World Academy of Science, Engineering and Technology
International Journal of Energy and Power Engineering
Vol:17, No:2, 2023

FACTS Impact on Grid Stability and Power Markets

Abdulrahman Alsuhaibani, Martin Macken

***Abstract*—**FACTS devices have great influence on the grid stability and power markets price. Recently, there is intent to integrate a large scale of renewable energy sources to the power system which in turn pushes the power system to operate closer to the security limits. This paper discusses the power system stability and reliability improvement that could be achieved by using FACTS. There is a comparison between FACTS devices to evaluate their performance for different functions. A case study has also been made about its effect on reducing generation cost and minimizing transmission losses which have good impact on efficient and economic operation of electricity markets.

***Keywords*—**FACTS, grid stability, spot price, Optimal Power Flow.

I. Introduction

CHANGES in the power system in recent years, with an increase in energy production from renewable energy sources and a deregulation of the power market, have led to increased complexity of power systems and a change of grid structure. Previously, the primary goals of power system operation were security and reliability and losses in the system were of secondary significance, cost optimization and loss minimization has now become the main concern. Power systems were used to operate well within the security constrains; they are now pushed to operate much closer to security limits.

Wind power has overturned the traditional linear energy chain, with a centralized power generation, is being interchanged with dispersed power generation, even on medium and low voltage levels. This puts a whole new demand on the power system, which has to be “smart”, acting according to system stability and reliability requirements of the grid code.

In 2012, 11 895 MW of wind power capacity was installed in the EU. Renewable energy accounted for 70% of new installations; 31.3 GW of a total 44.9 GW new power capacity. Wind power alone accounted for 26.5% of new installations. The new installations make up to a total of 106 GW of installed wind power within the EU, a cumulative capacity increase of 12.6% from the previous year [1]. European Wind Energy Association (EWEA) forecasts an installed wind power capacity in the EU 400 GW in 2030. This could, according to EWEA, account for about 28.2% of the total energy produced in the EU, depending on the scenario [2]. This will of course put huge demands on the transmission system.

Traditionally, power production and transportation has been a linear operation with production taking place at one side of the grid, and power transported to the consumer on the other side, using conventional power plants (CPP). CPPs utilize synchronous machines that assist with voltage control, frequency control, transient stability control and reactive power support, which satisfy the demands set by transmissions system operators (TSOs) on generating units [3]. Wind power plants (WPP) on the other hand, have different characteristics from CPPs with more disturbances to voltage and frequency. In the past, since WPPs were so small, the rules governing their connection to the grid have been more relaxed to encourage a further development. Lack of rules, regulations and standards dealing with WPP grid connection has grown to be a problem as the installed capacity has increased in later years. Disturbances from WPPs have proven to become a threat to stability and power quality in interconnected grids [4].

The increase of wind powers penetration into the power grid has given rise to new challenges for TSOs when it comes to upholding stability and reliability of supplied power. Hence, interconnection rules for WPPs have been included in national grid code requirements (GCR), where every country employs their own rules. Most commonly, GCR govern active power control, frequency control, voltage control, fault ride-through requirements, supervisory control and data acquisition [3].

Deregulation of the power market has changed the electric utilities fundamentally. The main reason for deregulation of the power markets is introducing competition; hence make the markets operate more efficiently. If every market participant has the incentive to maximize their own welfare, it follows that welfare for everyone involved in the power market will be maximized. Electric energy is now treated as a commodity with transmission pricing as a key issue.

To make sure the market operates smoothly with generation and load dispatch planned accordingly, one method is to use the spot price theory. In short, the spot price theory is based on pricing a commodity at what value it could be bought or sold at a specified time and place. Real-time pricing is believed to improve market efficiency and the optimal usage of power systems. All utility to customer transactions is based on the hourly spot price; defined as marginal cost subject to a number of constrains [5]. Hourly spot price has the advantage of customers always seeing the actual price, hence can decide when to buy to optimize pricing. Buying and selling bids are submitted to a pool operator who then can determine the dispatch to optimize system operation. One important method of deciding spot price is based on the optimal power flow (OPF) calculations, for both active and reactive power. Reactive power as an ancillary service is of importance in a power system as lack of it may cause voltage instability. Therefore, pricing of reactive power in both normal and emergency operation must

Abdulrahman M. Alsuhaibani is with Saudi Aramco Company, Saudi Arabia (e-mail: abdualrahman.alsuhaibani@aramco.com).

be decided [6].

