d,i}^{new} = P_{d,i}^{base} + \Delta P_{d,i} = (1+\lambda) P_{d,i}^{base} \tag{5}$$

λ = loading parameter

$$\Delta P_{d,i} = \lambda \times P_{d,i}^{base} \tag{6}$$

$$P_D^{new} = \sum_{i=1}^{NB} P_{d,i}^{new} \tag{7}$$

3) New Generation Schedule

$$P_{g,i}^{new} = P_{g,i}^{old} + \Delta P_{g,i} \tag{8}$$

$$\Delta P_{g,i} = GPF_i \times \Delta P_D \tag{9}$$

$$\Delta P_D = P_D^{new} - \sum_{i=1}^{NB} P_{d,i}^{base} \tag{10}$$

4) Maximum Loading Capability (MLC)

$$MLC = P_D^{cri} - P_D^{base} \tag{11}$$

$$P_D^{cri} = (1+\lambda^{cri}) P_D^{base} \tag{12}$$

P_D^{cri} = critical loading where the bus voltage is just equal to 1 pu and λ^{cri} (critical loading parameter) at that instant. The same theory is applied to reactive power also and same factors are similarly defined. In this paper, both the combined real and reactive power increments are considered.

STEADY STATE MODEL OF UPFC

The active power demand of series converter is sucked in by shunt converter from the AC supply and transferred to bus **j** via DC link. The series converter voltage output is added to the bus **i**, voltage, to improve the nodal voltage at bus **j**. The magnitude of voltage output V_{CR} provides the voltage regulation whereas phase angle of V_{CR} determines the control mode of power flow.

In order to provide the sustaining role in the exchange of active power, that take place between AC system and the series converter, shunt converter generates (or absorbs) reactive power in lieu of providing independent regulation of voltage magnitude at its spot of connection with AC system.

Equivalent Circuit of Unified power flow controller is shown in figure 1, with two back–to-back voltage source converters (VSCs), with one VSC controller connected to AC system through one shunt transformer and second VSC is connected to AC system through a series transformer [5].

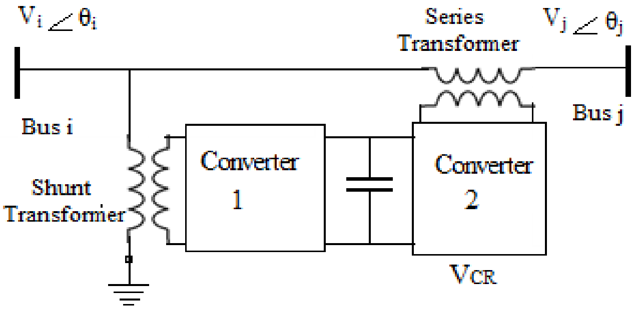

Figure 1: Solid-state voltage sources based UPFC Equivalent circuit

The two voltage sources are linked to AC system through inductive reactances representing the VSC transformers. The voltage sources (converters) are operating from common DC link provided by a DC storage capacitor.

The AC voltage is injected by the series converter with controllable phase angle and magnitude, in series with transmission line through series transformer, thereby provides control of reactive and real power flow in transmission line.

The shunt converter would supply or absorb the real power demand by series converter at the common dc link.

The power injection model (steady state) is shown in figure 2.It is helpful for understanding the UPFC impact on the power system. UPFC is represented by two voltage sources to represent the fundamental components of output voltage waveforms with effective reactances of the two converters

A series connected voltage source has been located between the nodes **i** and **j** in the power system. The series voltage source converter is modeled as shown in figure 3, with an ideal series voltage V_{se} in series with a reactance X_{se}

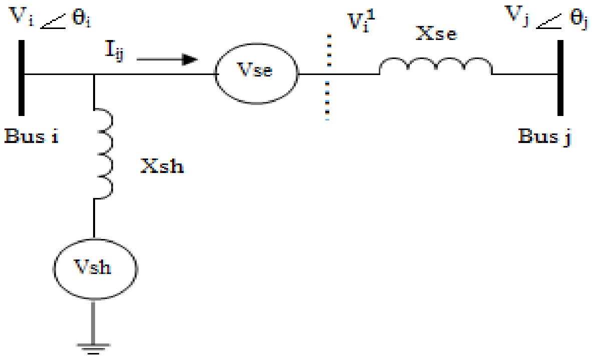

Figure 2: Power injection model of UPFC

The injection model is obtained by replacing series connected voltage source equivalent circuit with Norton's equivalent circuit as shown in figure 4.

