

Load Flow Analysis on Statcom Incorporated Interconnected Power System Networks Using Newton Raphson Method

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Abstract: *With the advancement of technology the demand of electrical energy has also increased. The demand of electricity has become the parameter of development of a nation. An electrical utility company has to use its existing transmission capacity to feed the ever increasing demand of electricity, due to that the transmission lines has to be operated near its thermal stability limits. Operating the lines near or above thermal stability limits makes system vulnerable to faults moreover it also increases the losses in the system. One way to increase the transmission capacity of the system without operating it to its thermal stability limit is to provide reactive power compensation at various locations. Reactive power compensation improves the voltage profile of the system, increase the power transfer in the lines and reduce losses. STATCOM is one such device that is used for reactive power compensation. It provides reactive power compensation thereby improving the voltage profile of the system. In this thesis reactive power compensation is attempted using STATCOM. To study its effect Load flow study is performed on IEEE (Institute of Electrical & Electronics engineer) 5 bus with and without STATCOM and the results are then compared to show the effect of STATCOM on the system. Newton Raphson method is used for the load flow study of the system. Simulation is done using MATLAB (Matrix Laboratories).*

Keywords: *Statcom, Ieee 5 Bus, Matlab.*

I. Introduction

Over the time human race has become very much dependent upon electrical energy, to fulfil their daily needs. This has resulted in the rapid growth of power system. There are few problems that we face. They are power disruption and individual power outages. To maintain the urban lifestyle there is enormous demand of power so transmission systems are being pushed to operate closer to their stability limit and also reaching close to their thermal limits. The constraint faced in keeping the demand and supply of power equal or matched are:

- To full fill the demand of power within the thermal limit.
- Sometimes when the power demand is greater than the supply then there is a stability

Problem and this causes blackouts incurring huge losses. The quality of the power delivered is affected by the above two reasons. Now the need arises to check the above constraints and they can be done by enhancing the power system control. These constraints can be controlled by FACTS devices. FACTS devices mean Flexible AC Transmission Systems devices. To establish the match between the demand and supplies of power, control over the power flow and enhancement in system stability is important which can be achieved by the FACTS devices. FACTS devices have now become the need of the hour. It is now becoming our necessity to use FACTS devices to improve the efficiency of the power system. FACTS devices are cost effective alternatives to new transmission line construction.

To minimize the power transmission loss reactive power compensation is used. Reactive power compensation is also used to maintain power transmission capability and to maintain the supply voltage. In a transmission line, control of line impedance is known as Series compensation. When the impedance of a line changes it means that either capacitive or

Inductive compensation can be obtained thus controlling active power. TCSC (Thyristor Controlled Series Capacitor) is connected in series with the transmission line to enhance the power transfer capability. To increase the steady state transmittable power and to control the voltage profile shunt compensation is used. STATCOM (Static Compensator) is a shunt compensator and comes under FACTS device category that is being applied to long transmission lines. They are used for the control of power system. Applications such as scheduling of power flow, decreasing unsymmetrical components, decreasing the power oscillations and increasing the transient stability.

II. Load Flow Study

With the huge increase in population, the demand for the electrical power has increased proportionally. It is an enormous task for the electrical utility company to supply this large amount of power to the consumer continuously and safely. Apart all these points, efforts have to be made to reduce the transmission cost of the system. There are lots of constraints for an electrical utility company to be followed for smooth, economical and profitable operation. Furthermore addition of generator or any other equipment makes the power system more vulnerable to faults. So from the discussion we conclude that the power system network is a huge interconnection of generators, buses and transformers combined together to supply load at various points of the system any chances of fault should be minimized as it would lead to large economic losses. Moreover it should be made to function so as to draw maximum efficiency with safety. Load flow study is employed to the power system to study the power system network, and its behaviour when it is subjected to any expansion or upgraded for any system.

III. General Power Flow Concept

A power flow equation when solved will tell about the steady state complex voltages at all the buses of the network and we can calculate the real and reactive power flows from these equations. The problem with these power flow equations are that they are non-linear in nature and cannot be solved by basic mathematical calculation. These non-linear equations are normally solved by taking an approximate of a value and correcting it in continuous iterations process until the solution lies within the permissible values. There are many methods available to solve these equations like Gauss Method, Gauss Seidel, Newton Raphson and Fast Decoupled Load Flow.