IEEE describes FACTS as: “Alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability” [12]. FACTS devices may not only help controlling voltage levels of the power systems, but also increase the flow of active power, hence reducing transmission costs and help maximizing social welfare benefits and at the same time minimizing system losses.

This paper will focus on giving an overview of FACTS; different type of applications and how they operate. There are different FACTS devices for different applications. This paper is going to discuss the most popular devices briefly. There will be a discussion and examples of how FACTS can help to improve stability of the power system and how FACTS can help to decrease the spot price of the power markets.

II. Overview of FACTS Devices

Flexible AC Transmission Systems (FACTS) devices become a fundamental part in the power system to ensure the high performance and stability. FACTS devices could be represented by different group and categories but the majority of these devices operate based on the power electronics applications. In general, FACTS devices can be modeled in steady state case, as shown in Fig. 1, where E_c is a series voltage source for series control and I_c is a parallels current source for the parallel control. Practically, FACTS devices control all the parameters that determine the flow of the power in the system. In other words, it controls voltages magnitudes, angles and line reactance which are not totally independent [7].

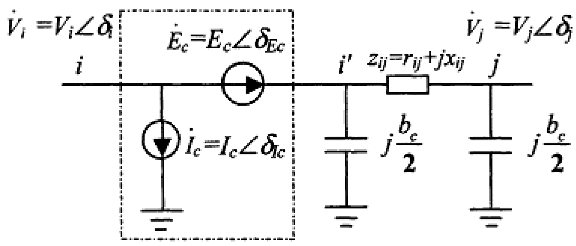

Fig. 1 Uniform steady state model of FACTS devices

FACTS devices can be classified by the way they connected to the system either shunt or series compensation and in some cases the combination of the two.

The main function of the shunt devices is to exchange the reactive power with the system to regulate the voltage at the bus against load variation or improve the steady state transmission characteristics. Static VAR Compensator (SVC) and STATCOM are popular shunt compensators. Both SVC and STATCOM have similar functional compensation capability. However, the operation principle and the V-I characteristic are different. The operation principle of SVC is based on Thyristor Controlled Reactors (TCR) and Thyristor Switched Capacitors (TSC). This could be seen as an adjustable controlled reactive admittance over a large range from capacitive to inductive. On the other hands, STATCOM Function as a shunt synchronous voltage source which can exchange the reactive power. The main advantage of STATCOM is its ability to sustain the reactive current at the nominal value over a wide range of voltage. This is not the case for SVC when the voltage reduces. Also, STATCOM contains DC to AC converter which makes it possible to provide the active power. However, the SVC is still the most commonly used shunt compensation device due to the cost and the large power range that can provide [8].

Series compensator is another type of the FACTS devices and the main idea behind it is to reduce the line effective impedance. In the series compensators devices appears Thyristor Controlled Series Capacitor (TCSC), which can be seen as variable reactance connected in series with the line reactance. The same purpose could be achieved by using Static Synchronous Series Compensator (SSSC), which act as a series voltage source that reduce the voltage drop across the line. One big advantage of SSSC over TCSC is that its control characteristic is not affected by the amount of the line current. Hence, it offers better performance than TCSC [8]. However SSSC has not been used in the transmission networks due to the high cost.

Table I shows comparison between functionality of different FACTS devices. It is important to point out for STATCOM and SSSC, it has been assumed that the energy storage is available to provide the active power.

TABLE I
Comparison between FACTS Devices

Function \ FACTS	SVC	STATCOM	TSCS	SSSC
Exchange Active Power		Green		Green
Exchange Reactive Power	Yellow	Green	Red	Green
Power Flow Control	Red	Red	Yellow	Green
Power Oscillation Damping	Red	Yellow	Yellow	Green
Voltage Stability Improvement	Yellow	Green	Yellow	Green
Rotor Angle Stability Improvement	Red	Yellow	Yellow	Green
Frequency Stability Improvement		Blue		Blue
Performance	Excellent	Good	Limited	Dependent
Color	Green	Yellow	Red	Blue

III. FACTS Impact on Grid Stability

From power system operation point of view, there always has been an argument about the impact of using wind energy on the power system stability. Basically, one of the main reasons for losing the stability is the limitation of the reactive power which in turn explains the essential need for FACTS devices. Nowadays, the fast growth of the renewable energy sources requires using more power compensators to ensure the system stability.

