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POWER SYSTEM SECURITY ASSESSMENT OF AN INTERCONNECTED POWER SYSTEM CONSIDERING VOLTAGE DEPENDENT LOADS WITH DYNAMIC TAP CHANGER / EXPONENTIAL RECOVERY LOADS WITH VARIOUS FACTS DEVICES

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ABSTRACT
This paper proposes the security enhancement depending on system conditions, the dynamic behaviour of the reactive part of loads can be more significant than the real part. This paper had indicated that the dynamic load models will not only affect the damping of electromechanical modes, but can also have an influence on which generators participated in the mode. As load parameters vary, this participation can also vary. In this approach, with voltage dependent loads with dynamic tap changer / exponential recovery loads are considered for the quick restoration few FACTS devices are incorporated with boundary values. The security enhancement results are provided to highlight the overall security and suitability of the approach. The significant of the corrective measures to be adopted for the load uncertainty was also considered with load parameters variation. The proposed scheme is adopted in IEEE 14 bus test system. The optimized result can be utilized for the improvement of the system performance.

Keywords: Flexible AC Transmission System (FACTS), Interline Power Flow Controller (IPFC), Mixed Load and Thermostatically Controlled Loads

I. INTRODUCTION

This proposes the overview of control strategies for power system security assessment of an interconnected power system considering Voltage Dependent Load with Dynamic tap changer / Exponential Recovery Loads which is governed by the Flexible AC Transmission System (FACTS) devices when the system is approaching an extreme emergency state [1,2]. In this method, the island is prevented from the total loss of supply using few FACTS devices. The proposed scheme is adopted in IEEE 14 bus test system. The optimization process is carried out using bacterial foraging optimization algorithm. The optimized result exhibits tremendous improvement in the system performance. The basic restoration assessment for the interconnected power system considering Voltage Dependent Load Voltage Dependent Load with Dynamic tap changer/ Exponential Recovery Loads has been carried out and various control corrective actions using few FACTS devices are considered for the power system security enhancement [3,4]. The maximum allowable transfer level is then fixed at the last acceptable level after performing various levels of power transfers for various credible contingencies[5,6], or reduced by some small amount to provide a margin that would account for changes in conditions when the actual limit is in force.

II. MATHEMATICAL MODELING OF VOLTAGE DEPENDENT LOADS WITH DYNAMIC TAP CHANGER (VDTL)

Voltage Dependent Loads with Dynamic Tap Changer are nonlinear load model which represents the power relationship to voltage as an exponential equation [7,8]. The transformer model consists of an ideal circuit with tap ratio *n*, hence the voltage on the secondary winding is $v_s = v/n$. The voltage control is obtained by means of a quasi-integral anti-windup regulator. Where v_s = secondary bus voltage and v = primary bus voltage of the transformer. The load powers P_H and Q_H are preceded as negative power as these powers are absorbed from the bus, as follows

$$-P_H = P_0 (v/n)^{\gamma p} \tag{2.1}$$

$$-Q_H = Q_0 (v/n)^{\gamma q} \tag{2.2}$$

and the differential equation is

$$\dot{m} = K_d n + K_i \left(V/_n - V^{ref} \right) \tag{2.3}$$

Where K_d is the Anti-windup regulator deviation K_i is the Anti-windup regulator gain. γ_p and γ_q the active and reactive power exponents. The reference voltage sign is negative due to the characteristic of the stable equilibrium point. If voltage dependent loads with embedded dynamic tap changer are initialized after the power flow analysis, the powers P_0 and Q_0 are computed based on the constant PQ load powers P_{L0} and Q_{L0} as (2.5 and 2.6) and the state variable *n* and the voltage reference v_{ref} are initialized as follows

ISSN 2394 - 7780

$$-\,m_0 = V_0 \quad (2.4)$$

$$V_{ref} = 1 + \frac{K_d}{K_i}\; V_0$$

Where v_0 is the value of the initial load bus voltage obtained from power flow solution. The parameters of this model are γ_p, γ_q and P_0 and Q_0 are the values of the active and reactive power at the initial conditions. Common values for the exponents of the model for different load components γ_p and γ_q are (0, 1, 2). The value of P_0 and Q_0 depends on the status parameter (k). If k =1, the Voltage Dependent Loads with Dynamic Tap Changer is initialized after the power flow analysis [9,10], and P_0 and Q_0 are the percentage PQ load connected at the Voltage Dependent Loads with Dynamic Tap Changer.

$$P_0 = \frac{K_P}{100}\; P_L \quad (2.5)$$

$$Q_0 = \frac{K_Q}{100}\; Q_L \quad (2.6)$$

Where K_P and K_Q are Active and Reactive power rating of the loads and P_L and Q_L are the Active and Reactive load powers.

III. MATHEMATICAL MODELING OF EXPONENTIAL RECOVERY LOAD (ERL)

The load model is represented using the power relationship to voltage as an exponential equation as

$$\dot{x}_p = -\frac{x_p}{T_p} + p_s - p_t \quad (2.7)$$

Where p_s and p_t are the static and transient real power absorptions, which depends on the load voltage

$$-P_s = P_0 \left(\frac{V}{V_0}\right)^{\gamma s} \quad (2.8)$$

$$-P_t = P_0 \left(\frac{V}{V_0}\right)^{\gamma t}$$

Where γt is a static active power exponent, γs is a dynamic active power exponent, β_s is a static reactive power exponent, β_t is a dynamic reactive power exponent of the load models, V is the actual voltage and V_o is the nominal voltage.

Similar equation holds for the reactive power

$$\dot{x}_q = \frac{-x_q}{T_q} + q_s - q_t$$

$$-Q_H = \frac{x_q}{T_q} + q_t \quad (2.9)$$

$$-Q_s = Q_0 \left(\frac{V}{V_0}\right)^{\beta s} \quad (2.10)$$

$$-Q_t = Q_0 \left(\frac{V}{V_0}\right)^{\beta t}$$

Where Q_s is the Static reactive load power as a function of bus voltage magnitude and Q_s is the Dynamic reactive load power as a function of bus voltage magnitude. The power flow solution and the PQ load data are used for determining the value of P_o, $Q_{o,}$ and $V_{o.}$

The parameters of the load can be defined based on the PQ load powers P_{L0} and Q_{L0}. Where v_0 is the initial voltage of the load bus and is obtained from the power flow solution. Other parameters of ERL is initialized after the power flow analysis [11,12], the parameters can be defined based on the PQ load powers P_{L0} and Q_{L0}.