IV. The Newton Raphson Load Flow Algorithm

For practical power system load flow problem Newton Raphson method is very popular due to its very strong convergence characteristic. This method uses iteration to solve the non-linear equations of power system. A value is assumed and it is corrected in continuous steps or iteration until the required value falls in permissible limit. An example is shown for how Newton raphson method can be used to solve a set of non-linear equations

Suppose there are set of equations

$$f_1(x_1, x_2, \dots, x_n) = 0$$

$$f_2(x_1, x_2, \dots, x_n) = 0$$

$$f_3(x_1, x_2, \dots, x_n) = 0$$

$$f_n(x_1, x_2, \dots, x_n) = 0$$

Or it can be written as

$$F(X) = 0$$

Where,

F = set of "n" nonlinear equations

X = vector of "n" unknown state variable

In Newton raphson method the vector of state variable is determined by performing an expansion of F(X) by Taylor's series by taking an initial estimate X(0)

$$F(X) = F(X(0)) + J(X(0))(X - X(0)) + \text{higher order terms}$$

Where J (X0) is a matrix of first order partial derivatives of F(X) with respect to X, it is known as jacobian, evaluated at X=X0

Now X⁰ becomes the iteration at step 1 and is initially close to X¹. Now the equation can be written...

$$\begin{bmatrix} f_1(X^{(1)}) \\ f_3(X^{(1)}) \\ \vdots \\ f_n(X^{(1)}) \end{bmatrix} \approx \begin{bmatrix} f_1(X^{(0)}) \\ f_3(X^{(0)}) \\ \vdots \\ f_n(X^{(0)}) \end{bmatrix} + \begin{bmatrix} \frac{\partial f_1(X)}{\partial X_1} & \frac{\partial f_1(X)}{\partial X_3} & \cdots & \frac{\partial f_1(X)}{\partial X_n} \\ \frac{\partial f_3(X)}{\partial X_1} & \frac{\partial f_3(X)}{\partial X_3} & \cdots & \frac{\partial f_3(X)}{\partial X_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_n(X)}{\partial X_1} & \frac{\partial f_n(X)}{\partial X_3} & \cdots & \frac{\partial f_n(X)}{\partial X_n} \end{bmatrix} \begin{bmatrix} X_1^{(1)} - X_1^{(0)} \\ X_3^{(1)} - X_3^{(0)} \\ \vdots \\ X_n^{(1)} - X_n^{(0)} \end{bmatrix}$$

Generalizing the term for the i^{th} iteration, the equation become

$$F(X^i) \approx F(X^{(i-1)}) + J(x(I-1))(x(i) - x(I-1)) \quad (3.26)$$

Now $i=1, 3, 4, \dots$ and x^i is assumed to be the solution then $F(x^{(i)})=0$. Hence equation 3.26 becomes

$$F(x(I-1)) + J(x(I-1))(x(i) - x(I-1)) = 0 \quad (3.27)$$

Now solving for $x(i)$ will yield the form

$$x(i) = x(I-1) - J^{-1}x(I-1) F(x^{(i-1)}) \quad (3.28)$$

The iterative solution can be expressed as

$$\Delta x^{(i)} = X^{(i)} - X^{(i-1)} \quad (3.29)$$

So from equation 3.38

$$\Delta x^{(i)} = -j(x^{(i-1)})(x^{(i)} - x^{(i-1)}) \quad (3.30)$$

The iterations can be corrected in advance steps as

$$x^{(i)} = \Delta x^{(i)} + x(I-1) \quad (3.31)$$

The iterations are done again and again until the mismatches Δx are in the prescribed limits. This was the generalized form of Newton Raphson method, its incorporation in load flow should be in the form of equation 3.30 so

This is the form of the equation

$$F(x^{(i-1)}) = j(x^{(i-1)}) \Delta x^{(i)} \quad (3.33)$$

This jacobian term contains $(nb-1) \times (nb-1)$ numbers of element of forms like

$$\left. \begin{matrix} \frac{\partial P_k}{\partial \theta_m} & \frac{\partial P_k}{\partial V_m} V_m \\ \frac{\partial Q_k}{\partial \theta_m} & \frac{\partial Q_k}{\partial V_m} V_m \end{matrix} \right\} \quad (3.34)$$

Where $k=1, 3, 4, \dots, nb$ and $m=1, 3, 4, \dots, nb$ neglecting the slack bus terms. Also columns terms and row terms of voltage magnitude and reactive power of PV bus are neglected. The transmission line not connected by the bus k and m are zero. There entry in the jacobian matrix is omitted. So we can say that the jacobian matrix thus formed will be highly sparse, also there are symmetrical in nature but not in nature.

