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Enhancement of Power Transfer Capability of Interconnected Power System by Using FACTS Controllers with OPF Method

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Abstract **:** *The power transfer between two or more power systems is a very useful concept in restructuring. Anumber of experiments have been done on power systemsto maximize its power transfer capability. In deregulated power systems, Analysis of Available transfer capability (ATC) is necessary issue either in terms of planning or operating because of higher requirements with FACTS devices which can normally reduces power flow in heavily loaded lines, resulting in an increased transfer capability, low system loss, improved stability of the network, reduced cost of production and fulfilled contractual requirement by controlling the power flows in the network. It is important to ascertain the location for placement of these devices because of their considerable costs. The optimal flow method is adopted for IEEE 14 & 30 bus systems with different FACTS compensators for enhancing power transfer capability.*

Keywords - *FACTS devices, UPFC, SVC, TCSC, IEEE 14-Bus, IEEE 30-Bus Systems, MATLAB-SIMULINK, OPF.*

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I. INTRODUCTION

Transmission open access has been an important issue in the ongoing deregulation and restructuring of power sector in many countries. Transmission open access is a vehicle for promoting competition in generation. Open access to the transmission systems places a new emphasis on the more intensive shared use of the interconnected networks reliably by utilities and third party generators. As system becomes deregulated, loop networks introduced technical issues with the definition and calculation of the ATC. In addition, the differences between contract path and actual power flow path introduced additional complexity to the quantification of ATC. When systems were isolated and largely radial, these capabilities were fairly easy to determine and consisted mainly of a combination of thermal ratings and voltage drop limitations. In most cases, these two limitations were easily combined into a single power limitation (either MW or MVA or surge impedance loading). As such, ATC for a given transmission line at a given time could be interpreted as the difference between the power limit and the power flow at that time. Owing to the commercial and technological significance of ATC in the power industry deregulated environment, more and more institutes and utilities have shown increased interest and are undertaking studies of evaluation and enhancement of ATC. In recent years various approaches have been proposed to modal and calculate ATC. Under open access power system complexity has grown and system stabilities became an important constraint for some areas of the interconnected network and this required the consideration of the third limiting phenomena. The introduction of St. Clair curves were one of the first attempts to include thermal, voltage and stability into a single transmission line loading. These results were later verified and extended from a more theoretical basis. Linear load flow and linear programming solutions made transmission transfer capability determination relatively fast and easy. It is highly recognized that flexible AC transmission systems (FACTS) devices, specially the series devices such as thyristor controlled series capacitor (TCSC), thyristor controlled phase angle regulator (TCPAR), unified power flow controller (UPFC) etc. can be applied to increase the ATC of power network. In [1] a comparative study to improve ATC has been done and it is shown that FACTS technology can redistribute load flow and regulate bus voltage, so a promising method to improve TTC. In [9] location of FACTS devices has been suggested with increase in total transfer capability.

II. FACTS DEVICES

The insertion of FACTS devices in Electrical systems seems to be a promising strategy to increase available transfer capability (ATC) [7]-[10].

1.1 Selection of Devices

FACTS devices are categorized under four different categories as series controllers, shunt controllers, combined series and shunt controllers. In this paper, one device from each category is selected i.e., TCSC from series controllers, SVC from shunt controllers and UPFC from combined series-shunt controllers. TCSC is connected in series with the line conductors to compensate for the inductive reactance of the line. It may have one of the two possible characteristics namely capacitive or inductive, respectively to decrease or increase the reactance of the line XL respectively. Moreover, in order not to overcompensate the line, the maximum value of the capacitance is fixed at - 0.8 XL while that for inductance, it is 0.2 XL. Although TCSC is not usually installed for voltage control purpose, it does contribute for better voltage profile and reactive power control.

SVC is used for voltage control applications. It helps to maintain a bus voltage at a desired value during load variations. The SVC may have two characteristics namely, inductive or capacitive. In the inductive mode, it absorbs reactive power, whereas in the capacitive mode, reactive power is injected. It may take values characterized by the reactive power injected or absorbed at the voltage of 1 p.u.