ISSN 2394 - 7780

$g = \frac{g}{100}\frac{P_{L0}}{v_0^2},\qquad I_p = \frac{I_p}{100}\frac{P_{L0}}{v_0},\qquad P_m = \frac{p_m}{100}P_{L0}$

$b = \frac{b}{100}\frac{Q_{L0}}{v_0^2},\qquad I_q = \frac{I_q}{100}\frac{Q_{L0}}{v_0},\qquad q_m = \frac{q_m}{100}Q_{L0}$

In this case initial voltage V_0 is also not known, thus following equation is used.

$$-p_H = gv^2 + I_p v + p_m \tag{2.11}$$

$$-q_H = bv^2 + I_q v + q_m \tag{2.12}$$

The parameters are constants and indicate the nominal power which is divided into constant power, constant current and constant impedance.

IV.COMPUTATION OF VOLTAGE COLLAPSE PERFORMANCE INDICES (VCPI)

With the power flow model, Jacobian Matrix J represents the first derivatives of active and reactive power mismatch equations, ΔP = ΔP(θ, E) and ΔQ = ΔQ(θ, E), with respect to the voltage magnitude E and angles θ, i.e., the linearization of these equations yields

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = J\begin{bmatrix}\Delta\theta\\ \Delta E\end{bmatrix} \tag{4.42}$$

Where [ΔP], [ΔQ], [Δθ] and [ΔE] are the increments change in nodal bus powers, reactive power, angles and voltage magnitudes.

$$[J] = \begin{bmatrix}J_1 & J_2\\ J_3 & J_4\end{bmatrix} \tag{2.13}$$

$$J_1 = \frac{\partial P}{\partial\theta},\quad J_2 = \frac{\partial P}{\partial E},\quad J_3 = \frac{\partial Q}{\partial\theta},\quad J_4 = \frac{\partial Q}{\partial E} \tag{2.14}$$

The voltage stability of the system is affected by both P and Q. However, at each operation point we keep P constant and evaluate voltage stability by considering the incremental relationship between Q and (E or V). This is analogous to the Q-V curve approach. In [13,14], the authors proposed to reduce the load-flow Jacobian to the first derivative of reactive power equations in relation to voltage magnitude, by assuming that the generator and load buses present no active power variation, i.e., ΔP = 0. Thus,

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J_1 & J_2\\ J_3 & J_4\end{bmatrix}\begin{bmatrix}\Delta\theta\\ \Delta E\end{bmatrix} \tag{4.45}$$

$$[\Delta\theta] = -[J_{P\theta}]^{-1}.\,[J_{PE}].\,[\Delta E] \tag{2.15}$$

$$[\Delta Q] = [J_{Q\theta}]\ [\Delta E] + .\,[J_{QE}].\,[\Delta E] \tag{2.16}$$

After substituting $[\Delta\vartheta]$, $[\Delta Q]$

$$[\Delta Q] = \left([J_{QE}] - [J_{Q\theta}].[J_{P\theta}]^{-1}.\,[J_{PE}].\,[\Delta E]\right) \tag{2.17}$$

or

$$\left[\Delta Q_{load}\right] = [J].[R].\left[\Delta E_{load}\right] \tag{2.18}$$

$$\Delta Q = \left(J_4 - J_3 J_1^{-1} J_2\right)\Delta E = JR\ \Delta E \tag{2.19}$$

Where

$$[J].[R] = \left([J_{QE}] - [J_{Q\theta}].[J_{P\theta}]^{-1}.\,[J_{PE}]\right) \tag{2.20}$$

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$$\left[\Delta V_{load}\right] = [J].[R]^{-1}.\left[\Delta Q_{load}\right] \tag{2.21}$$

$$\Delta E = \left(J_4 - J_3 J_1^{-1} J_2\right)^{-1} \Delta Q \;\; = JR^{-1} \; \Delta Q \tag{2.22}$$

Where $[J][R]^{-1}$ is called inverse reduced V-Q Jacobian matrix. Its i^{th} diagonal element is the V-Q sensitivity at the bus i.

Few parameters can be directly measured and can be used in real time application to compute proximity to collapse index quickly. An example of such indicator is sensitivity of the generated reactive powers with respect to load parameters and voltage magnitude. Voltage Collapse Performance Index (VCPI) is obtained using sensitivity analysis computation using the relation between voltage change and reactive power change and the elements of the inverse of the reduced Jacobian matrix *JR* are Q-V sensitivities. The diagonal components $\partial Vi/\partial Qi$ are the self sensitivities and the nondiagonal elements $\partial Ek/\partial Qi$ are the mutual sensitivities [15,16]. The sensitivities of voltage controlled buses are equal to zero. For a quite stable system when Q decreases at specified bus or buses, its effect on the voltage magnitude of the system buses should be minor. The sensitivity indices are interpreted as follows:

Positive sensitivities: Stable operation; the smaller the sensitivity, the more stable the system. As stability decreases, the magnitude of the sensitivity increases, becoming infinite at the stability limit (maximum loadability).

Negative sensitivities: Unstable operation. The system is not controllable, because all reactive power control devices are designed to operate satisfactorily when an increase in Q is accomplished by an increase in V.

III. IN BFO FINNALY BY ELIMINATION AND DISPERSAL

In order to keeping the number of bacteria in the population constant, if a bacterium is eliminated, simply disperse one to a random location on the optimization domain [17,18].

Problem Formulation

$$Min\ J = k_2 p_i^2 + k_1 p_i + k_0 \tag{2.23}$$

Subject to:

$P_{\min} \le P \le P_{\max}\ ;\ Q_{\min} \le Q \le Q_{\max}\ ;\ V_{\min} \le V \le V_{\max}$

Where k_0, k_1, k_2 are cost coefficient and p_i are the parameters to be optimised[19,20].