The injected power into the ith bus is,

$$S_{is} = V_i * (-I_{se})* \tag{13}$$

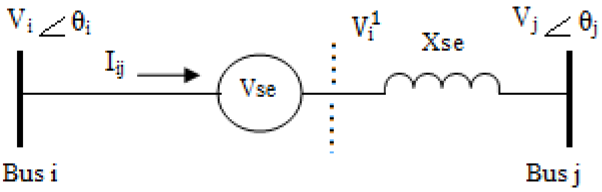

Figure 3: Series connected VSC representation

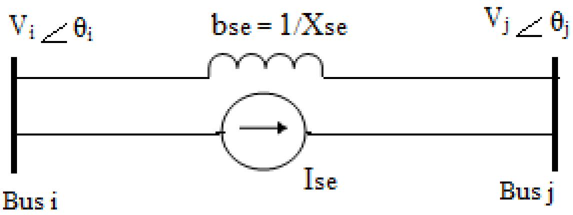

Figure 4: Series connected VSC equivalent Norton's circuit

The active and reactive powers at ith bus are

$$P_{is} = -r * b_{se} * V_i^2 \sin(\gamma) \tag{14}$$

$$Q_{is} = -j * r * b_{se} * V_i^2 \cos(\gamma) \tag{15}$$

The injected power into the jth bus is,

$$S_{js} = V_j * (I_{se})^* \tag{16}$$

The reactive and active powers at jth bus are

$$P_{js} = r * b_{se} * V_i * V_j * \sin(\theta_{ij} + \gamma) \tag{17}$$

$$Q_{js} = r * b_{se} * V_i * V_j * \cos(\theta_{ij} + \gamma) \tag{18}$$

According to the equations 14,15,17 and 18,the power injection model of series-connected voltage source can be treated as two dependent power injections at auxiliary buses **i** and **j** as shown in figure 5.

In UPFC, the shunt connected voltage source converter is used to provide the active power, which is injected through the series connected voltage source into the system and the total losses within the UPFC. When the losses are neglected,

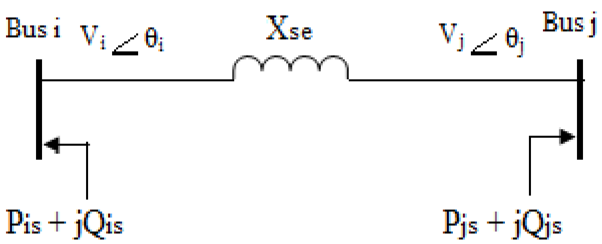

Figure 5: Injection model for series connected VSC

$$P_{shunt} = -P_{series} \tag{19}$$

The total losses of switching of the two converters are assumed to be around 2% of power transferred for PWM converters based thyristors [10]. When the losses are incorporated in the real power injection of shunt connected voltage source at bus **i**,

$$P_{shunt} = -1.02 * P_{series} \tag{20}$$

The reactive and active powers supplied by the series voltage source converter are

$$\begin{aligned} P_{series} &= r * b_{se} * V_i * V_j * \sin(\theta_{ij} + \gamma) \\ &- r * b_{se} * V_i^2 * \sin(\gamma) \end{aligned} \tag{21}$$

$$\begin{aligned} Q_{series} &= -r * b_{se} * V_i * V_j * \cos(\theta_{ij} + \gamma) \\ &+ r * b_{se} * V_I^2 \cos(\gamma) + r^2 b_{se} * V_i^2 \end{aligned} \tag{22}$$

Since the reactive power delivered or absorbed by shunt converter is independently controllable, it is modeled as a separate controllable shunt reactive source.