A. *Increase of Transmissible Power*

By inserting a shunt compensation device in the midpoint, the power transmission capacity increases. In the best case, the transmissible active power will be double its maximum value. However, this results fast increasing of reactive power demand at the midpoint [9]. Fig. 2 shows the relation between active power P, reactive power Q and angle δ.

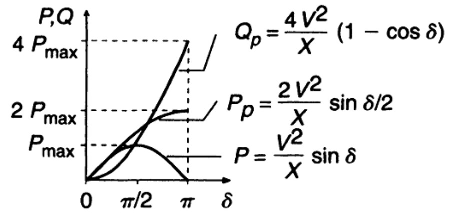

Fig. 2 The relation between active power P, reactive power Q, and angle δ for a two-machine power system with an ideal midpoint reactive compensator.

Similarly, by using series compensators, the power transmission capacity increases. The series compensator cancels portion of the line reactance, which represents the effective line impedance. So, physically it will act as if the line was shortened. In other words, in order to increase the power by increasing the current through fixed impedance, the voltage should be increased which explains the series capacitive element. Fig. 3 shows the relation between active power P, reactive power Q and angle δ for series compensation where k is the degree of series compensation. It could be noticed that the sharp increasing of reactive power demand in order to increase the active power transmission capacity [9].

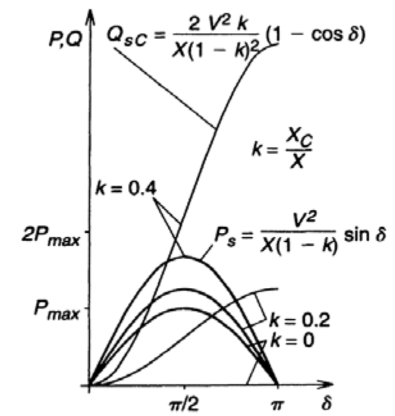

Fig. 3 The relation between active power P, reactive power Q and angle δ for two machine power system with series compensation

B. *Improvement of Transient Stability*

The impact of the FACTS devices on the transient stability can be evaluated by the equal area criterion. This could be illustrated with the help of Fig. 4 which represents two machine systems: (a) without compensation (b) ideal midpoint shunt compensators. It has been assumed that the same fault has occurred in both cases for the same period of time. As can be seen in Fig. 4 before the fault, the mechanical power is constant. During the fault, the electric power drops to zero and the mechanical power is still constant so the generator angle accelerates. After the fault is cleared, the electric power become larger than the mechanical power and the machine starts to decelerate until a balance between the accelerating and decelerating energy is reached. This limit is reached at δ_3 and δ_{p3} which represent the maximum angular swing for both cases [9].

As can be obtained from Fig. 4 and the above discussion, the shunt compensation results a large improvement in the transient stability margin. Due to increasing power transmission capability, the transmission line voltage increases during the accelerating swing of the disturbed machine since the balance is reached with smaller swing angle in the computation case which allows a larger stability margin.

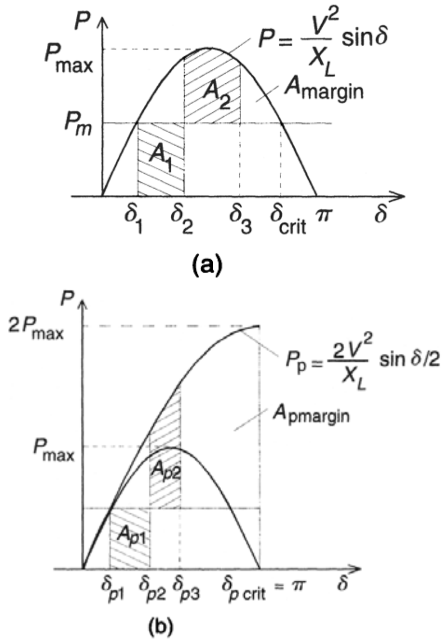

Fig. 4 Equal area criterion to illustrate the transient stability margin for a simple two machine system where (a) is without compensation and (b) is with an ideal midpoint compensator