V.SIMULATION RESULTS AND OBSERVATIONS

IEEE 14 bus system is considered for the Stability Assessment studies. The performance analysis of a IEEE 14-bus, 5-generator system coordinated with different types of Dynamic load models especially VDL with dynamic tap changer/ ERL without / with FACTS devices were studied. And the optimum utilization requirement with the FACTS devices for each load was determined using BFO technique. In this case of study the buses 4, 5 and 14 are connected with VDTL and ERL Loads. The FACTS devise are connected as follows

1. SVC at Buses 4, 5 and 14.
2. UPFC between Buses 4 and 5, i.e. in Line 7.
3. UPFC between Buses 14 and 13, i.e. in Line 20.
4. IPFC between Buses 4 and 5, i.e. between Lines 7 and 9.
5. IPFC at Bus 14 i.e. in between Lines 17 and 20

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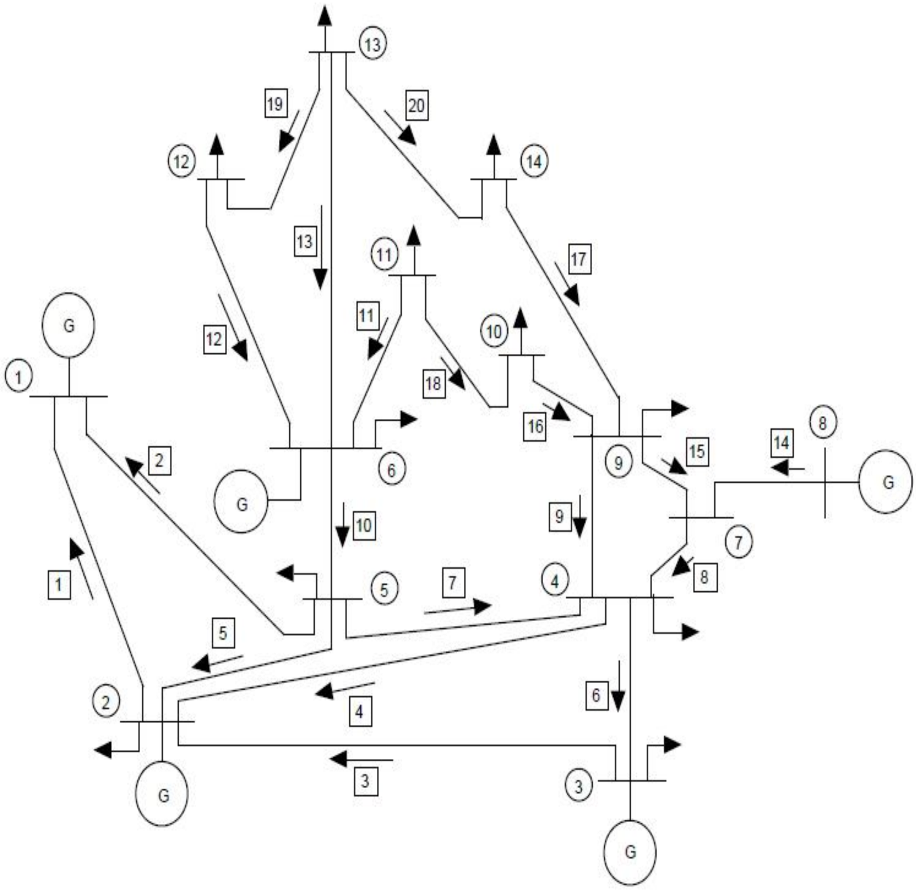

Fig-1: IEEE 14 Bus Systems

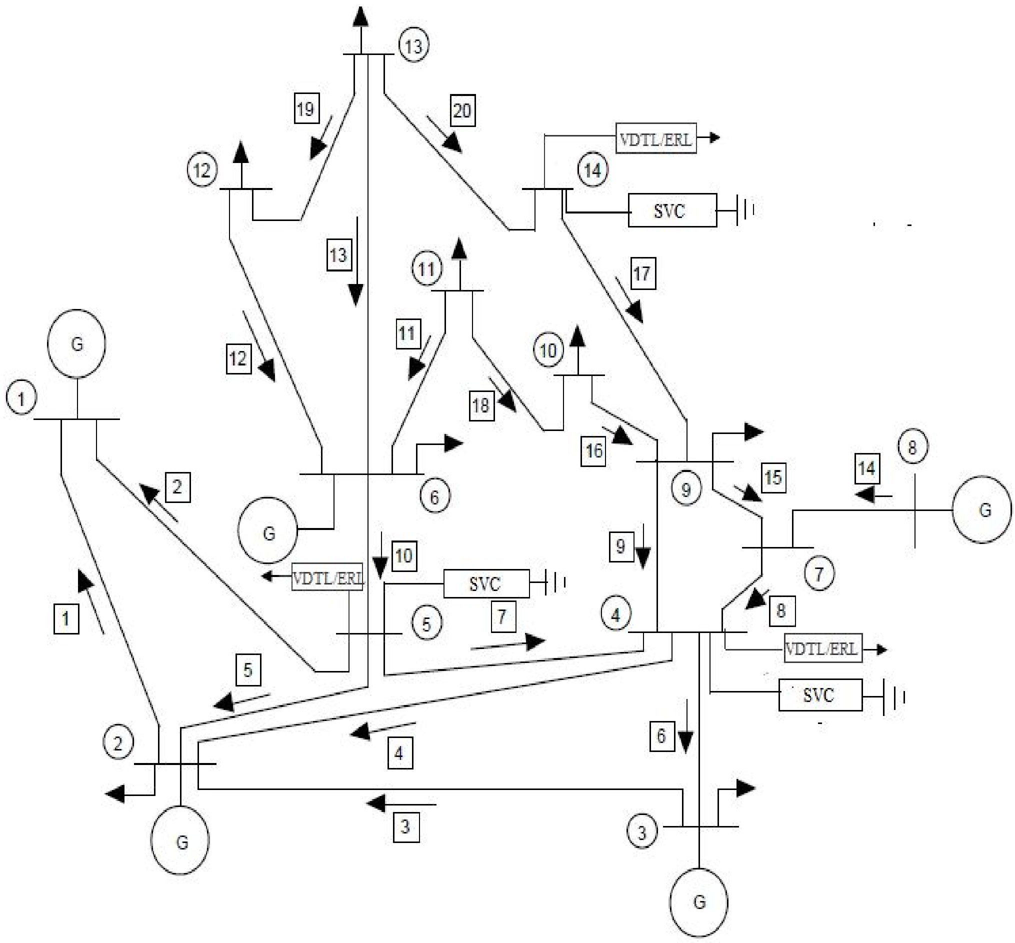

Fig-2: Single line diagram representation of IEEE 14 bus system with various SVC controllers