V. Facts In Power System

Active (real) and reactive power in a transmission line depend on the voltage magnitudes and phase angles at the sending and receiving ends as well as line impedance. Assuming that the resistances of high voltage transmission lines are very small, there is equivalent reactance connected in between sending and receiving ends. The receiving end is modeled as an infinite bus with a fixed angle of 0° .

$$S_R = P_R + jQ_R = V_R I^* \quad (4.1)$$

$$P_R = V_s V_R \sin \delta$$

$$Q_R = V_s V_R \cos \delta - V_R^2 \quad (4.2)$$

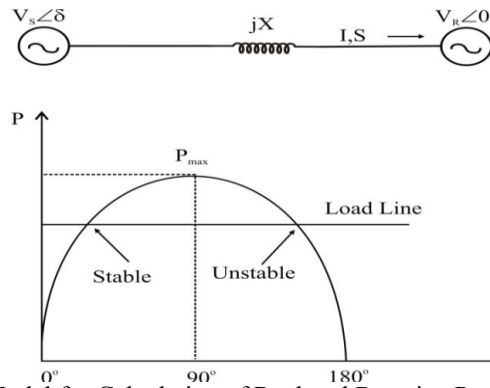


Fig. Model for Calculation of Real and Reactive Power Flow

Different FACTS Controller

- 1 Static Var Compensator (SVC)
- 2 Thyristor Controlled Series Compensator (TCSC)
- 3 Static Synchronous series compensator (SSSC)
- 4 Static Synchronous Compensator (STATCOM)
- 5 Unified Power Flow Controller (UPFC)
- 6 Convertible Static Compensator (CSC)
- 7 Interline Power Flow Controller (IPFC)
- 8 Generalized Unified Power Flow Controller (GUPFC)

Static Synchronous Compensator (STATCOM)

It is designed based on Voltage source converter (VSC) electronic device with Gate turn offthyristor and dc capacitor coupled with a step down transformer tied to a transmission line as shown in below figure. It converts the dc input voltage into ac output voltages to compensate the active and reactive power of the system. STATCOM has better characteristics than SVC and it is used for voltage control and reactive power compensation.

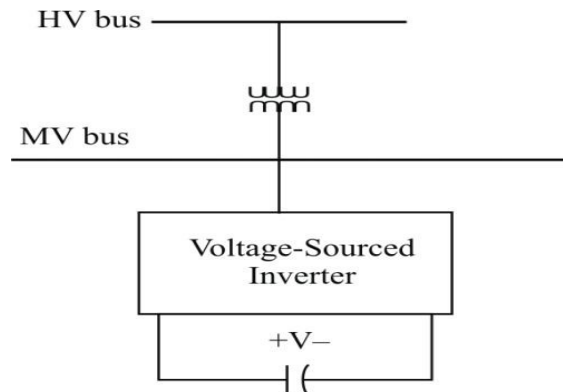


Fig. Static Synchronous Compensator (STATCOM)

Characteristics of Static Synchronous Compensator (STATCOM)- STATCOM placed on a transmission network improve the voltage stability of a power system by controlling the voltage in transmission and distribution systems, improves the damping power oscillation in transmission system, provides the desired reactive power compensation of a power system.

VI. Case Study And Results

Case Study for an IEEE 5 Bus System

Consider a standard IEEE 5 bus system for load flow study by Newton Raphson load flow method. It has 5 buses namely North, South, Lake, Main and Elm. The source impedance is $X_{vr} = 0.1$ p. u. For simplicity the bus has been denoted as

- North= bus 1
- South = bus 2
- Lake= bus 3

Main = bus 4

Elm = bus 5

Bus 3, 4 and 5 are considered load bus. Bus 1 is slack bus while bus 2 is voltage controlled bus.

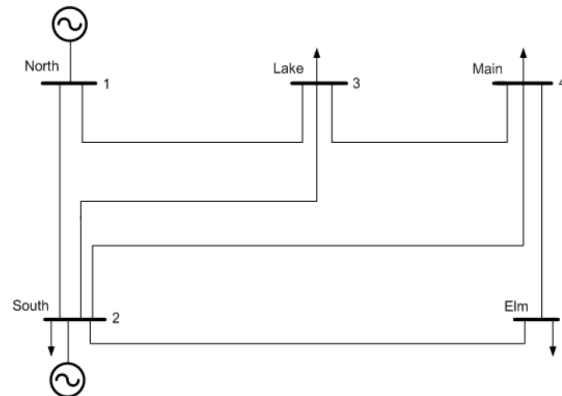


Fig. An IEEE 5 bus system

For the figure, the table shows the bus number and type of Bus.