The values are between -100 Mvar and 100 Mvar. The UPFC is capable of providing active and reactive power control, as well as adaptive voltage magnitude control and regulates all the three variables simultaneously or any combination of them, provided no operating limits are violated. The UPFC may act as an SVC, a TCSC or a phase shift controller. The versatility afforded by the UPFC makes it a prime contender to provide many of the control functions required to solve a wide range of dynamic and steady state problems encountered in electrical power networks [9]. UPFC can be modeled as a combination of one series element i.e., TCSC and a shunt element i.e., SVC [3]. Hence the operational range limits of TCSC and SVC can be applied to UPFC as well.

2.2 Modeling of FACTS Devices

TCSC has been modeled as a variable reactance inserted in the transmission line connected between buses. SVC is modeled as a reactive power source added or connected at the bus. Based on previous research [2], UPFC is modeled as combination of an SVC at a bus and a TCSC in the line connected to the same bus.

2.3 Device Placement Strategy

ATC value is greatly influenced by the power flow in the limiting line of the system. Therefore, a FACTS device is placed in the limiting line or at the corresponding bus to which the limiting line is connected depending on the type of device. Only one FACTS device per line is allowed. If only one device is used, it is placed in the first limiting line of the system. If three devices are to be inserted, then the first three limiting lines are selected. For this purpose, the limiting lines in the considered test systems are ranked and ordered based upon the power carrying capacity in the line. For the multi-type device category, TCSC is considered as the first device, SVC as the second and UPFC as the third. If the device is TCSC, it is connected in series with the limiting line. If the device is SVC, then the type of originating bus and terminating bus of the limiting line is checked. If the one end bus is PV bus, it is discarded and if the other end bus is PQ bus, then SVC is connected. Suppose if two end buses happen to be PV buses, then the next limiting line in the order is selected and checked for type of bus. For UPFC, the series device TCSC is connected in series with the limiting line and the shunt device SVC is connected at PQ bus after checking the type of the end buses where the limiting line is connected.

III. OPTIMAL POWER FLOW METHOD

In an OPF, the values of some or all of the control variables need to be found so as to optimize (minimize or maximize) a predefined objective. It is also important that the proper problem definition with clearly stated objectives be given at the onset. The quality of the solution depends on the accuracy of the model studied. Objectives must be modeled and its practicality with possible solutions. Objective function takes various forms such as fuel cost, transmission losses and reactive source allocation. Usually the objective function of interest is the minimization of total production cost of scheduled generating units. This is most used as it reflects current economic dispatch practice and importantly cost related aspect is always ranked high among operational requirements in Power Systems. OPF aims to optimize a certain objective, subject to the network power flow equations and system and equipment operating limits. The optimal condition is attained by adjusting the available controls to minimize an objective function subject to specified operating and security requirements. Some well-known objectives can be identified as below:

Active power objectives

1. Economic dispatch (minimum cost, losses, MW generation or transmission losses)

2. Environmental dispatch 3. Maximum power transfer Reactive power objectives MW and MVAr loss minimization.

General goals
1. Minimum deviation from a target schedule
2. Minimum control shifts to alleviate Violations
3. Least absolute shift approximation of control shift Among the above the following objectives are most commonly used: (a) Fuel or active power cost optimization (b) Active power loss minimization (c) VAr planning to minimize the cost of reactive power support The mathematical description of the OPF problem is presented below: OPF Objective Function for Fuel Cost Minimization The OPF problem can be formulated as follows:

Total Generation cost function is expressed as:

$F(P_G) = \sum(a_i + \beta P_{Gi} + \gamma P_{Gi}^2)$

The objective function is expressed as:
Min $F(P_{Gi}) = f(x,u)$

Subject to satisfaction of Non-Linear Equality Constraints:

$G(x,u) = 0$
And Non Linear Inequality Constraints:
$H(x,u) \leq 0$
$u_{min} \leq u \leq u_{max}$
$x_{min} \leq x \leq x_{max}$

IV. SIMULATION MODEL AND RESULTS

MATLAB (short for MATrix LABoratory) is a special purpose computer program optimized to perform engineering and scientific calculations. It started life as a program designed to perform matrix mathematics, but over the years it has grown into a flexible computing system capable of solving essentially any technical problem.