So, it is assumed that, $Q_{shunt} = 0$.The power injection model of the shunt connected voltage source converter is shown in figure 6.

The complete model of the UPFC has been obtained by combining the shunt connected voltage source model and the series connected voltage source model. The complete model is shown in figure 7.

The equivalent power injections at bus **i** and bus **j** **are** tabulated in the table I [4].

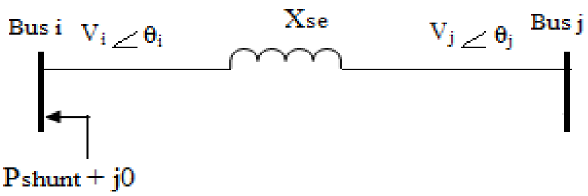

Figure 6: Injection model for shunt connected VSC

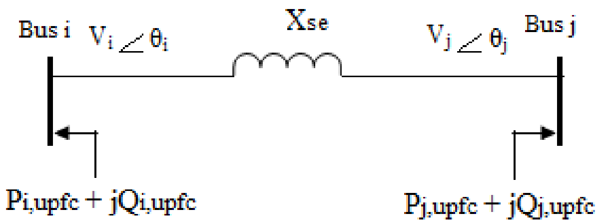

Figure 7: The injection model of UPFC

MODIFICATIONS IN NR METHOD

Suppose the UPFC is placed in the power system between the buses in **i** and **j**, as the shunt converter at the **ith** bus and series converter at the **jth** bus, the modifications that are to be made in the Jacobean matrix elements which are related to the **i** th and **j** th buses as shown in the table II.

And the corresponding power mismatches at buses '**i** and **j**' are modified as follows.

$$\Delta P_i = P_{iG} - P_{iL} - (P_{iCAL} + P_{iupfc}) \tag{23}$$

$$\Delta P_j = P_{jG} - P_{jL} - (P_{jCAL} + P_{jupfc}) \tag{24}$$

$$\Delta Q_i = Q_{iG} - Q_{iL} - (Q_{iCAL} + Q_{iupfc}) \tag{25}$$

$$\Delta Q_j = Q_{jG} - Q_{jL} - (Q_{iCAL} + Qjupfc) \qquad (26)$$

where the superscripts G, L, Cal and upfc denotes the powers of generation, load, calculated and UPFC respectively at buses **i** and **j** [4].

The bus data and line data are modified according to the double slack bus concept and UPFC data using in the NR method.

Table I. Equivalent power injections (where $\theta_{ij} = \theta_i - \theta_j$)

Bus	***0% losses***	***2% losses***
i	$P_{i,upfc}$= - r*bse*V_i*V_j* sin(θ_{ij}+ γ) $Q_{i,upfc}$= -r*bse*V_i^2*cos(γ)	$P_{i,upfc}$= 0.02*r*bse*V_i^2*sin(γ) -1.02*r*b_{se}*V_i*V_j*sin(θ_{ij}+ γ) $Q_{i,,upfc}$= -r*bse*V_i^2*cos(γ)
j	$P_{j,upfc}$= r*bse*V_i*V_j* sin(θ_{ij}+ γ) $Q_{j,upfc}$= r*bse*V_i*V_j* cos(θ_{ij}+ γ)	$P_{j,upfc}$= r*bse*V_i*V_j* sin(θ_{ij}+ γ) $Q_{j,upfc}$= r*bse*V_i*V_j* cos(θ_{ij}+ γ)

