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FACTS Based Power System Optimization by Using Newton Raphson Technique

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Abstract:

This paper presents the load flow calculation of the power system network with implementation of FACTS controller. The main aim of this paper show how standard load flow calculation techniques can be analytically be modified to include FACTS controller. Aspects of modelling and implementation of the STATCOM which is a shunt connected FACTS controllers is presented with the help of MATLAB programming using Newton Raphson load flow technique. This technique exhibits very strong convergence characteristics, no matter what size of network. The load flow analysis is performed on IEEE 5 bus power system with and without STATCOM by using MATLAB software.

Keywords: Load Flow Calculation (LFC); Newton Raphson (NR) Technique; FACTS Controller; STATCOM; Voltage Profile.

I. INTRODUCTION

In this contemporary era, as the need for electricity increasing, the system become strained, hence more arduous to operate and less secured with unscheduled power flows that resulted in greater losses. Hence this requires extension of already existing transmission system networks to redundant overloading of transmission system. It is difficult to incorporating a new transmission line due to environmental and right of way restrictions. So Nowadays, highly developed technology is used for reliable and amend operation of transmission and distribution in power system [1]. While improved utilization of the existing power system is provided through the application of advanced control technologies in this manner, power electronics are developed the Flexible AC transmission system which truncated as FACTS devices. These are effective and capable to enhancing the power transfer capability of a line and support the network to work convenient with comfortable margins of stability [2]. Whereas, to achieve all this in any specific system the implementation of FACTS devices is required, in order to tackle the main parameters basically voltage magnitude, phase angle and impedance which are affecting AC power transmission. The power system should be capable to support the line of power transfer with comfort and marginally stable. FACTS controller plays a very vital role; mainly the STATCOM is used for boost the performance of power system. The voltage and angle stability are upgraded by the concern of STATCOM [3].

II. LOAD FLOW ANALYSIS

The load flow studies are very prevalent in power system analysis. These are executed in power systems for planning and operation control [4]. The Load flow analysis permits us to know the present state of a system. Load flow calculation iteratively decided the power that is flowing through the lines, the power that is being consumed by the loads and generated by the generators, the losses arising during the transfer of power from source to load and so on. In several systems, the most important quantity is known as the voltage at different points all over the networks. As soon as the voltage and angles are computed, the real and reactive power flow in each line can be computed. Based on the variation among power flow in the transmitting and receiving ends, the losses in the transmission lines can also be calculated. The Newton Raphson technique is the most preferred load flow technique due to its reliability towards convergence, it has powerful convergence characteristics on the contrary to other alternative processes and considerably little computing times[3]-[4]. The NR load flow technique is predominant to many recently developed methods for the optimization of power system operation, transient stability and sensitivity analysis, state estimation of system, modelling of linear network modelling and many more [5].

III. THE NEWTON RAPHSON TECHNIQUE

In load flow analysis the Newton Raphson technique is proved as most successful on account of its highly robust convergence characteristics. The load flow Newton Raphson algorithm is expressed by the following relation [6]-[8].

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \theta} & V\frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \theta} & V\frac{\partial Q}{\partial V} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \frac{\Delta V}{V} \end{bmatrix} \qquad (1)$$

Where ΔP is the active power mismatches and ΔQ is the reactive power mismatches, V and δ are the magnitude of bus voltage and phase angle of bus voltage respectively. The power flow equation for a generic i^{th} bus of the power system network without STATCOM is given below.

$P_i^{cal} = \sum_{j=1}^{N} V_i V_j \left(G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j) \right)$ (2) $Q_i^{cal} = \sum_{j=1}^{N} V_i V_j \left(G_{ij} \sin(\theta_i - \theta_j) - B_{ij} \cos(\theta_i - \theta_j) \right)$ (3)

It may be pointed out that in equation (1) the correction terms ΔV are divided by V to compensate for the multiple fact that jacobian terms (∂P/∂V*V) and (∂Q/∂V*V) are multiplied by V. It is shown in the derivatives terms that this artifice yields valuable simplification computations. Deliberated that the element connected between i^{th} bus and j^{th} bus as shown in Figure1, for which self and mutual jacobian terms are given below.