A MATLAB program provides a very extensive library of predefined functions to make technical programming tasks easier and more efficient. It is a huge program, with an incredibly rich variety of functions. It has an extensive library of built-in functions for data manipulation and the toolkits extend this capability with many more functions in various specialties. MATLAB comes complete with a library of pre-programmed and tested models, ranging from simple passive elements and control functions, to more complex models, such as FACTS devices.

Optimal Power Flow method:

- Considered 14-bus and 30-bus systems for enhancement of power transfer capability.
- By using m-file programming OPF method is adopted (basic optimization method) – identified power losses, transmission losses and cost.
- Identified the weak buses and adopted different FACTS controllers for compensation.
- First considered compensation by shunt compensator.
- Second considered UPFC
- Third considered SVC
- Considered TCSC
- ATC improvement, loading margin improvement is also considered

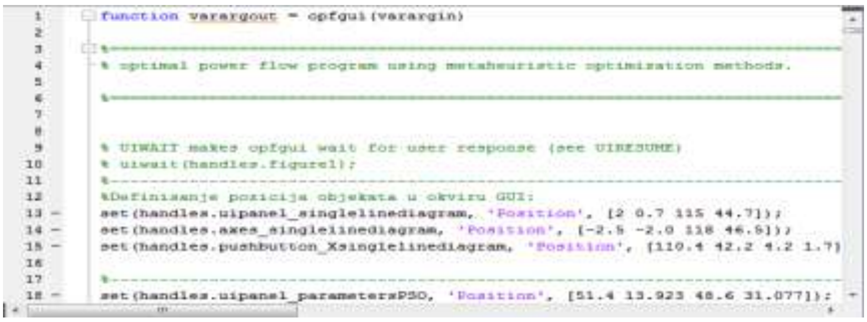

Fig 1: M-file Program for Optimal power flow – GUI

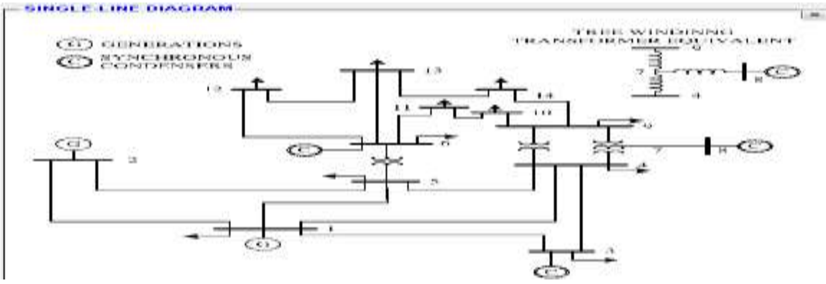

Fig 2: Single Line Diagram adopted

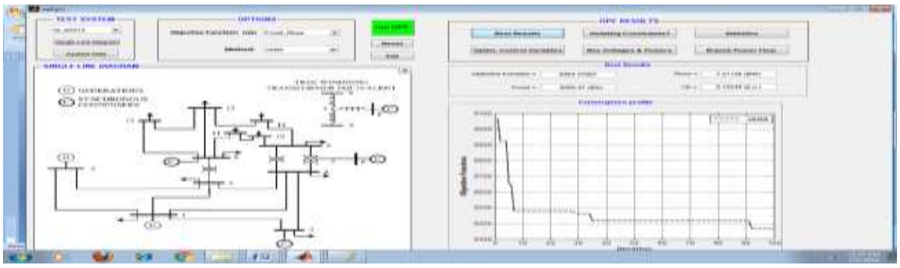

Fig 3: Optimization Results – Convergence profile

Optimum Control Variables

Generator active powers		Generator voltages		Transformer tap settings			Shunt VAR compensations	
Bus No	Pg (MW)	Bus No	Vg (p.u.)	From Bus	To Bus	T (p.u.)	Bus No	Qc (MVAr)
2	36.5646	1	1.0160	4	7	1.0186	14	1.9051e-14
3	36.7880	2	0.9890	4	9	1.0094		
6	11.8620	3	0.9951	5	6	0.9652		
8	25.3790	6	1.0175					
		8	1.0153					