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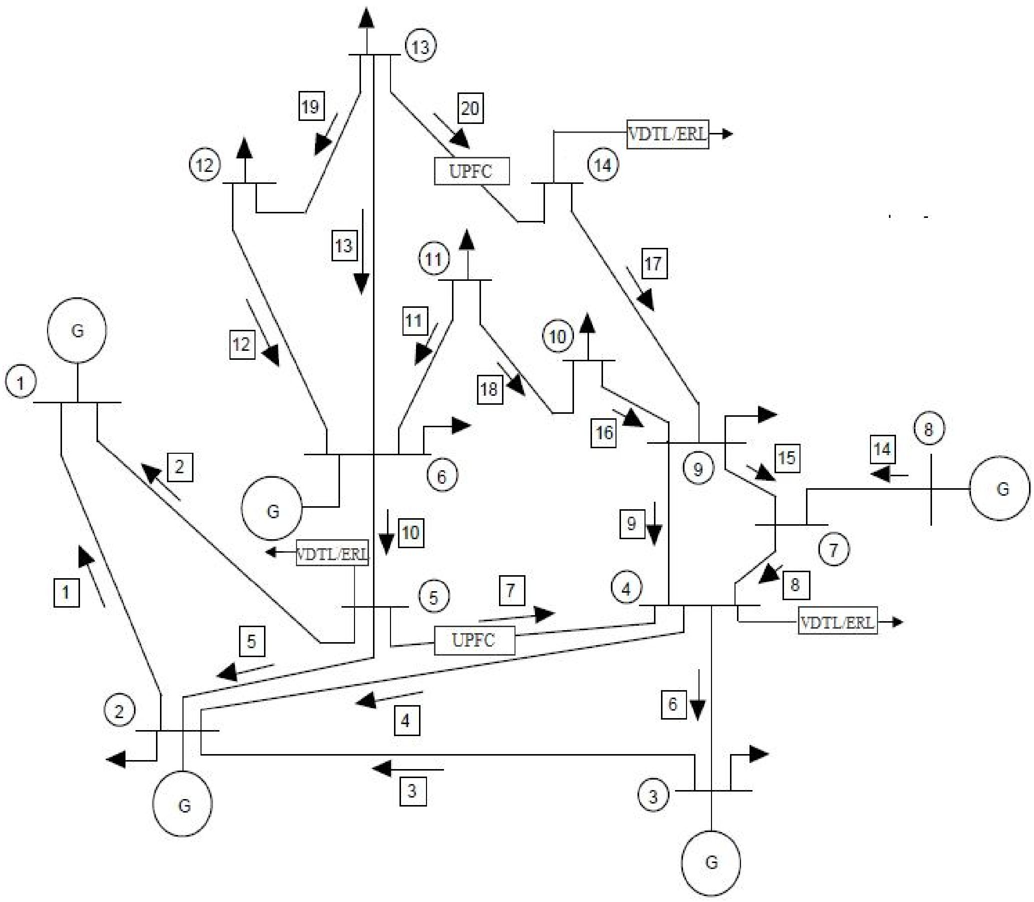

Fig-3: Single line diagram representation of IEEE 14 bus system with various UPFC controllers

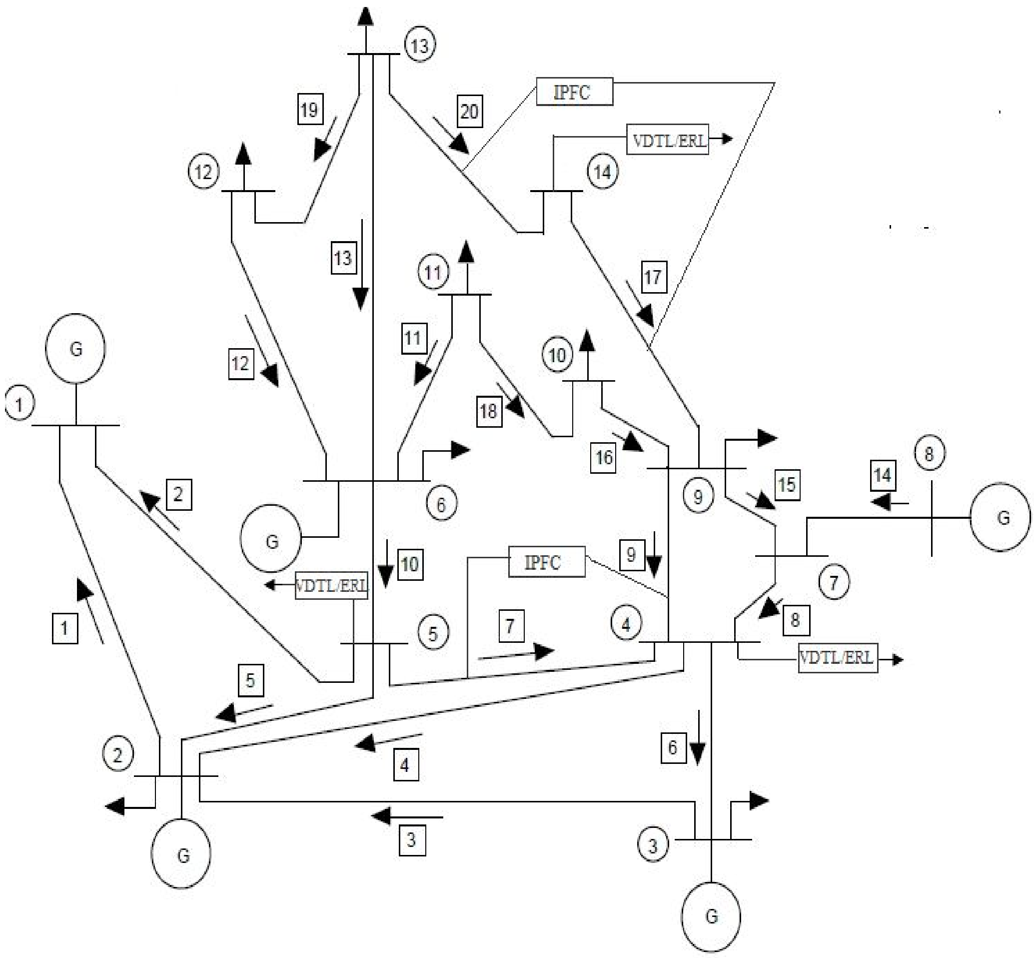

Fig-4: Single line diagram representation of IEEE 14 bus system with various IPFC controllers

Table-1: Power flow solution for IEEE 14 Bus systems with VDL with Dynamic tap changer in bus 4, 5 and bus 14