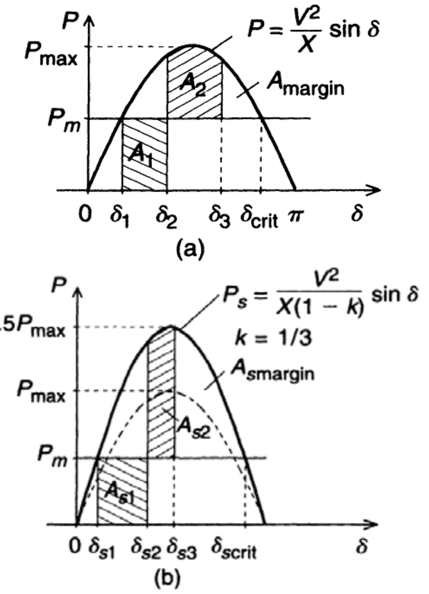

Fig. 5 Equal area criterion to illustrate the transient stability margin for a simple two-machine system, (a) without compensation, and (b) with a series capacitor

In a similar manner, the series compensators have good influence on increasing the transient stability margin and power oscillation damping. Fig. 5 shows the dynamic behavior of two machine system: (a) without compensation (b) with series compensators. As can be noticed, there is a substantial improvement in the transient stability margin Amargin and Asmargin. The improvement in the transient stability margin depends on the degree of series compensation [9]. Practically, for different reasons like sub-synchronous resonance, series capacitive compensation does not exceed 70%.

C. Voltage Stability

In case a heavy load is connected to the power system, the power flows in the transmission line increase which causes a voltage reduction in the voltage bus. In one expected scenario, the voltage continue decreases which results on losing system stability. In the worst case, it will lead to the system collapse. Hence, one of the key purposes of the shunt compensators FACTS devices is to maintain the bus voltage at the nominal value by providing the required reactive power.

One study case has been done by [10]; IEEE 14 bus system is simulated to evaluate the effect of the SVC and STATCOM on the PV curve at bus 14. Fig. 6 shows the results and it indicates the substantial improvement in the voltage profile with using SVC or STATCOM. As shown in Fig. 6, once the light load is connected (less than 1 p.u. loading), SVC and STATCOM have similar voltage profile. With increasing the load, both of the devices will continue in the same manner as long as they operate in the linear region of V-I characteristics. When the bus is heavily loaded (more than 4 p.u. loading), the SVC limit is reached and the STATCOM performance becomes more efficient to regulate the voltage in the bus. In this case, SVC acts as fixed shunt compensator [10].