Table II. Modification of Jacobean matrix

$H(P_{i,}\theta_i) = H^O(P_{i,}\theta_i) + \frac{\partial P_{i,upfc}}{\partial \theta_i}$ $H(P_{i,}\theta_j) = H^O(P_{i,}\theta_j) + \frac{\partial P_{i,upfc}}{\partial \theta_j}$ $H(P_{j,}\theta_i) = H^O(P_{j,}\theta_i) + \frac{\partial P_{j,upfc}}{\partial \theta_i}$ $H(P_{j,}\theta_j) = H^O(P_{j,}\theta_j) + \frac{\partial P_{j,upfc}}{\partial \theta_j}$	$N(P_{i,}V_i) = N^O(P_{i,}V_i) + \frac{\partial P_{i,upfc}}{\partial V_i}$ $N(P_{i,}V_j) = N^O(P_{i,}V_j) + \frac{\partial P_{i,upfc}}{\partial V_j}$ $N(P_{j,}V_i) = N^O(P_{j,}V_i) + \frac{\partial P_{j,upfc}}{\partial V_i}$ $N(P_{j,}V_j) = N^O(P_{j,}V_j) + \frac{\partial P_{j,upfc}}{\partial V_j}$
$M(Q_{i,}\theta_i) = M^O(Q_{i,}\theta_i) + \frac{\partial Q_{i,upfc}}{\partial \theta_i}$ $M(Q_{i,}\theta_j) = M^O(Q_{i,}\theta_j) + \frac{\partial Q_{i,upfc}}{\partial \theta_j}$ $M(Q_{j,}\theta_i) = M^O(Q_{j,}\theta_i) + \frac{\partial Q_{j,upfc}}{\partial \theta_i}$ $M(Q_{j,}\theta_j) = M^O(Q_{j,}\theta_j) + \frac{\partial Q_{j,upfc}}{\partial \theta_j}$	$L(Q_{i,}V_i) = L^O(Q_{i,}V_i) + \frac{\partial Q_{i,upfc}}{\partial V_i}$ $L(Q_{i,}V_j) = L^O(Q_{i,}V_j) + \frac{\partial Q_{i,upfc}}{\partial V_j}$ $L(Q_{j,}V_i) = L^O(Q_{j,}V_i) + \frac{\partial Q_{j,upfc}}{\partial V_i}$ $L(Q_{j,}V_j) = L^O(Q_{j,}V_j) + \frac{\partial Q_{j,upfc}}{\partial V_j}$

CASE STUDY AND CONCLUSIONS

The 5 bus Hale network is considered for the case study. The bus 1 is taken as the slack bus and UPFC has been connected between the buses 4 and 5 as shunt converter at the 4 th and series converter at the 5 th bus as shown in the figure 8, in which power system and network data are shown.

The list of maximum generation limits of the generators and their respective generation participation factors (GPFps & GPFqs) for both active and reactive powers are tabulated in table-III. According to these factors, the power distribution among the generators is also given for a total load of 150 MW and 95 MVAR.

The critical loading margin has been determined by increasing the load (active and reactive) in equal increments at all the load buses and the excessive load from the base case is distributed among all the generators according to their respective GPFps and GPFqs.

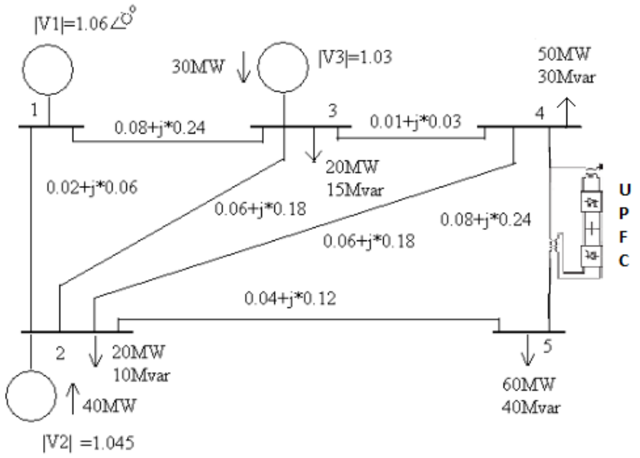

Figure 8:. 5-bus Hale Power system network.

Table-III. Participation factors

Gen#		1	2	3
Capacity	MW	85	80	70
	MVAR	50	50	40
GPFp		0.3617	0.3404	0.2979
GPFq		0.3571	0.3571	0.2857
Generation	MW	54.2553	51.0638	44.6809
	MVAR	33.9286	33.9286	27.1429

The line and bus data are given in the tables IV and V respectively, along with active and reactive loads and modifications to include the UPFC and distributed slack bus concept in the system.