Bus No.	Voltage Magnitude	Voltage Angle	Real Power	Reactive Power
1	1.0300	0.0000	2.3045	-0.4347
2	1.0000	-5.962	0.1830	0.6624
3	0.9800	-14.773	-0.9420	0.3103
4	0.9602	-11.694	-0.4780	0.0390
5	0.9616	-10.009	-0.0760	-0.0160
6	1.0000	-16.570	-0.1208	0.1122
7	0.9766	-15.192	0.0000	0.0000
8	1.0000	-15.191	0.0000	0.1328
9	0.9607	-17.071	-0.3093	-0.1740
10	0.9595	-17.309	-0.0900	-0.0580
11	0.9757	-17.075	-0.0350	-0.0180
12	0.9822	-17.549	-0.0610	-0.0160
13	0.9753	-17.597	-0.1350	-0.0580
14	0.9474	-18.488	-0.1490	-0.0500

Table-2: Weak bus identification using VCP indices with VDTL

BUS	VCP INDICES
4	37.1572
5	34.1539
14	23.1476
7	19.0196
10	14.1100
13	10.3469
11	8.2719
12	5.3153
9	5.0101

Table-3: Power flow solution for IEEE 14 Bus systems with VDL with Dynamic tap changer and SVC in bus 4

Bus No.	Voltage Magnitude	Voltage Angle	Real Power	Reactive Power
1	1.0300	0.00	2.2794	-0.0659
2	1.0000	-5.43	0.2473	-0.0326
3	0.9900	-14.23	-0.9420	0.3034
4	0.9800	-11.41	-0.4780	0.0430
5	0.9763	-9.66	-0.0591	0.0232
6	1.0000	-16.06	-0.1208	-0.0157
7	0.9855	-14.83	0.0000	0.0000
8	1.0000	-14.83	0.0000	-0.0822
9	0.9692	-16.70	-0.3093	-0.1740
10	0.9666	-16.91	-0.0900	-0.0580
11	0.9793	-16.62	-0.0350	-0.0180
12	0.9829	-17.04	-0.0610	-0.0160
13	0.9766	-17.10	-0.1350	-0.0580
14	0.9528	-18.05	-0.0490	-0.0500

Table-4: Power flow solution for IEEE 14 Bus systems with VDL with Dynamic tap changer and SVC in bus 5

Bus No.	Voltage Magnitude	Voltage Angle	Real Power	Reactive Power
1	1.0300	- 0.00	2.2790	-0.0764
2	1.0000	-5.42	0.2472	-0.0580
3	0.9900	-14.24	-0.9420	0.3451
4	0.9729	-11.26	-0.4780	0.0390
5	0.9800	-9.70	-0.0591	0.0196
6	1.0000	-16.06	-0.1208	0.0158
7	0.9824	-14.73	0.0000	0.0000
8	1.0000	-14.73	0.0000	-0.1001
9	0.9663	-16.61	-0.3093	-0.1740
10	0.9641	-16.84	-0.0900	-0.0580
11	0.9780	-16.59	-0.0351	-0.0180
12	0.9827	-17.04	-0.0610	-0.0i60
13	0.9762	-17.10	-0.1350	-0.0580
14	0.9510	-18.00	-0.1495	-0.0490

Table-5: Power flow solution for IEEE 14 Bus systems with VDL with Dynamic tap changer and SVC in bus 14

Bus No.	Voltage Magnitude	Voltage Angle	Real Power	Reactive Power
1	1.0300	0.00	2.2801	-0.0337
2	1.0000	-5.45	0.2473	-0.1437
3	0.9900	-14.34	-0.9420	0.3752
4	0.9666	-11.24	-0.4780	0.0390
5	0.9682	-9.56	-0.0594	0.0229
6	1.0000	-15.95	-0.1208	0.0193
7	0.9839	-14.75	0.0000	0.0000
8	1.0000	-14.75	0.0000	-0.0888
9	0.9729	-16.63	0.3093	-0.1740
10	0.9696	-16.83	-0.0900	-0.0580
11	0.9829	-16.53	-0.0350	-0.0180
12	0.9862	-16.98	-0.0614	-0.0160
13	0.9827	-17.17	-0.1352	-0.0580
14	0.9800	-18.62	-0.1493	-0.0486

Table-5: Weak bus identification indices after incorporating SVC units in a IEEE 14 Bus system considering VDL with Dynamic Tap Changer (VDTL)

BUS	VCP INDICES
4	32.1803
5	28.3731
14	19.9878
7	17.2071
10	12.5262
13	8.7490
11	7.4766
12	4.9158
9	4.6146

Table-6: Power flow solution for IEEE 14 Bus systems with VDL with Dynamic tap changer and UPFC connected to the Bus 4 in line7

Bus No.	Voltage Magnitude	Voltage Angle	Real Power	Reactive Power
1	1.0300	0.00	2.2822	-0.0939
2	1.0000	-5.43	0.2473	-0.1066
3	1.0000	-14.29	-0.9420	0.3546
4	0.9900	-11.54	-0.4781	0.0437
5	0.9826	-9.73	-0.0590	0.0234
6	1.0000	-15.99	-0.1208	-0.0244

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7	0.9900	-14.69	0.0000	0.0024
8	1.0000	-14.69	0.0000	0.0580
9	0.9737	-16.61	-0.3093	-0.1740
10	0.9703	-16.83	-0.0900	-0.0580
11	0.9812	-16.55	-0.0351	-0.0181
12	0.9832	-16.96	-0.0610	-0.0160
13	0.9773	-17.03	-0.1350	-0.0582
14	0.9557	-17.96	-0.0490	-0.0500

Table-7: Power flow solution for IEEE 14 Bus systems with VDL with Dynamic tap changer and UPFC connected to the Bus 5 in line7

Bus No.	Voltage Magnitude	Voltage Angle	Real Power	Reactive Power
1	1.0300	0.00	2.2802	-0.1199
2	1.0000	-5.39	0.2472	-0.1440
3	1.0000	-14.20	-0.9420	0.3547
4	0.9900	-11.40	-0.4780	0.0435
5	0.9900	-9.86	-0.0588	0.0201
6	1.0100	-16.08	-0.1208	0.0086
7	0.9917	-14.77	0.0000	0.0000
8	1.0000	-14.77	0.0000	-0.0472
9	0.9771	-16.61	-0.3093	-0.1740
10	0.9749	-16.84	-0.0900	-0.0581
11	0.9885	-16.60	-0.0350	-0.0180
12	0.9929	-17.04	-0.0610	-0.0163
13	0.9865	-17.09	-0.1350	-0.0580
14	0.9618	-17.98	-0.1490	-0.0500