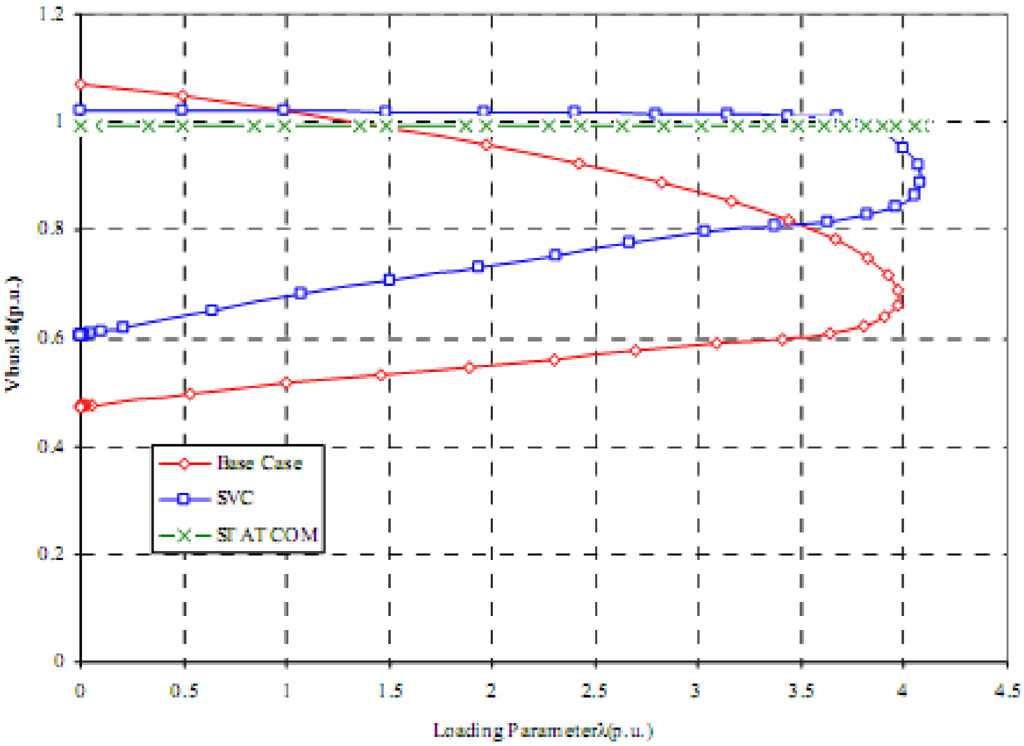

Fig. 6 PV curve for bus 14 with and without SVC & STATCOM [10]

It can be obtained obviously from Fig. 6 at the maximum load condition, that STATCOM provides the maximum loading margin. The voltage profile is the best with STATCOM and the worst without any FACTS device [10].

D. Frequency Stability

To keep the frequency of the power system grid near the nominal value, there should be balance between the generated and consumed power. When the generation power does not cover the load consumption, the synchronous generator tends to slow down that causes the frequency drop in the grid. In contract, if there is over power generation, the synchronous generator will speed up; as a result, synchronous frequency rises.

Recently, some researches have been focused on the energy storage to improve the active power control [8]. In turn, this will be reflected on the frequency and voltage stability. The practical interest is to use FACTS to integrate storage devices into power system. STATCOM contains a voltage source inverter with DC link capacitor. By injecting a current with 90 degree phase shift with the line voltage, the reactive power is supplied. However, if a bulk energy storage device is connected in parallel with the DC capacitor, STATCOM can provide the active power compensation.

One study has been done to evaluate the performance of STATCOM with Energy Storage for Smoothing Intermittent

Wind Farm Power [11]. The simulation results under predicted wind speed show that 5 MWh storage helps a 50 MVA SCIG wind farm to compensate half an hour active power set point. Therefore, wind power could be better dispatched and power system network will be more balance. It is important to point out that the energy not only improves frequency control and inertia emulation. However, it has good impact on the reliability and stability of the system and the power quality.

IV. FACTS Impact on Power Markets

The OPF is most commonly a nonlinear optimization problem consisting of an objective function that should be minimized, limited by some constraints. The problem could be solved to minimize the cost of the dispatch, but could also be solved for other purposes, such as minimizing losses or maximizing social welfare. Constrains could be for example bus voltage limits, load flow, power generation limits, power consumption limits, power factor constraints, transmission limits and real and reactive power loss. To determine price for active and reactive power, the marginal cost that is associated with the load flow constraints is used.

A. General OPF Equations

The way of solving the OPF is derived from [5]. The cost function for generating active power at bus i is described by:

$$C_i(P_{Gi}) = (a_i P_{Gi}^2 + b_i P_{Gi} + c_i)\ \$/h \tag{1}$$

where a_i, b_i, and c_i are cost coefficients. The objective function of the OPF problem is formulated as:

$$Minimize\left[\sum_{i\in NG} C_i(P_{Gi}) - \sum_{i\in NG} B_j(PD_j)\right] \tag{2}$$

where $B_j(PD_j)$ is the benefit function which represents the marginal benefit of consuming unit quantity of electricity and can be described as:

$$B(P) = \int_0^P \left(\frac{D}{K}\right)^{1/E} dD \tag{3}$$

where D is the demand function, K is a constant parameter, and E is the elasticity of the consumption. E is, as in [5], assumed to be -0.2. Since using a value of 0 will render infinite benefits, a lower level with a small quantity compared to the value of P, is chosen. For constant parameter K, a value of 2 I used [5].