Table 2.- Bus type

Bus Number	Type of bus
Bus 1	Slack bus
Bus 2	Voltage controlled bus
Bus 3	Load bus
Bus 4	Load bus
Bus 5	Load bus

Bus Data

Table below shows the bus data for the 6 bus system. Column 1 and column 2 shows the bus number and bus type. Columns 3 and 4 show the voltage magnitudes in p.u. and phase angle in degrees. Columns 5 and 6 outline the size of the active and reactive loads connected to the corresponding buses in MW and MVAR. Columns 7 through to 10 are MW, MVAR, minimum MVAR and maximum MVA of generation, in that order. The bus code entered in column 2 is used for identifying load, voltage-controlled, and slack buses as outlined below;

Code 1 is used for the slack bus.

Code 2 is used for voltage controlled bus.

Code 3 is used for load bus.

Below is the table for bus data of an IEEE 5 bus system. The column is divided into bus number, bus code, voltage magnitude at the bus, phase angle, load in MW at that bus, reactive power at the bus in MVAR, Generator real and reactive power. The last two columns show the specified limit for the minimum reactive and maximum reactive power limits.

Table 3- Bus Data, IEEE 5 Bus System

Bus No.	Bus code	Voltage magnitude	Angle degree	Load MW	Load MVAR	Gen MW	Gen MVAR	Q _{min}	Q _{max}
1	1	1.06	0	0.0	0.0	0.0	0.0	-600	600
2	2	1	0	20.0	10.0	40.0	0.0	-300	300
3	3	1	0	46.0	16.0	0.0	0.0	0	0
4	3	1	0	40.0	6.0	0.0	0.0	0	0
6	3	1	0	60.0	10.0	0.0	0.0	0	0

Line Data

The table 4.shows the transmission line data. Columns 1 and 2 outline the corresponding line bus numbers. Columns 3 through to 6 contain the line resistance, reactance, and one half of the total line charging susceptance in per unit on the MVA base of 100MVA.

Table 4- Line Data for IEEE 5 Bus

Bus nl	Bus nr	R	X	B
1	2	.02	0.06	0.06
1	3	.08	0.24	0.05
2	3	.06	0.18	0.04
2	4	.06	0.18	0.04
2	5	.04	0.12	0.03
3	4	.01	0.03	0.02
4	5	.08	0.24	0.05

Results:- Bus voltages and phase angle

The Newton Raphson load flow IEEE 5 bus system implemented on MATLAB return following results For Iteration count = 6 The bus voltages and phase angle obtained are shown in table- Line Data for IEEE 5 Bus

Table 5- Bus Voltage and Phase Angle, IEEE 5 Bus without STATCOM

Nodal Voltage Magnitude (p.u.)	Bus voltage without STATCOM				
	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5
	1.0600	1.0000	0.9872	0.9841	0.9717
Phase angle (degree)	0.000	-2.0612	-4.6367	-4.9670	-6.764

The table above shows the bus voltage magnitude and phase angle of the power system without STATCOM, now performing load flow on this system with STATCOM at bus 3 following results were obtained For iteration count = 6

Table 6- Bus Voltage and Phase Angle, IEEE 5 Bus with STATCOM

Buses	Sending end		Receiving end	
	P(MW)	Q(MVAR)	P(MW)	Q(MVAR)
1-2	89.11	74.06	-86.83	-72.99
1-3	41.96	11.28	-40.66	-12.41
2-3	24.49	-9.69	-24.09	6.69
2-4	27.66	-7.32	-27.18	4.77
2-6	64.88	2.76	-63.29	-2.09
3-4	19.66	11.19	-19.69	-13.02
4-6	6.78	3.26	-6.71	-7.91

From the results it can be seen that voltage profile has been improved with the inclusion of STATCOM in the network. Clearly voltage at bus 3 is increased 0.98 p.u. to 1.00 p.u. also the nodal voltages of bus 4 (main bus) is improved and is almost equal to 1 p.u. The effect of STATCOM on the nodal voltage of bus 5 (elm bus) is minimum as it is far away from it.