Table-8: Power flow solution for IEEE 14 Bus systems with VDL with Dynamic tap changer and UPFC connected to the Bus 14 in line 20

Bus No.	Voltage Magnitude	Voltage Angle	Real Power	Reactive Power
1	1.0300	0.00	2.2803	-0.1433
2	1.0000	-5.44	0.2473	0.1203
3	0.9900	-14.31	-0.9420	0.3641
4	0.9685	-11.26	-0.4780	0.0390
5	0.9704	-9.59	-0.0593	0.0230
6	1.0100	-15.97	-0.1208	0.0469
7	0.9868	-14.72	0.0000	-0.0000
8	1.0000	-14.72	0.0000	-0.0721
9	0.9782	-16.56	0.3093	-0.1740
10	0.9758	-16.77	-0.0900	-0.0580
11	0.9889	-16.51	-0.0350	-0.0180
12	0.9948	-16.97	-0.0610	-0.0160
13	0.9900	-17.10	-0.1350	-0.0576
14	0.9900	-18.60	-0.1490	-0.0485

Table-9: Weak bus identification indices after incorporating UPFC units in a IEEE 14 Bus system considering VDL with Dynamic Tap Changer (VDTL)

BUS	VCP INDICES
4	28.3207
5	24.4566
14	16.2944
7	13.8694
10	8.6075
13	4.7594
11	3.4012
12	0.8973
9	0.7985

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Table-10: Power flow solution for IEEE 14 Bus systems with VDL with Dynamic tap changer and IPFC between lines 9 and 7 at bus 4

Bus No.	Voltage Magnitude	Voltage Angle	Real Power	Reactive Power
1	1.0300	0.00	2.2821	-0.1639
2	1.0000	-5.38	0.2471	-0.2569
3	1.0000	-14.12	-0.9420	0.2953
4	1.0000	-11.52	-0.4780	0.0438
5	1.0000	-9.98	-0.0585	0.0209
6	1.0100	-16.01	-0.1208	-0.0563
7	1.0000	-14.64	0.0000	0.0023
8	1.0000	-14.64	0.0000	0.0000
9	0.9841	-16.54	-0.3093	-0.1740
10	0.9807	-16.76	-0.0900	-0.0580
11	0.9915	-16.52	-0.0350	-0.0180
12	0.9934	-16.96	-0.0610	-0.0160
13	0.9875	-17.02	-0.1350	-0.0580
14	0.9663	-17.89	-0.0490	-0.0500

Table-11: Power flow solution for IEEE 14 Bus systems with VDL with Dynamic tap changer and IPFC Between lines 9 and 7 at bus 5

Bus No.	Voltage Magnitude	Voltage Angle	Real Power	Reactive Power
1	1.0300	0.00	2.2809	-0.1637
2	1.0000	-5.37	0.2471	-0.2570
3	1.0000	-14.12	-0.9420	0.2953
4	1.0000	-11.52	-0.4780	0.0438
5	1.0000	-9.97	-0.0585	0.0209
6	1.0200	-15.90	-0.1208	0.0381
7	1.0049	-14.77	0.0000	0.0000
8	1.0000	-14.77	0.0000	-0.0277
9	1.0000	-16.52	-0.3093	-0.1691
10	0.9957	-16.72	-0.0900	-0.0580
11	1.0041	-16.45	-0.0350	-0.0180
12	1.0040	-16.83	-0.0610	-0.0i62
13	0.9986	-16.91	-0.1350	-0.0583
14	0.9804	-17.80	-0.1490	-0.0495

Table-12: Power flow solution for IEEE 14 Bus systems with VDL with Dynamic tap changer and IPFC between lines 17 and 20 at bus 14

Bus No.	Voltage Magnitude	Voltage Angle	Real Power	Reactive Power
1	1.0300	0.00	2.2782	-0.0601
2	1.0000	-5.43	0.2473	-0.0732
3	0.9900	-14.27	-0.9420	0.3383
4	0.9729	-11.31	-0.4780	0.0390
5	0.9743	-9.63	-0.0592	0.0231
6	1.0200	-15.80	-0.1208	0.0494
7	0.9981	-14.76	0.0000	0.0000
8	1.0000	-14.76	0.0000	-0.0094
9	1.0000	-16.57	-0.3093	-0.1684
10	0.9957	-16.75	-0.0900	-0.0580
11	1.0040	-16.42	-0.0350	-0.0180
12	1.0048	-16.75	-0.0610	-0.0160
13	1.0000	-16.86	-0.1350	-0.0578
14	1.0000	-18.21	-0.1490	-0.0489

ISSN 2394 - 7780

Table-13: Weak bus identification indices after incorporating IPFC units in a IEEE 14 Bus system considering VDL with Dynamic Tap Changer (VDTL)

BUS	VCP INDICES
4	26.2509
5	22.4802
14	10.7220
7	8.2742
10	7.9210
13	4.7275
11	3.3335
12	0.6957
9	0.6166

Table-14: Weak bus identification indices with its percentage before and after incorporating FACTS in IEEE 14 Bus system with Dynamic Tap Changer (VDTL)

Bus No.	VCP Index							
	Without FACTS		SVC		UPFC		IPFC	
	Actual	%	Actual	%	Actual	%	Actual	%
4	37.15	**100**	32.18	**86.62**	28.32	**76.23**	26.25	**70.65**
5	34.15	**100**	28.37	**83.37**	24.45	**71.59**	22.48	**65.82**
14	23.14	**100**	19.98	**86.63**	16.29	**70.39**	10.72	**46.32**

Table-15: Power flow solution for IEEE 14 Bus systems with Exponential Recovery Loads in bus 4, 5 and bus 14.