The power flow analysis by NR method is carried out in the MATLAB environment with suitable modifications as listed above, for different ranges of UPFC parameters **r, γ** and **Xse**, as **r** is varied between 0 and 0.09, **γ** is varied between 0 and 2*pi and **Xse** is varied between 0.01 to 0.8 ohms, along with increase in the maximum load from 100 to 110%.In this test case, the normal (maximum) load of the system is 235 MW and 140 MVAR.

It is found that only the bus voltage Vm (5) is less than 1 pu in the typical and other cases, so the results are filtered out by using the criteria 1.000 pu≤ Vm (5) ≤ 1.001 pu. The set of UPFC values for which the criteria is satisfied, are listed out in the table VI, along with Vm (5) pu value and slack bus powers. The bar charts are also prepared for the results obtained. The load at which the criteria is satisfied is 110 % i.e., 235*110/100 = 258.5 Mw, i.e., the extra load that the system can carry without voltage drooping is 10 % (23.5MW). From the table VI, it is observed that the voltage profile is improved when UPFC is connected in the system. And the slack bus is also relieved from the over loading very much from 1.7632 pu to 0.9925 pu, when both distributed slack bus and UPFC are implemented in the system.

CONCLUSIONS

In this paper, the issue of Distributed Slack Bus Concept is catered to in addition to the UPFC power injection model to increase the loadability or available transfer capability of the power system subjected to the voltage stability constraint i.e., 1.000 pu≤ Vm (5) ≤ 1.001 pu, which is found to be less than 1 pu under typical load conditions. As a test case to our proposal, the 5 bus Hale network is considered.

The NR method is modified in order to incorporate the UPFC power injection model and distributed slack bus concept in the system, for the power flow analysis. The results are tabulated in table VI, it is observed that, up to an additional power of 10% is available for the transmission in the system without losing the voltage stability.

Table IV: Line Data (modified)

(Xse- UPFC series impedance)

Line No.	*From Bus*	*To Bus*	*R (ohms)*	*X (ohms)*	*B / 2 (susceptance) (ohms)*
1	1	2	0.02	0.06	0.030
2	1	3	0.08	0.24	0.025
3	2	3	0.06	0.18	0.020
4	2	4	0.06	0.18	0.020
5	2	5	0.04	0.12	0.015
6	3	4	0.01	0.03	0.010
7	4	5	0.08	0.24+ Xse	0.025

Table V: Bus Data (typical loading)

Bus no.	*Bus Type*	*Voltage (pu)*	*Angle (deg)*	*PL (Mw)*	*QL (Mvar)*	*PG (Mw)*	*QG (Mvar)*	*Pmin (Mw)*	*Pmax (Mw)*	*Qmin (Mvar)*	*Qmax (Mvar)*
1	1	1.06	0.0	0	0	0	0	10	85	10	50
2	2	1.045	0.0	20	10	40	30	10	80	10	50
3	2	1.03	0.0	20	15	30	10	10	70	10	40
4	0	1.00	0.0	50	30	0	0	0	0	0	0
5	0	1.00	0.0	60	40	0	0	0	0	0	0