Fig 4: Optimum Control Variables

Bus Voltages and Powers under Optimum Control Variables

Bus No	V (p.u.)	teta (deg)	Pg (MW)	Qg (MVAr)	Qc (MVAr)	Pload (MW)	Qload (MVAr)
1	1.0160	0	155.6177	13.5867	0	0	0
2	0.9890	-3.3161	36.5646	-33.8543	0	21.7000	12.7000
3	0.9951	-9.1418	36.7880	42.0994	0	94.2000	19
4	0.9869	-7.6917	0	0	0	47.8000	-3.9000
5	0.9869	-6.5004	0	0	0	7.6000	1.6000
6	1.0175	-10.9360	11.8620	26.0046	0	11.2000	7.5000
7	0.9901	-8.8692	0	0	0	0	0
8	1.0153	-6.3204	25.3790	15.1223	0	0	0
9	0.9870	-11.1147	0	0	0	29.5000	16.6000
10	0.9845	-11.3980	0	0	0	9	5.8000
11	0.9971	-11.3006	0	0	0	3.5000	1.8000
12	1.0006	-11.8537	0	0	0	6.1000	1.6000
13	0.9945	-11.8850	0	0	0	13.5000	5.8000
14	0.9711	-12.5833	0	0	1.9051e-14	14.9000	5

Fig 5: Bus voltages and powers under Optimum control variables

Statistics

No. runs	1
Minimum O.F.	8.3644e+03
Maximum O.F.	8.3644e+03
Mean O.F.	8.3644e+03
Std. deviation O.F.	0
Mean TOC (s)	10.0877

Fig 6: Statistics

Table 1: Branch power flow and Loss under optimum control variables

From Bus	To Bus	Active power	Reactive power	Ploss	Qloss
1	2	103.2515	12.6176	2.0459	6.2464
1	5	52.3661	0.9691	1.4419	5.9522
2	1	-101.2056	-11.6783	2.0459	6.2464
2	3	47.6588	-13.9288	1.1580	4.8786
2	4	38.9269	-11.6883	0.9600	2.9128
2	5	29.4846	-9.2589	0.5395	1.6473
3	2	-46.5008	14.4969	1.1580	4.8786
3	4	-10.9111	8.6025	0.1383	0.3530
4	2	-37.9669	11.2828	0.9600	2.9128
4	3	11.0495	-9.5065	0.1383	0.3530
4	5	-40.6671	13.2140	0.2506	0.7906
4	7	9.4259	-9.7559	0	0.1986
4	9	10.3587	-1.3344	0	0.6190
5	1	-50.9242	0.0480	1.4419	5.9522
5	2	-28.9450	7.5290	0.5395	1.6473
5	4	40.9178	-12.4234	0.2506	0.7906
5	6	31.3515	3.2464	0	2.7681
6	5	-31.3515	-0.8518	0	2.7681
6	11	6.6898	7.2118	0.0888	0.1859
6	12	7.8183	3.0061	0.0833	0.1734
6	13	17.5053	9.1385	0.2492	0.4907
7	4	-9.4259	10.1659	0	0.1986
7	8	-25.3790	-13.6310	0	1.4913
7	9	34.8049	3.4651	0	1.3729
8	7	25.3790	15.1223	0	1.4913
9	4	-10.3587	1.9692	0	0.6190
9	7	-34.8049	-2.0921	0	1.3729
9	9	0	-18.5091	0	0
9	10	5.9411	0.6765	0.0117	0.0310
9	14	9.7225	1.3556	0.1257	0.2675
10	9	-5.9294	-0.6455	0.0117	0.0310
10	11	-3.0706	-5.1545	0.0305	0.0713
11	6	-6.6011	-7.0258	0.0888	0.1859
11	10	3.1011	5.2258	0.0305	0.0713
12	6	-7.7350	-2.8327	0.0833	0.1734
12	13	1.6344	1.2327	0.0092	0.0084
13	6	-17.2562	-8.6478	0.2492	0.4907
13	12	-1.6252	-1.2243	0.0092	0.0084
13	14	5.3819	4.0721	0.0787	0.1603
14	9	-9.5968	-1.0882	0.1257	0.2675
14	13	-5.3032	-3.9118	0.0787	0.1603