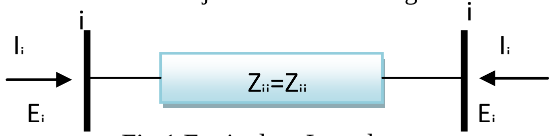

Fig.1 Equivalent Impedance

For i≠j

$$\frac{\partial P_i}{\partial \theta_j} = \sum_{j=1}^{N} V_i V_j \left(G_{ij} \sin(\theta_i - \theta_j) - B_{ij} \cos(\theta_i - \theta_j) \right) \quad (4)$$

$$\frac{\partial P_i}{\partial V_j / V_j} = \sum_{j=1}^{N} V_i V_j \left(G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j) \right) \quad (5)$$

$$\frac{\partial Q_i}{\partial \theta_j} = -\sum_{j=1}^{N} V_i V_j \left(G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j) \right) = -\frac{\partial P_i}{\partial V_j / V_j} \quad (6)$$

$$\frac{\partial Q_i}{\frac{\partial V_j}{V_j}} = \sum_{j=1}^{N} V_i V_j \left(G_{ij} \sin(\theta_i - \theta_j) - B_{ij} \cos(\theta_i - \theta_j) \right) = \frac{\partial P_i}{\partial \theta_j} \quad (7)$$

For i= j

$$\frac{\partial P_i}{\partial \theta_i} = -\sum_{j=1}^{N} V_i V_j \left(G_{ij} \sin(\theta_i - \theta_j) - B_{ij} \cos(\theta_i - \theta_j) \right) - V_i^2 B_{ii} = -Q_i^{cal} - V_i^2 B_{ii} \quad (8)$$

$$\frac{\partial P_i}{\frac{\partial V_i}{V_i}} = \sum_{j=1}^{N} V_i V_j \left(G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j) \right) + V_i^2 G_{ii} = P_i^{cal} + V_i^2 G_{ii} \quad (9)$$

$$\frac{\partial Q_i}{\partial \theta_i} = \sum_{j=1}^{N} V_i V_j \left(G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j) \right) - V_i^2 G_{ii} = P_i^{cal} - V_i^2 G_{ii} \quad (10)$$

$$\frac{\partial Q_i}{\frac{\partial V_i}{V_i}} = \sum_{j=1}^{N} V_i V_j \left(G_{ij} \sin(\theta_i - \theta_j) - B_{ij} \cos(\theta_i - \theta_j) \right) - V_i^2 B_{ii} = Q_i^{cal} - V_i^2 B_{ii} \quad (11$$

The mutual elements remain the same whether we have one transmission line or N transmission lines coming to an end at the bus.

IV. MODELING OF SYSTEM WITH STATCOM

The block diagram illustrates in Figure 2 shows a symbolic representation of a power system that inculcates several generators, several loads, STATCOM.