Table VI : Results

Sl.no	*Typeof loading*	*Load (pu)*		*UPFC parameters*			*PLoss (pu)*	*QLoss (pu)*	*Vm(5) (pu)*	*PG1 (slack bus- pu)*
		PL	*QL*	*γ (radians)*	*r (pu magni-tude*	*Xse (ohms)*				
1	typical	1.50	0.95				0.0305	-0.2177	0.990	0.8305
2	typical-ds	1.50	0.95				0.0248	-0.2346	0.990	0.5675
3	normal	2.35	1.40				0.0113	0.0551	0.911	1.7632
4	normal-ds	2.35	1.40				0.0613	-0.1218	0.959	0.9113
5	110%-ds	2.585	1.54				0.0755	-0.0784	0.949	1.0105
6(Case-1)	110%-ds (upfc)	2.585	1.54	4.1888	0.0300	0.0400	0.0575	-0.1493	1.0003	0.9925
7(Case-2)	110%-ds (upfc)	2.585	1.54	3.6652	0.0300	0.0500	0.0579	-0.1289	1.0009	0.9929
8(Case-3)	110%-ds (upfc)	2.585	1.54	4.7124	0.0700	0.0500	0.0902	-0.1929	1.0004	1.0250
9(Case-4)	110%-ds (upfc)	2.585	1.54	4.1888	0.0600	0.0800	0.0575	-0.1498	1.0003	0.9925
10(Case-5)	110%-ds (upfc)	2.585	1.54	4.1888	0.0900	0.1200	0.0575	-0.1503	1.0003	0.9925

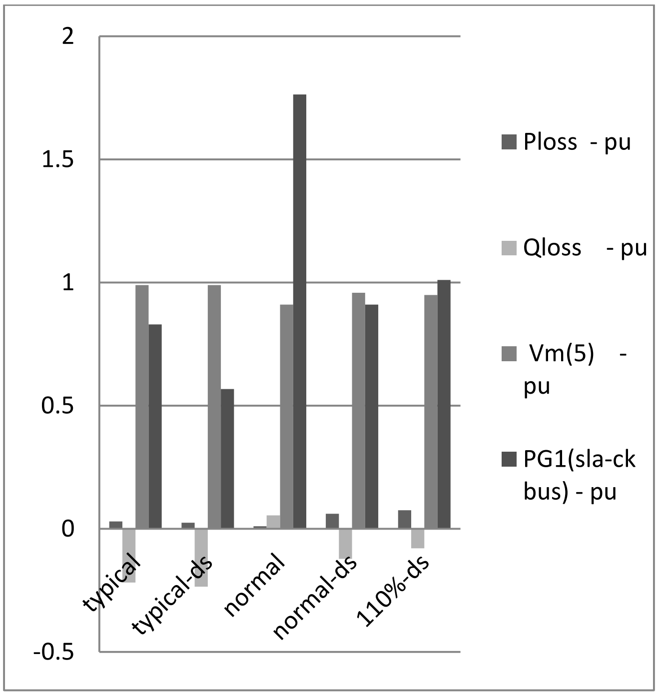

Figure 9: Bar Chart for without UPFC

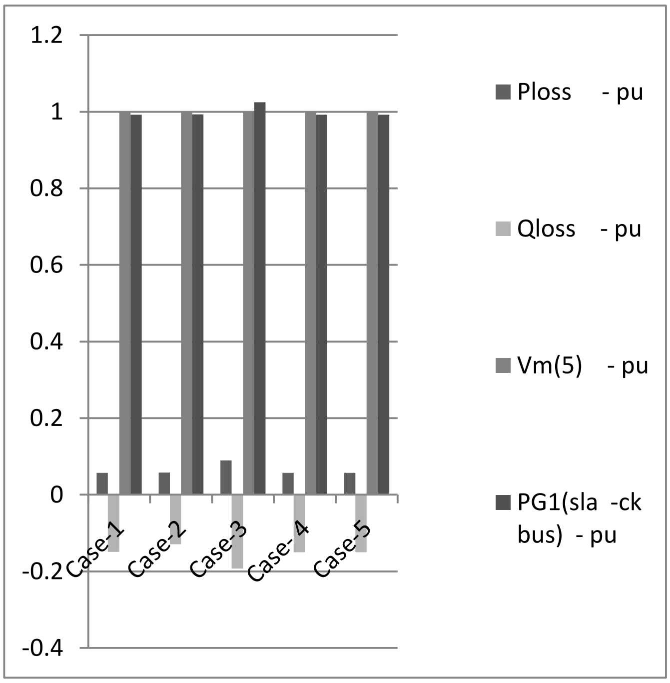

Figure 10: Bar Chart for with UPFC

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