Bus No.	Voltage Magnitude	Voltage Angle	Real Power	Reactive Power
1	1.0300	0.0000	2.3502	-0.4376
2	1.0000	-6.071	0.1830	0.6812
3	0.9800	-14.955	-0.9420	0.3166
4	0.9591	-11.915	-0.4780	0.0390
5	0.9606	-10.222	-0.0760	-0.0160
6	1.0000	-17.105	-0.1454	0.1281
7	0.9747	-15.586	0.0100	0.0100
8	1.0000	-15.890	0.0000	0.1435
9	0.9585	-17.493	-0.3150	-0.1860
10	0.9577	-17.750	-0.0900	-0.0580
11	0.9748	-17.562	-0.0350	-0.0180
12	0.9821	-18.079	-0.0610	-0.0160
13	0.9750	-18.166	-0.1350	-0.0580
14	0.9460	-18.956	-0.1490	0.0500

Table-16: Weak bus identification using VCP indices with ERL Loads

BUS	VCP INDICES
4	37.1141
5	34.1173
14	23.0808
7	19.0445
10	14.0830
13	10.0830
11	8.2640
12	5.3143
9	5.0025

Table-17: Power flow solution for IEEE 14 Bus systems with Exponential Recovery Loads and SVC in bus 4

Bus No.	Voltage Magnitude	Voltage Angle	Real Power	Reactive Power
1	1.0300	0.00	2.3242	-0.0722
2	1.0000	-5.53	0.2475	0.0406
3	0.9900	-14.40	-0.9420	0.3032
4	0.9800	-11.64	-0.4780	0.0432
5	0.9760	-9.88	-0.0590	0.0231
6	1.0000	-16.58	-0.1454	0.0267
7	0.9841	-15.23	-0.0100	-0.0100
8	1.0000	-15.24	0.0000	0.0900
9	0.9675	-17.12	-0.3150	-0.1860
10	0.9652	-17.35	-0.0900	-0.0580
11	0.9786	-17.10	-0.0350	-0.0180
12	0.9828	-17.56	-0.0610	-0.0160
13	0.9763	-17.61	0.1350	0.0580
14	0.9518	-18.51	-0.1490	-0.0500

Table 18: Power flow solution for IEEE 14 Bus systems with Exponential Recovery Loads and SVC in bus 5

Bus No.	Voltage Magnitude	Voltage Angle	Real Power	Reactive Power
1	1.0300	0.00	2.3238	-0.0841
2	1.0000	-5.52	0.2475	0.0668
3	0.9900	-14.41	-0.9420	0.3478
4	0.9724	-11.48	-0.4780	0.0390
5	0.9800	-9.92	-0.0589	0.0195
6	1.0000	-16.59	-0.1454	0.0262
7	0.9808	-15.12	-0.0100	-0.0100
8	1.0000	-15.13	0.0000	0.1092
9	0.9643	-17.02	-0.3150	-0.1860
10	0.9625	-17.27	-0.0900	-0.0580
11	0.9772	-17.07	-0.0350	-0.0181
12	0.9825	-17.56	-0.0611	-0.0162
13	0.9759	-17.61	-0.1350	-0.0583
14	0.9497	-18.46	-0.1490	-0.0499

Table-19: Power flow solution for IEEE 14 Bus systems with Exponential Recovery Loads and SVC in bus 14

Bus No.	Voltage Magnitude	Voltage Angle	Real Power	Reactive Power
1	1.0300	0.00	2.3249	-0.0372
2	1.0000	-5.55	0.2476	0.1611
3	0.9900	-14.51	-0.9420	0.3811
4	0.9656	-11.46	-0.4780	0.0390
5	0.9672	-9.77	-0.0592	0.0228
6	1.0000	-16.47	-0.1454	-0.0078
7	0.9822	-15.14	-0.0100	-0.0100
8	1.0000	-15.14	0.0000	0.0981
9	0.9712	-17.05	-0.3150	-0.1860
10	0.9682	-17.27	-0.0900	-0.0580
11	0.9801	-17.01	-0.0350	-0.0180
12	0.9862	-17.49	-0.0610	-0.0162
13	0.9827	-17.68	-0.1350	-0.0580
14	0.9800	-19.11	-0.1490	-0.0495

Table-20: Weak bus identification indices after incorporating SVC units in a IEEE 14 Bus system considering Exponential Recovery Loads (ERL)

BUS	VCP INDICES
4	29.9803
5	21.4731
14	19.9878
7	17.6071
10	12.9262
13	9.1490
11	7.5766
12	5.1158
9	4.8146

Table-21: Power flow solution for IEEE 14 Bus systems with Exponential Recovery Loads and UPFC connected to the Bus 4 in line7

Bus No.	Voltage Magnitude	Voltage Angle	Real Power	Reactive Power
1	1.0300	0.00	2.3270	-0.1001
2	1.0000	-5.53	0.2475	-0.0986
3	1.0000	-14.46	-0.9420	0.3544
4	0.9900	-11.77	-0.4780	0.0439
5	0.9822	-9.94	-0.0589	0.0233
6	1.0000	-16.49	-0.1454	-0.0164
7	0.9900	-15.07	-0.0100	-0.0075
8	1.0000	-15.07	0.0000	-0.0568
9	0.9729	-17.02	-0.3150	-0.1860
10	0.9696	-17.25	-0.0900	-0.0581
11	0.9809	-17.01	-0.0350	-0.0180
12	0.9831	-17.46	-0.0611	-0.0161
13	0.9771	-17.52	-0.1350	-0.0580
14	0.9552	-18.41	-0.0490	-0.0500

Table-22: Power flow solution for IEEE 14 Bus systems with Exponential Recovery Loads and UPFC connected to the Bus 5 in line7

Bus No.	Voltage Magnitude	Voltage Angle	Real Power	Reactive Power
1	1.0300	0.00	2.3249	-0.1361
2	1.0000	-5.50	0.2474	-0.2391
3	1.0000	-14.37	-0.9420	0.2955
4	0.9900	-11.63	-0.4780	0.0442
5	0.9900	-10.07	-0.0586	0.0238
6	1.0000	-16.58	-0.1454	0.0193
7	0.9887	-15.21	0.0100	0.0000
8	1.0000	-15.21	0.0000	-0.0146
9	0.9720	-17.11	-0.3150	-0.1740
10	0.9689	-17.34	0.0900	-0.0580
11	0.9805	-17.10	-0.0350	-0.0180
12	0.9831	-17.55	-0.0611	-0.0i60
13	0.9770	-17.61	-0.1350	-0.0580
14	0.9546	-18.50	-0.1492	-0.0499

ISSN 2394 - 7780

Table-23: Power flow solution for IEEE 14 Bus systems with Exponential Recovery Loads and UPFC connected to the Bus 14 in line20