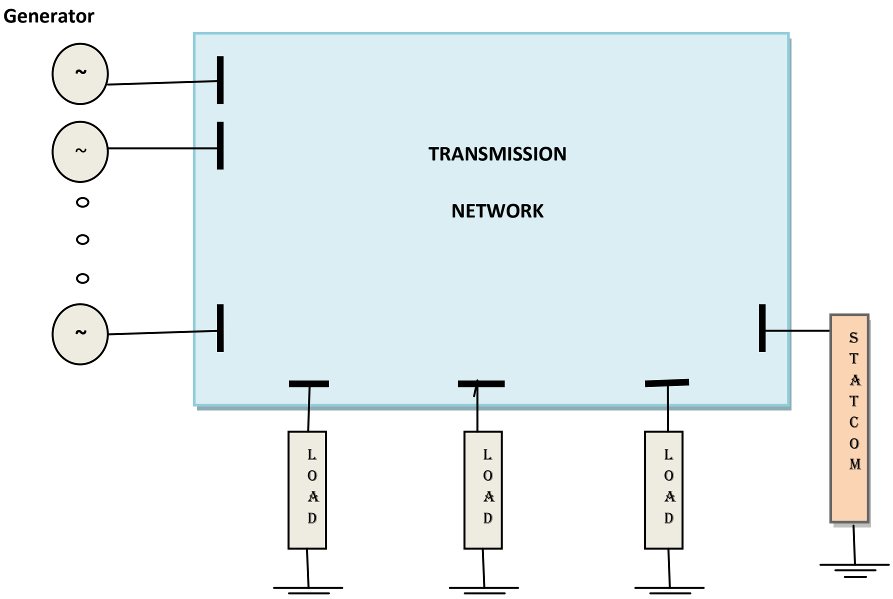

Fig.2 Symbolic representation of a power system

The different equipments are unified with the transmission network modeled by its YBus matrix. It should be reserved that, the YBus matrix does not consider the admittances of the loads and the FACTS controllers. The load flow model of the system assimilate, predominantly, the equality constrained which imposed by the transmission system for transmitting the demands load at distinct buses [3].

V. POWER FLOW MODEL OF STATCOM

The STATCOM is represented by a synchronous voltage source with maximum and minimum magnitude of voltage span. Whereas, the bus at which STATCOM connected is symbolized by a generator bus which may be automatically converted into a load bus when the cross over the limits. In such circumstances, the generated or absorbed reactive power would proportional to the violated limit. [6],[9]. The power flow equations for STATCOM are derived from the First principle and presuming the subsequent voltage source representation (Gyugyi 1994). Depend upon the shunt connection an equivalent circuit for the STATCOM is depict in Figure 3, where as the power flow equations for the STATCOM are determined as given by:

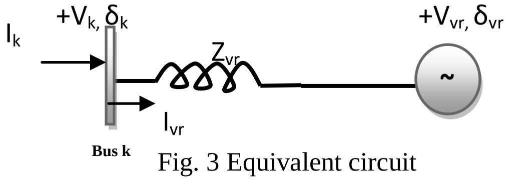

Fig. 3 Equivalent circuit

$$E_{vr} = V_{vr}(\cos\delta_{vr} + j\sin\delta_{vr}) \qquad (12)$$
$$S_{vr} = V_{vr} I_{vr}^* = V_{vr} Y_{vr}^* (V_{vr}^* - V_k^*) \qquad (13)$$

Where symbol * represents the complex conjugate. After go through from the certain complex operations, the following active and reactive power equations are obtained for the converter and bus k, respectively

a. *Active Power Equations Obtained for the Converter*

$$P_{vr} = V_{vr}^2 G_{vr} + V_{vr} V_k (G_{vr}\cos(\delta_{vr} - \theta_k) + B_{vr}\sin(\delta_{vr} - \theta_k)) \qquad (14)$$

b. *Active Power Equations Obtained for the Converter*

$$Q_{vr} = -V_{vr}^2 B_{vr} + V_{vr} V_k (G_{vr}\sin(\delta_{vr} - \theta_k) + B_{vr}\cos(\delta_{vr} - \theta_k)) \qquad (15)$$

c. *Active Power Equations Obtained at bus k*

$$P_k = V_k^2 G_{vr} + V_k V_{vr} (G_{vr}\cos(\theta_k - \delta_{vr}) + B_{vr}\sin(\theta_k - \delta_{vr})) \qquad (16)$$

d. *Reactive Power Equations Obtained at bus k*

$$Q_k = -V_k^2 B_{vr} + V_k V_{vr} (G_{vr}\sin(\theta_k - \delta_{vr}) - B_{vr}\cos\ (\theta_k - \delta_{vr})) \qquad (17)$$

The influence of STATCOM on load flow is accommodated by addition of new entries and by modulation of some existing entries in the Jacobian equation of the power system with no FACTS controllers. Moreover, by using these above mentioned power equations the STATCOM model is given, where the voltage magnitude V_{vr} and phase angle δ_{vr} are taken as the state variables.