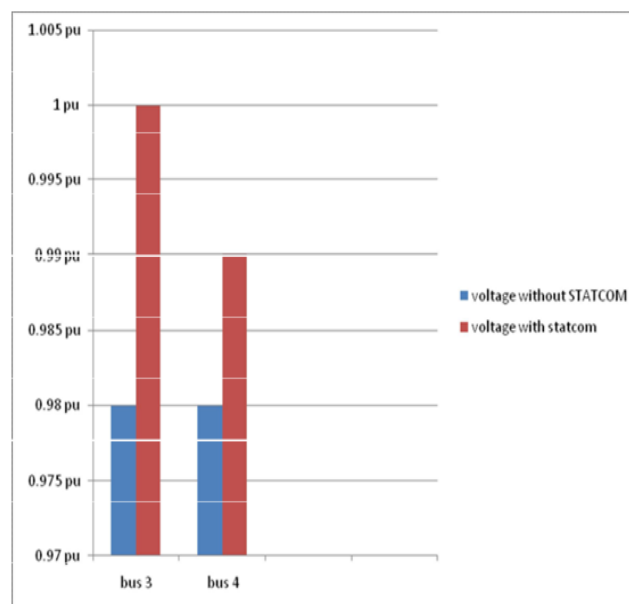


Fig. Graphical Representation of Improved Voltage Profile with STATCOM (IEEE 5 Bus)

STATCOM injected powers

To calculate the STATCOM injected bus power at the bus where STATCOM is inserted that is at bus 3. The real and reactive power flows in the bus is considered. According to load flow data the reactive power requirement at bus 3 that is lake bus is $46 + j16$. Now all the incoming power coming to the bus is equal to outgoing power. At lake bus the incoming and outgoing powers can be obtained through table 6.

Complex power flowing into the bus – complex power flowing out of the bus = $46 + j16$

$40.64 + j12.4 + 24.1 - j6.7 - 19.64 - j11.2 + \text{statcom injected power} = 46 + j16$

$46 - j6.6 + \text{statcom injected power} = 46 + j16$

Statcom injected power = 20.6 MVAR

So STATCOM is injecting 20.6 MVAR of reactive power to keep the voltage magnitude at bus3 close to 1 p.u.

The STATCOM parameters associated with this amount of reactive power generation are

$V_{vr} = 1.0206$ p.u.

$\delta_{vs} = -4.83^\circ$.

VII. Conclusion

Power flow study determines the best operating condition of a Power System Network. Newton-Raphson load flow method has been used for solving the power-flow equation. To study the effect of STATCOM on power system, a modified power flow model of the STATCOM is attempted. STATCOM is placed at different locations in various bus systems and the modified load flow program is used to access the effect of STATCOM on the system. The simulation is done using MATLAB.

Load flow study of all three bus (IEEE 5) is considered and it is shown that the voltage profile of the system is improved and it is shown using plots. It was also evident that the voltage magnitude of that particular bus at which STATCOM is placed is maintained at 1 p.u. The reactive power generation and absorption of the slack bus generator is reduced. The buses placed far away from the STATCOM are least effected while there was no effect of STATCOM on the real power.

VIII. Future Scope

- The completion of one research project opens the avenues for work in many other related areas. The following areas are identified for future work:
- The load flow study can be done on larger interconnected power system like IEEE 14 & IEEE 30 and IEEE 118 bus and even larger
- UPFC, IPFC and other FACTS controller can also be incorporated along with the STATCOM and their effect on the system can be studied
- Optimal location of STATCOM can be found out using Genetic Algorithm and fuzzy logic
- Economic Assessment of FACTS devices against other methods can be studied.