IEEE 30-Bus System with FACTS Compensators:

The IEEE 30 Bus system is considered in estimation of TTC using different controllers. The 11 kV and 1.0 kV base voltages are considered as initial conditions. The model actually has these buses at either 132 or 33 kV.

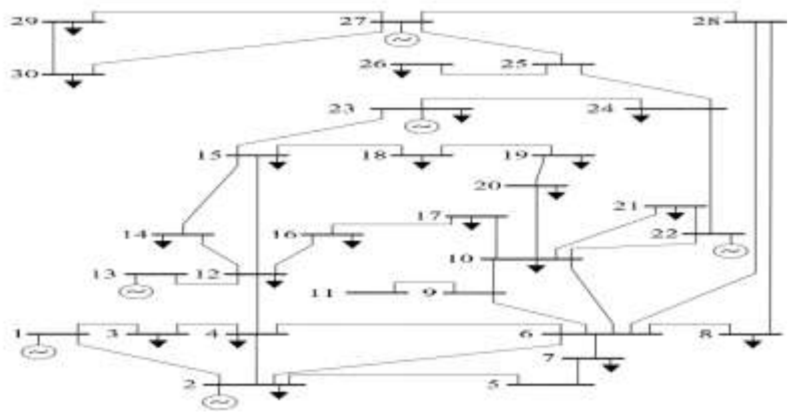

Fig 7: Single line diagram of IEEE 30 bus system

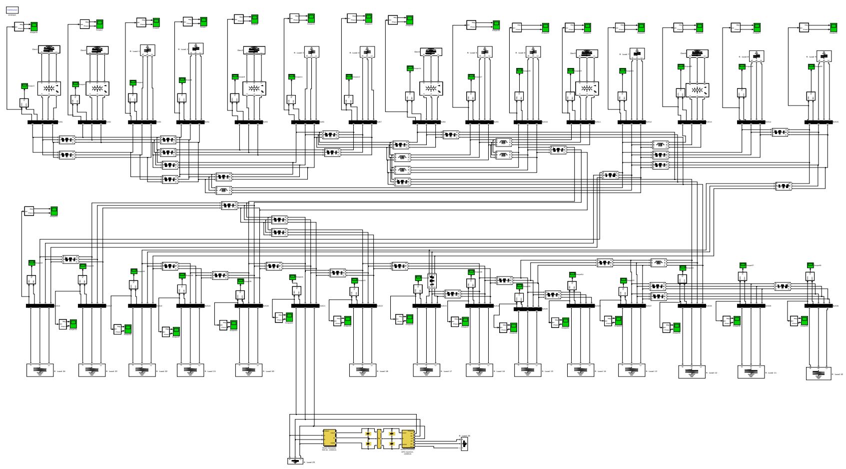

Fig 8: Simulation model of IEEE 30-bus system

25	1.0032	-16.0720
26	0.9852	-16.5038
30	0.9828	-17.8067

Fig 9: Weakest Buses obtained before compensation for IEEE 30 bus system

FACTS controllers placed at 30 Bus system

STATCOM Bus	Vsh pu	Thst Degree	Qsh pu
26	1.0014	-16.7872	-0.0137
30	1.0020	-18.0321	-0.0202

Fig 10: Voltage improvement with FACTS controller in IEEE 30 bus system

Analysis without FACTS controllers for IEEE 14 Bus system:

From the Optimal power flow the weak buses with power losses are identified for inter and intra buses.