$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \\ \Delta P_{vr} \\ \Delta Q_{vr} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_k}{\partial \theta_k} & \frac{\partial P_k}{\partial V_k} V_k & \frac{\partial P_k}{\partial \delta_{vr}} & \frac{\partial P_k}{\partial V_{vr}} V_{vr} \\ \frac{\partial Q_k}{\partial \theta_k} & \frac{\partial Q_k}{\partial V_k} V_k & \frac{\partial Q_k}{\partial \delta_{vr}} & \frac{\partial Q_k}{\partial V_{vr}} V_{vr} \\ \frac{\partial P_{vr}}{\partial \theta_k} & \frac{\partial P_{vr}}{\partial V_k} V_k & \frac{\partial P_{vr}}{\partial \delta_{vr}} & \frac{\partial P_{vr}}{\partial V_{vr}} V_{vr} \\ \frac{\partial Q_{vr}}{\partial \theta_k} & \frac{\partial Q_{vr}}{\partial V_k} V_k & \frac{\partial Q_{vr}}{\partial \delta_{vr}} & \frac{\partial Q_{vr}}{\partial V_{vr}} V_{vr} \end{bmatrix} \begin{bmatrix} \Delta\theta_k \\ \frac{\Delta V_k}{V_k} \\ \Delta\delta_{vr} \\ \frac{\Delta V_{vr}}{V_{vr}} \end{bmatrix} \qquad (18)$$

VI. CRITERIA FOR PLACEMENT OF STATCOM

The STATCOM can tackle the voltage and power flows in the wide power system. The location of the STATCOM should be chosen according to their contribution to the general aim of power system operation and has been subjected to equality and non equality constraints. The STATCOM should be located on the most sensitive bus to maintain the voltage in the power system and after the placement of STATCOM that bus will act as generator bus. Proceeding criteria have been used for their optimal placement.

1. The STATCOM should be placed at the bus which is most sensitive to the change in load.
2. Also the STATCOM can be connected to the weakest bus in the system (the bus at which voltage is minimum as compare to the voltage at other bus)

VII. NUMERICAL ANALYSIS

The procedure for load flow analysis of a power system with and without STATCOM is tested on IEEE 5 bus system. The single line diagram of the system is shown in Appendix A. Also the Busdata and transmission line data is shown in Appendix B. All these values are given in per unit considering a base power of 100 MVA for the overall power system. Initially the IEEE 5 bus system is tested without STATCOM. The real and reactive power flow is analyzed by using the Newton Raphson technique. The load flow program converged in the 6 iteration with a tolerance of 0.001 for both the active and reactive power. The preceding Table 1 reveal the result of load flow calculation of IEEE 5 bus power system without STATCOM and Table 2 shows the power flow and the line losses in the IEEE 5 bus system without STATCOM. From the Table 1, it can be observed that the magnitudes of voltage at bus 3, 4 and 5 are below than 1.0 p.u. and therefore in order to control the bus voltage STATCOM is needed. In order to control the voltage magnitude and to reduce the system losses the STATCOM model has been installed in the IEEE 5 bus system.

Table 1: Load Flow Analysis by Newton Raphson with STATCOM

Bus no	Voltage V(p.u)	Angle (degree)	Injection		Generation		Load	
			MW	MVAR	MW	MVAR	MW	MVAR
1.	1.060	0.00	125.757	19.052	125.757	19.052	0.000	0.000
2.	1.040	-2.1840	90.820	19.638	90.820	19.638	0.000	0.000
3.	0.9968	-6.1714	-70.000	-20.250	0.000	0.000	70.00	20.25
4.	**0.9943**	-6.5582	-69.000	-15.980	0.000	0.000	69.00	15.98
5.	0.9992	-6.6457	-70.000	-10.000	10.00	0.000	80.00	10.00
TOTAL			**7.577**	**-7.539**	**226.577**	**38.691**	**219.00**	**46.230**