B. OPF Constrains

The constrains, used to calculate the OPF are, as given in [5], are the following:

- Load flow constrains, limiting flow of active and reactive power as each bus, given by:

$$P_{Gi} - P_{Di} = \sum_{j\in NB} |V_i||V_j||Y_{ij}| \cos(\delta_i - \delta_j - \theta_{ij}) \tag{4}$$

$$Q_{Gi} - Q_{Di} = \sum_{j\in NB} |V_i||V_j||Y_{ij}| \sin(\delta_i - \delta_j - \theta_{ij}). \tag{5}$$

- Power generation limit constrains, as both upper and lower limits for generation of both active and reactive power at each bus, given by:

$$P_{Gi,min} \le P_{Gi} \le P_{Gi,max} \tag{6}$$

$$Q_{Gi,min} \le Q_{Gi} \le Q_{Gi,max}. \tag{7}$$

- Power consumption constrains, which give the limits of consumption capacity at the load buses, given by:

$$P_{Di,min} \le P_{Di} \le P_{Di,max} \tag{8}$$

$$Q_{Di,min} \le Q_{Di} \le Q_{Di,max}. \tag{9}$$

- Power factor constrains, where a constant power factor for the loads is considered, given by:

$$Q_{Di} = \gamma P_{Di} \tag{10}$$

where γ is given by:

$$\gamma = \frac{\sqrt{1 - pf_i^2}}{pf_i}. \tag{11}$$

- Bus voltage limit constrains, which impose a maximum and minimum bus voltage, given by:

$$V_{i,min} \le V_i \le V_{i,max}. \tag{12}$$

- Transmission limit constrains, which limit the maximum current or power that can be transferred on between two buses. In [5], this limit has been decided from thermal constrains and is given by:

$$I_k^2 \le I_{k,max}^2 \tag{13}$$

where I_k is depending on active power generation and generalized generation distribution factor (GGDF), given by:

$$I_k = \sum_{j\in NG} D_{kj} P_j \tag{14}$$

where D_{kj} is GGDF depending on power flow in line k and active power generation of generation j.

- The last constraint used in [5] is the active and reactive power loss constrains. Total active power generation (TPG), active power loss (TPL), and active power demand (TPD), as well as total reactive power generation (TQG), reactive power loss (TQL), and reactive power demand (TQD) are accounting for the coupling between active and reactive power spot price. The system power balance is given by:

$$TPG - TPL - TPD = 0 \tag{15}$$

$$TQG - TQL - TQD = 0 \tag{16}$$

The loss formulas considered in [5] are given by

$$TPL = \sum_{j=1}^{NB}\sum_{k=1}^{NB}\left[\alpha_{jk}(P_j P_k + Q_j Q_k) + \beta_{jk}(Q_j P_k - P_j Q_k)\right] \tag{17}$$

$$TQL = \sum_{j=1}^{NB}\sum_{k=1}^{NB}\left[\gamma_{jk}\left(P_jP_k + Q_jQ_k\right) + \xi_{jk}\left(Q_jP_k - P_jQ_k\right)\right] \quad (18)$$

where α, β, γ, and ξ are loss constants. See Appendix *A* for definitions.

C. Calculating Price of Electricity

At a particular time instant, price of active and reactive power respectively are given by:

$$\rho_i^p = \frac{\partial L}{\partial P_i} = MC_{pi} \quad (19)$$

$$\rho_i^q = \frac{\partial L}{\partial Q} = MC_{qi} \quad (20)$$

where P_i and Q_i are net injected active and reactive power respectively at bus i. Marginal costs MC_{pi} and MC_{qi} are given by the Langrangian multipliers found when minimizing Langrangian function given by objective function (2) and constrains (4)-(18). By applying the first order condition to the Langrangian, it results in,

$$\frac{\partial L}{\partial P_i} = \frac{\partial\left[\sum_{i\in NG} C_i(P_i) - \sum_{j\in NL} B_j(P_j)\right]}{\partial P_i} - \mu_{ipf}\frac{\sqrt{1-pf_i^2}}{pf_i} - MC_{pi} - \mu_{ip,min} + \mu_{ip,max} + \lambda_{pl}\left[1 - \frac{\partial(TPL)}{\partial P_i}\right] - \lambda_{ql}\frac{\partial(TQL)}{\partial P_i} = 0 \quad (21)$$

$$\frac{\partial L}{\partial Q_i} = \mu_{ipf} - MC_{Qi} - \mu_{iQ,min} + \mu_{iQ,max} - \lambda_{pl}\frac{\partial(TPL)}{\partial Q_i} + \lambda_{ql}\left[1 - \frac{\partial(TQL)}{\partial Q_i}\right] = 0 \quad (22)$$