From Bus	To Bus	Active power	Reactive power	Ploss	Qloss
1	2	103.2515	12.6176	2.0459	6.2464
1	5	52.3661	0.9691	1.4419	5.9522
2	1	-101.2056	-11.6783	2.0459	6.2464
3	2	-46.5008	14.4969	1.1580	4.8786
5	1	-50.9242	0.0480	1.4419	5.9522

Analysis with FACTS controllers for IEEE 14 and 30 bus system:

a) TCSC Result

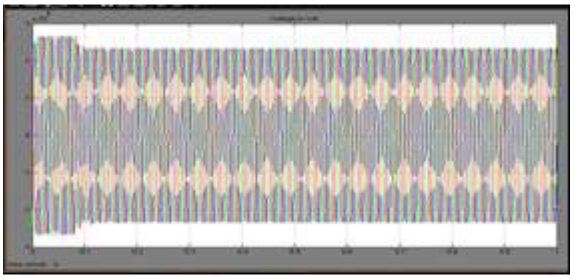

Fig 11: Load Voltage

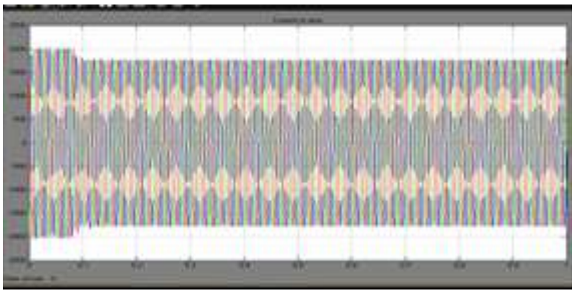

Fig 12: Load Current

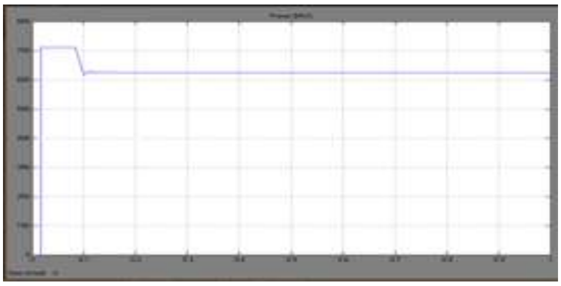

Fig 13: Active Power Verus Time (secs)

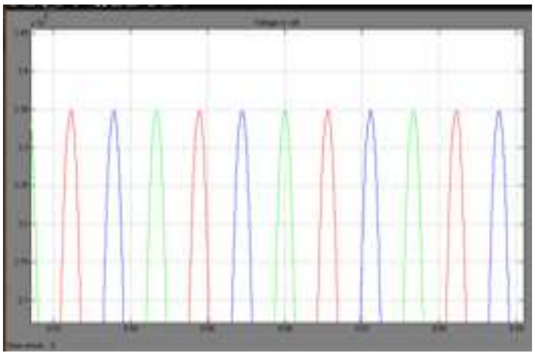

Fig 14: Regulated Load Voltage

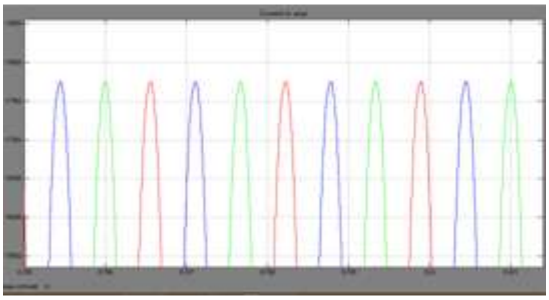

Fig 15: Regulated Load Current

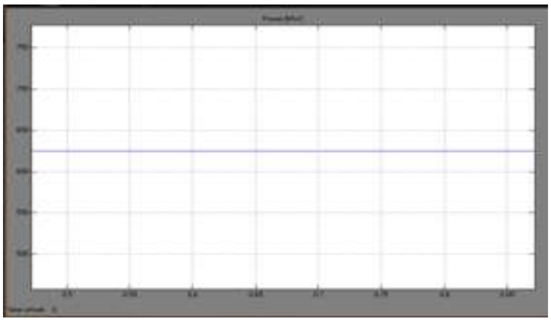

Fig 16: Regulated Load Power

b) UPFC Result:

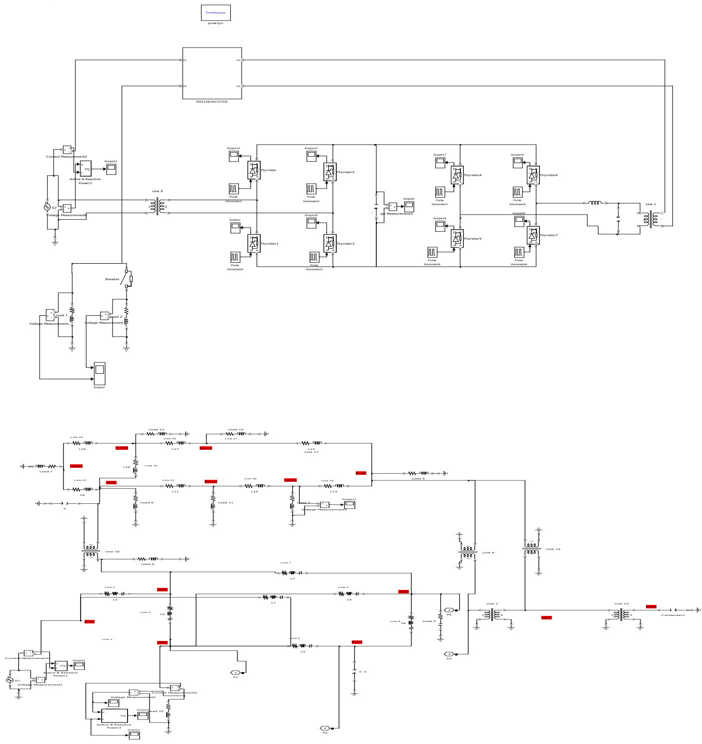

Fig 17: Subsystem of 14-bus system with UPFC

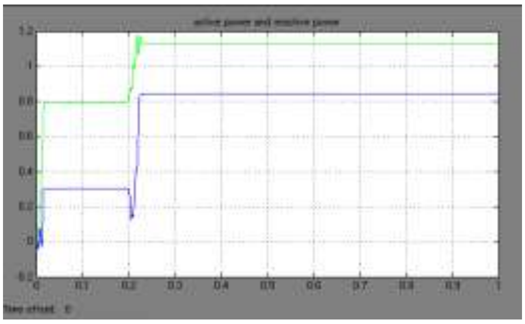

Fig 18: Active and Reactive Power Versus Time (Secs)

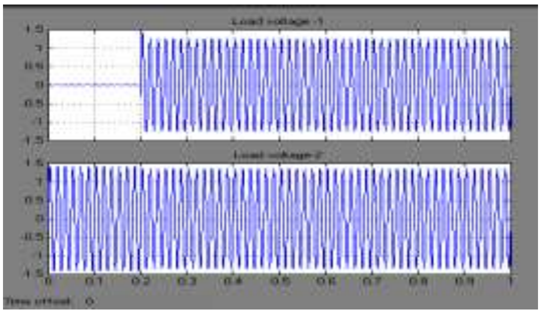

Fig 19: Load Voltage – 1 & 2

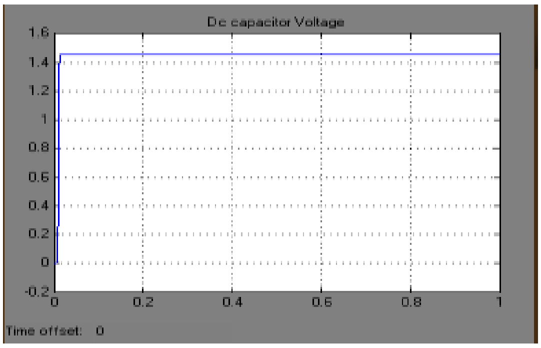

Fig 20: DC capacitor Voltage

c) SVC Controller:

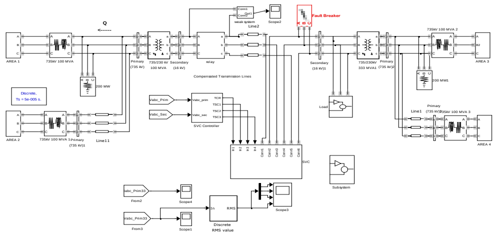

Fig 21: Simulation model with SVC output controller

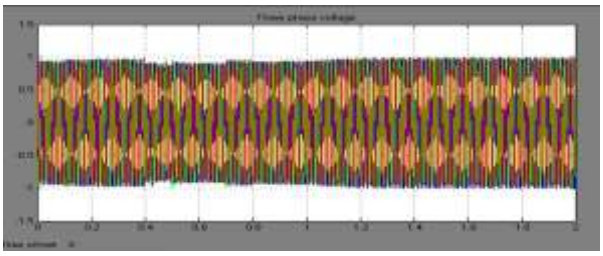

Fig 22: Three Phase Voltages Versus Time (secs)

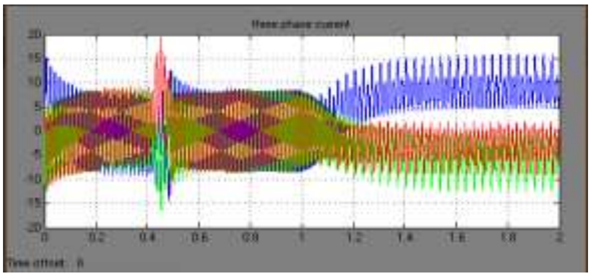

Fig 23: Three Phase Currents Versus Time (secs)

Enhancement of power transfer capability IEEE 14 Bus System:

	Transfer		OPF method	
	From Area	To Area	TTC (MW)	Constraint
Without FACTS devices	1	2	26	No Reactive power Limits
FACTS devices (TCSC)			34.2	Violating reactive power limit of generator at bus: 1;
FACTS devices (UPFC)			36	
FACTS devices (SVC)			28	
	From Area	To Area	TTC(MW)	Constraint
Without FACTS devices	1	5	31	No Reactive power Limits
FACTS devices (TCSC)			39	Violating reactive power limit of generator at bus: 5;
FACTS devices (UPFC)			43	
FACTS devices (SVC)			35	
	From Area	To Area	TTC(MW)	Constraint
Without FACTS devices	3	2	38.6	No Reactive power Limits
FACTS devices (TCSC)			39.1	Violating reactive power limit of generator at bus: 3;
FACTS devices (UPFC)			44	
FACTS devices (SVC)			38.2	

Enhancement of power transfer capability IEEE 30 Bus System

	Transfer		OPF method	
	From Area	To Area	TTC(MW)	Constraint
Without FACTS devices	29	30	115.9	No Reactive power Limits
FACTS devices(TCSC)			115.1	Violating reactive power limit of generator at bus: 30;
FACTS devices(UPFC)			168.1	
FACTS devices(SVC)			107.5	
	From Area	To Area	TTC(MW)	Constraint
Without FACTS devices	25	26	115.9	No Reactive power Limits
FACTS devices(TCSC)			117.729	Violating reactive power limit of generator at bus: 30;
FACTS devices(UPFC)			149.2	
FACTS devices(SVC)			110.228	

V. CONCLUSION

These simulation results gives us a clear idea about the use of FACTs controllers on the interconnection of two different power system in order to maximize the real and reactive power flow between them. The FACTs devices are capable to control the real and reactive power as well as the line impedance, phase angle and voltage magnitude. From the results it is clear that UPFC able to control the flow of active power better than other two controllers (SVC and TCSC) and enhances TTC.

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