Table 2: Losses and Line Flows in IEEE- 5 Bus System without STATCOM

From bus	To bus	P (MW)	Q (MVAR)	From Bus	To bus	P (MW)	Q (MVAR)	Line losses	
								MW	MVAR
1	2	74.018	11.995	2	1	-73.017	-8.993	1.001	3.002
1	3	51.739	13.237	3	1	-49.708	-7.145	2.031	6.092
2	3	43.955	11.726	3	2	-42.807	-8.282	1.148	3.444
2	4	47.853	12.110	4	2	-46.502	-8.055	1.352	4.055
2	5	72.028	13.989	5	2	-7.037	-8.016	1.991	5.973
3	4	22.515	0.641	4	3	-22.464	-0.488	0.051	0.153
4	5	-0.034	-1.999	5	4	0.037	2.009	0.003	0.010
TOTAL LOSSES								**7.577**	**22.730**

With reference to criterion which illustrated above the STATCOM must be placed to bus number 4 which is the weakest bus in the system to control the voltage magnitude and voltage profile of the system and to sink the power flow losses. The preceding Table 3 reveals the result of load flow calculation of Five bus power system with implementation of STATCOM, which upgrading the system voltage to 1 p.u. Also, the absorption of reactive power in swing generator increase as compared to the system without STATCOM. Table 4 show the effect on power flow and line losses in the system when STATCOM is connected in the system. The active power flow losses in the system are 7.450 MW and the reactive power flow losses in the system are 22.351 MVAR.

Table 3: Load Flow Analysis by Newton Raphson with STATCOM

Bus no	Voltage V(p.u)	Angle	Injection		Generation		Load	
			(MW)	(MVAR)	(MW)	(MVAR)	(MW)	(MVAR)
1.	1.060	0.000	125.638	17.194	125.638	17.194	0.000	0.000
2.	1.040	-2.1795	90.820	12.284	90.820	12.284	0.000	0.000
3.	1.0012	-6.2281	-70.000	-20.250	-0.000	-0.000	70.000	20.250
4.	**1.000**	-6.6353	-69.008	-7.273	-0.008	8.707	69.000	15.980
5.	1.0011	-6.6620	-70.00	-10.000	10.000	0.000	80.000	10.00
TOTAL			**7.450**	**-8.045**	**226.450**	**38.185**	**219.00**	**46.230**

Table 4: Losses and Line Flows in IEEE- 5 Bus System without STATCOM

From Bus	To Bus	P (MW)	Q (MVAR)	From Bus	To Bus	P (MW)	Q (MVAR)	Line losses	
								MW	MVAR
1	2	73.887	12.034	2	1	-72.889	-9.041	0.998	2.993
1	3	51.751	11.340	3	1	-49.753	-5.345	1.995	5.995
2	3	43.918	9.236	3	2	-42.801	-5.884	1.117	3.352
2	4	47.856	8.905	4	2	-46.542	-4.962	1.314	3.943
2	5	71.935	12.378	5	2	-69.965	-6.467	1.970	5.911
3	4	22.554	-3.509	4	3	-22.502	3.664	0.052	0.156
4	5	0.036	-0.475	5	4	-0.035	0.476	0.000	0.001
TOTAL LOSSES								**7.450**	**22.351**

VIII. COMPARISON OF LFC RESULT OF IEEE 5 BUS POWER SYSTEM WITH AND WITHOUT STATCOM

On the contrary, the load flow results of IEEE 5 bus system with and without STATCOM, it is observed, that after the connection of STATCOM the bus voltages are improved and the line losses dropped down. The magnitude of bus voltages is contrast before and after connection of FACTS devices illustrate in Table 5, the voltage changes from 0.994 per unit to 1.0 per unit due to the STATCOM implemented in the system. The parameter of STATCOM has been shown in Table 6 in order to maintain the bus voltage at 1 per unit.