Bus No.	Voltage Magnitude	Voltage Angle	Real Power	Reactive Power
1	1.0300	0.00	2.3252	-0.1469
2	1.0000	-5.55	0.2476	0.1377
3	0.9900	-14.49	-0.9420	0.3700
4	0.9675	-11.47	-0.4780	0.0390
5	0.9694	-9.80	-0.0592	0.0229
6	1.0100	-16.49	-0.1454	0.0581
7	0.9852	-15.10	-0.0100	-0.0100
8	1.0000	-15.10	0.0000	-0.0814
9	0.9765	-16.97	-0.3150	-0.1860
10	0.9744	-17.21	-0.0900	-0.0580
11	0.9882	-16.98	-0.0350	-0.0181
12	0.9948	-17.48	-0.0610	-0.0162
13	0.9900	-17.61	-0.1350	-0.0580
14	0.9900	-19.08	-0.1490	-0.0485

Table-24: Weak bus identification indices after incorporating UPFC units in a IEEE 14 Bus system considering Exponential Recovery Loads (ERL)

BUS	VCP INDICES
4	26.1207
5	17.5566
14	16.2944
7	14.2694
10	9.0075
13	5.1594
11	3.5012
12	1.0973
9	0.9985

Table-25: Power flow solution for IEEE 14 Bus systems with Exponential Recovery Loads and IPFC Between lines 9 and 7 at bus 4

Bus No.	Voltage Magnitude	Voltage Angle	Real Power	Reactive Power
1	1.0300	0.00	2.3287	-0.1365
2	1.0000	-5.52	0.2475	-0.2012
3	1.0000	-14.38	-0.9420	0.2950
4	1.0000	-11.88	-0.4780	0.0446
5	1.0000	-10.06	-0.0586	0.0236
6	1.0200	-16.51	-0.1454	-0.0303
7	1.0007	-15.35	-0.0100	-0.0100
8	1.0000	-15.34	0.0000	-0.0042
9	0.9923	-17.15	-0.3150	-0.1861
10	0.9893	-17.35	-0.0900	-0.0581
11	1.0008	-17.07	-0.0350	-0.0180
12	1.0064	-17.50	-0.0610	-0.0160
13	1.0030	-17.68	0.1350	0.0580
14	1.0000	-19.08	-0.0499	-0.0498

Table-26: Power flow solution for IEEE 14 Bus systems with Exponential Recovery Loads and IPFC Between lines 9 and 7 at bus 5

Bus No.	Voltage Magnitude	Voltage Angle	Real Power	Reactive Power
1	1.0300	- 0.00	2.3256	-0.1361
2	1.0000	-5.44	0.2473	-0.2391
3	1.0000	-14.12	-0.9420	0.2955
4	1.0000	-11.47	-0.4780	0.0442
5	1.0000	-9.76	-0.0588	0.0238
6	1.0300	-16.05	-0.1208	0.0193
7	1.0026	-14.66	0.0000	0.0000
8	1.0000	-14.65	0.0000	-0.0146
9	1.9950	-16.38	-0.3093	-0.1740
10	0.9933	-16.63	0.0900	-0.0580
11	1.0078	-16.47	-0.0350	-0.0180
12	1.0163	-17.08	-0.0610	-0.0i60
13	1.0121	-17.32	-0.1350	-0.0580
14	1.0000	-17.84	-0.1499	-0.0499

Table-27: Power flow solution for IEEE 14 Bus systems with Exponential Recovery Loads and IPFC Between lines 17 and 20 at bus 14

Bus No.	Voltage Magnitude	Voltage Angle	Real Power	Reactive Power
1	1.0300	0.00	2.3336	-0.1467
2	1.0000	-5.55	0.2476	-0.2364
3	1.0000	-14.29	-0.9420	0.2953
4	1.0000	-11.68	-0.4780	0.0443
5	0.9924	-10.02	-0.0586	0.0237
6	1.0400	-16.82	-0.1454	0.0291
7	1.0020	-14.89	-0.0100	-0.0100
8	1.0000	-16.57	0.0000	-0.0114
9	0.9949	-16.91	-0.3150	-0.1860
10	0.9951	-16.98	-0.0900	-0.0580
11	1.0137	-16.52	-0.0350	-0.0180
12	1.0291	-17.96	-0.0611	-0.0160
13	1.0267	-18.39	-0.1351	-0.0580
14	1.0000	-17.58	-0.1490	-0.0495

Table-28: Weak bus identification indices after incorporating IPFC units in a IEEE 14 Bus system considering Exponential Recovery Loads (ERL)

BUS	VCP INDICES
4	24.0509
5	15.5802
14	10.7220
7	8.6742
10	8.3210
13	5.1275
11	3.4335
12	0.8957
9	0.8166

Table-29: Weak bus identification indices with its percentage before and after incorporating FACTS in IEEE 14 Bus system considering Exponential Recovery Loads (ERL)

Bus No.	VCP Index							
	Without FACTS		SVC		UPFC		IPFC	
	Actual	%	Actual	%	Actual	%	Actual	%
4	37.11	**100**	29.98	**80.78**	26.12	**70.38**	24.05	**64.80**
5	24.12	**100**	21.47	**89.01**	17.55	**72.26**	15.58	**64.58**
14	23.08	**100**	19.98	**86.56**	16.29	**70.58**	10.72	**46.44**

VI. CONCLUSION

This paper proposes the synchronized essential control with the usage of various FACTS devices especially SVC, UPFC, IPFC units. A method is needed to rapidly re-balance the power by either shedding some loads to maintain power flow to the remaining loads or directing the power flow across transmission corridors with greater capacity In this study, Bacterial Foraging optimization (BFO) technique was adopted to ensure the stability of the system with various types of loads. Using the BFO algorithm the FACTS devices are turned to ensure sufficient power flow capacity so as to meet out the load effectively if the network is reconfigured to bypass the loss in the transmission capability. IEEE 14 bus system was considered for the study. With the preliminary Load flow studies the week bus identified by obtaining VCPI index. It was found that hierarchical weak bus listing was Bus No 4, 5 and 14. VDL with dynamic tap changer/ERL Loads are considered along the week Buses ie with buses 4,5 and 14. Then the power system security assessment was carried out individually by accommodating various FACTS devices like SVC, UPFC and IPFC respectively and it has been found that with the UPFC, IPFC controller, the load shedding adoption is significantly reduced and can be utilized for emergency control. From the results it has been found that the FACTS devices especially UPFC and IPFC effectively avert the system from blackout and reinstate the system faster.

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