Reference

- [1]. K.R.Padiyar and A.M.Kulkarni, "FACTS- Flexible AC Transmission System: A Status Review", *sadhna*, Vol. 22, No. 6, December 1997, pp. 781-796.
- [2]. Joseph Mutale and Goran Strbac, "Transmission Network Reinforcement versus FACTS: An Economic Assessment", *IEEE Transaction on Power Systems*, Vol. 15, No. 3, August 2000, pp. 961-967.
- [3]. Diego Soto "Comparison of High-Power Converter Topologies for the Implementation of FACTS Controllers", *IEEE Transactions on Industrial Electronics*, Vol. 49, No. 5, October 2002, pp. 1072-1080.
- [4]. Ying Xiao, Y.H.Song and Chen-Ching Liu, "Available Transfer Capability Enhancement Using FACTS Devices", *IEEE Transactions On Power Systems*, Vol. 18, No. 1, February 2003, pp. 305-312.
- [5]. M. Sh. Misrikhanov, V.F.Sitnikov, and Yu.V.Sharov, "Modal Synthesis of Regulators for an Electrical Power System on the Basis of FACTS Devices", *Russian Electrical Engineering*, Vol. 78, No. 10, 2007, pp. 22-29.
- [6]. M. Sh. Misrikhanov, V.F.Sitnikov, and Yu.V.Sharov, "Operation Coordination of FACTS Devices in Backbone Networks Based on Fuzzy Logic Methods", *Russian Electrical Engineering*, Vol. 79, No. 1, 2008, pp. 51-55.
- [7]. Xia Jiang, Joe H. Chow, Abdel-Aty Edris, Bruce Fardanesh, and Edvina Uzunovic, "Transfer Path Stability Enhancement by Voltage-Sourced Converter-Based FACTS Controllers", *IEEE Transactions on Power Delivery*, Vol. 25, No. 2, April 2010, pp. 1019-1025.
- [8]. K.N.Shubhanga and Anil Kulkarni, "Application of Structure Preserving Energy Margin Sensitivity to Determine the Effectiveness of Shunt and Series FACTS Devices", *IEEE Transactions on Power Systems*, Vol. 17, No. 3, August 2002, pp. 730-738.
- [9]. Anju Meghiani and A.M.Kulkarni, "Development of a Laboratory Model of SSSC Using RTAI on Linux Platform", *Sadhana*, Vol. 33, Part 5, October 2008, pp. 643-661.xiv
- [10]. M. Kashki, M.A.Abido and Y.L.Abdel-Magid, "Pole Placement Approach for Robust Optimum Design of PSS and TCSC-Based Stabilizers Using Reinforcement Learning Automata", *ElectrEng*, January 2010, pp. 383-394.
- [11]. Mahdi Ghazizadeh Ahsae and Javad Sadeh, "A Novel Fault-Location Algorithm for Long Transmission Lines Compensated by Series FACTS Devices", *IEEE Transactions on Power Delivery*, Vol. 26, No. 4, October 2011, pp. 2299-2308.
- [12]. Nan Jiang, Bin Liu, Jixin Kang, Yuanwei Jing and Tie Zhang, "The Design of Nonlinear Disturbance Attenuation Controller for TCSC Robust Model of Power System", *Nonlinear Dyn*, June 2011, pp. 1863-1870.

- [13]. K.V.Patil, J. Senthil, J.Jiang and R.M.Mathur, "Application of Statcom for Damping Torsional Oscillations in Series Compensated AC Systems", IEEE Transactions on Energy Conversion, Vol. 13, No. 3, September 1998, pp. 237-243.
- [14]. J.B.Ekanayake and N.Jenkins, "Selection of Passive Elements for a Three-Level Inverter Based Static Synchronous Compensator", IEEE Transactions on Power Delivery, Vol. 14, No. 2, April 1999, pp. 655-661.
- [15]. M.H.Haque, "Improvement of First Swing Stability Limit by Utilizing Full Benefit of Shunt FACTS Devices", IEEE Transactions on Power Systems, Vol. 19, No. 4, November 2004, pp. 1894-1902.
- [16]. Hosseini Mehdi, ShayanfarHeidar Ali and Fotuhi-Firuzabad Mahmud, "Modeling of DSTATCOM in Distribution Systems Load Flow", HosseiniUnivSci A, Vol. 8, No. 10, July 2007, pp. 1532-1542.
- [17]. Chong Han, Alex Q. Huang and Mesut E. Baran, "STATCOM Impact Study on the Integration of a Large Wind Farm into a Weak Loop Power System", IEEE Transactions on Energy Conversion, Vol. 23, No. 1, March 2008, pp. 226-233.
- [18]. S.Hadjeri, FatihaGhezal and S.A.Zidi, "Simulation of Three-Level 48 Pulse STATCOM", Vol. 49, No. 2, 2008, pp. 189-193. xv
- [19]. E. Nasr Azadani, S.H.Hosseinian and P.Hasanpor, "Optimal placement of multiple STATCOM for voltage stability margin enhancement using particle swarm optimization", ElectrEng, July 2008, pp. 503-510.
- [20]. MehردادAhmadiKamarposhti and Hamid Lesani, "Effects of STATCOM, TCSC, SSSC and UPFC on Static Voltage Stability", ElectrEng, December 2010, pp. 33-42.
- [21]. AlirezaZare and Reza KhorramNia, "Sensitivity Analysis of STATCOM Parameters for Voltage Stability", American Journal of Scientific Research, 2012, pp. 89-96.
- [22]. HaiFeng Wang, "A Unified Model for the Analysis of FACTS Devices in Damping Power System Oscillations—Part III: Unified Power Flow", October 2002, pp. 60-61.