Table 5: Bus voltages and angels of IEEE 5 bus power system with and without STATCOM

Bus No.	Bus voltage and angles of IEEE-5 bus system Without STATCOM		Bus voltage and angles of IEEE-5 bus system with STATCOM	
1.	1.060	0.00	1.060	0.000
2.	1.040	-2.184	1.040	-2.179
3.	0.997	-6.171	1.001	-6.228
4.	***0.994***	*-6.558*	**1.000**	-6.635
5.	0.999	-6.646	1.001	-6.662

Table 6: PARAMETERS OF STATCOM

STATCOM (Bus)	Vsh (pu)	Thst(Degree)	Qsh (pu)
4	1.008	-6.6852	-0.00871

The voltage profile of the system before and after FACTS devices connected are shown in the Figure 4, it demonstrates the voltage magnitude for buses 1 to 5. The voltage at bus 1 and 2 remained stable but the voltage at other buses increases as depicted in Figure 4.

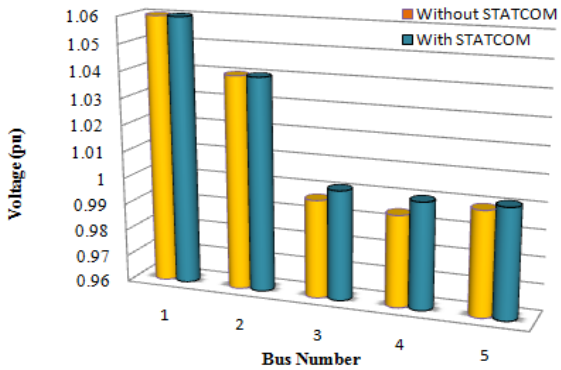

Fig. 4 Voltage profile of the system with and without STATCOM

The active power and reactive power losses in the system are also dipped after STATCOM connected. In contrast, result of loss reduction before and after FACTS devices connection shown in Table 7. The installation of the STATCOM resulted in improved line losses. The Table 7 shows that the active power losses reduced from 7.577 MW to 7.450 and the reactive power losses reduced from 22.730 MVAR to 22.351 MVAR.

Table 7: Total Losses for IEEE 5 bus system with and without STATCOM

Line losses	P(MW)	Q(MVAR)
Without STATCOM	7.577	22.730
With STATCOM	7.450	22.351

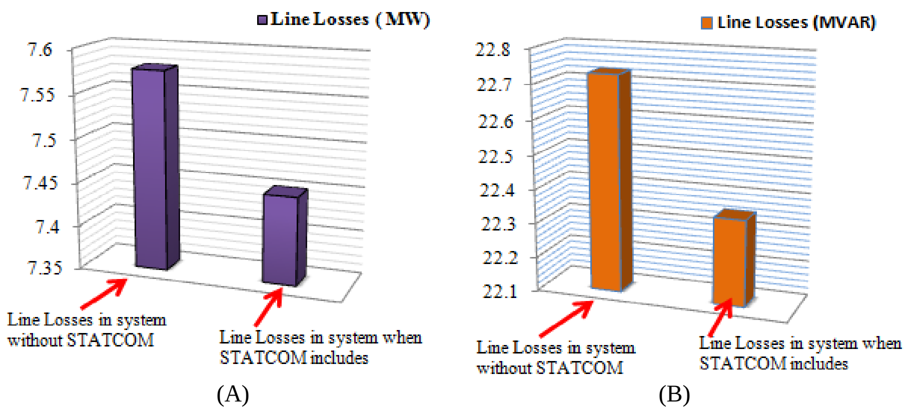

Fig.5 (A) and (B) shown the comparison between active and reactive power losses calculated by LFC method on IEEE 5 bus system with and without STATCOM

IX. CONCLUSION

This paper present the technique required for operation of system with STATCOM. The load flow analysis could be modified to include STATCOM. It was shown that the effect of FACTS controller on load flow can be provided by adding new entries and modified some exciting entries in Jacobian of equations without any FACTS controller. An exciting load flow program that uses the Newton Raphson techniques can easily modified through the procedure presented in this paper. This procedure was applied on the IEEE 5 bus power system and implemented using MATLAB software package. The steady state model of STATCOM are evaluated and the results shown that when the shunt controller were implemented in the system it control voltage, enhanced the voltage profile of the overall system and lowered the system line losses.

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APPENDIX A

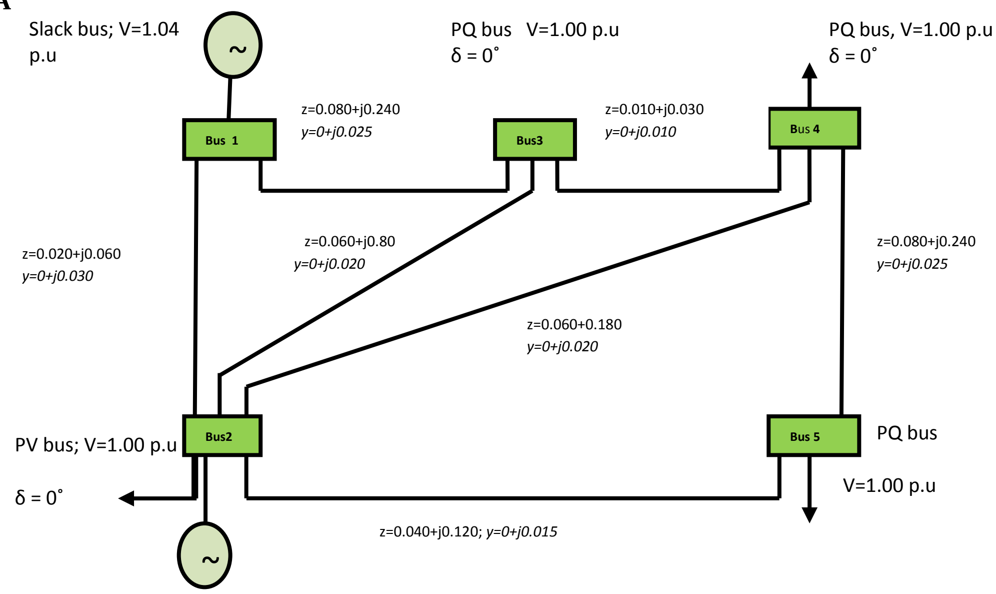

Fig. A1 Single Line diagram of IEEE 5 bus system

APPENDIX B

Table B1: Linedata for 5 Bus Test system

S.No	Sending End Bus	Receiving End Bus	Resistance R (pu)	Reactance X (pu)	Half susceptance B/2 (pu)	Transformer Tap
1.	1	2	0.020	0.060	0.030	1.0
2.	1	3	0.080	0.240	0.025	1.0
3.	2	3	0.060	0.180	0.020	1.0
4.	2	4	0.060	0.180	0.020	1.0
5.	2	5	0.040	0.120	0.015	1.0

6.	3	4	0.010	0.030	0.010	1.0
7.	4	5	0.080	0.240	0.025	1.0

Table B1: Linedata for 5 Bus Test system

Bus no.	**Bus Type**	**Voltage**	**Angle degree**	**Generator**		**Load**		**Generator**		**Injected MVAR**
				MW	**MVAR**	**MW**	**MVAR**	**Qmin**	**Qmax**	
1.	Slack bus	1.06	0	0	0	0	0	0	0	0
2.	PV	1.00	0	90.82	0	0	0	0	200	0
3.	PQ	1.00	0	0	0	70	20.25	0	0	0
4.	PQ	1.00	0	0	0	69	15.98	0	0	0
5.	PQ	1.00	0	10	0	80	10.00	0	0	0