and marginal costs are given by,

$$MC_{Pi} = \rho_i^P = \frac{\partial\left[\sum_{i\in NG} C_i(P_i) - \sum_{j\in NL} B_j(P_j)\right]}{\partial P_i} - \mu_{ipf}\frac{\sqrt{1-pf_i^2}}{pf_i} - \mu_{ip,min} + \mu_{ip,max} + \lambda_{pl}\left[1 - \frac{\partial(TPL)}{\partial P_i}\right] - \lambda_{ql}\frac{\partial(TQL)}{\partial P_i} \quad (23)$$

$$MC_{Qi} = \rho_i^Q = \mu_{ipf} - MC_{Qi} - \mu_{iQ,min} + \mu_{iQ,max} - \lambda_{pl}\frac{\partial(TPL)}{\partial Q_i} + \lambda_{ql}\left[1 - \frac{\partial(TQL)}{\partial Q_i}\right] \quad (24)$$

D. Study Results

Work carried out by Srivastava and Verma [5] using the modified IEEE 14 bus system has studied the impact of FACTS devices on the OPF. The system consists of FOUR generator buses (bus 1-4), 1 bus with a synchronous condenser (bus 5) and nine load buses (bus 6-14). All generators operate on their own cost functions, given by (1). Loads instead, have benefit functions, given by (3). The cost characteristics for the generators are found in Appendix *B*.

Three different cases were studied, the first is the OPF without FACTS devices, used as a reference. Two types of FACTS devices are considered; the TCSC and the SVC. For the TCSC, three levels of compensation were regarded; 20%, 40% and 60%, see Appendix *C* for further descriptions. Best placements for the FACTS devices were carried out by trial and error method which in the end corresponded in the minimum value of the objective function.

From the results, it is shown that the total active power generation increases slightly with use of FACTS, seen in Table II. At the same time, the total generation cost decreases. This is explained by the change of generation profile. The power generated by the more expensive generators at bus 2 and bus 3 has decreased, while the power production of the cheaper generator at bus 4 has increased a lot.

TABLE II
IMPACT OF OPF SOLUTION ON SYSTEM ACTIVE POWER PROFILE

	Base Case	TCSC in Line 20			SVC at Bus 9
		Case 1	Case 2	Case 3	
Total Active Power Generation (MW)	325.96	326.08	326.23	326.44	326.25
Total Generation Cost ($/h)	1586.3	1585.3	1584.4	1583.7	1581.6
Total Active Power Demand (MW)	311.36	311.57	311.79	312.05	312.84
Total Active Power Loss (MW)	14.6	14.51	14.44	14.39	13.41

Table III shows the active power generation at the generator buses for the different cases.

TABLE III
ACTIVE POWER GENERATION PATTERN (IN MW)

Bus No.	Base Case	TCSC in Line 20			SVC at Bus 9
		Case 1	Case 2	Case 3	
1	14.598	14.512	14.436	14.389	13.412
2	150.16	148.509	146.672	144.646	139.562
3	99.762	98.803	97.736	96.563	94.060
4	61.443	64.255	67.388	70.84	79.213

The minimization of cost is argued to be a positive outcome, since it helps to increase social welfare. It is also seen in Table II that the active power losses decreased with the use of FACTS. The FACTS devices help redistribute the line flow thus decreasing total system loss. In Table III, the reactive power generation, demand, losses and loss reduction for the different cases are seen. In all cases utilizing FACTS devices, the reactive power generation has decreased. It should be noted that according to [5], the SVC at bus 9 generates a large amount of reactive power, hence decreasing the need for reactive power transmission. As seen in Table IV, the SVC has helped decreasing reactive power losses with 87.57% over the base case.

TABLE IV
IMPACT OF OPF SOLUTION ON SYSTEM REACTIVE POWER PROFILE

	Base Case	TCSC in Line 20			SVC at Bus 9
		Case 1	Case 2	Case 3	
Reactive Power Generation (MVAr)	119.68	118.33	116.87	115.32	103.68
Reactive Power Demand (MVAr)	93.38	93.45	93.53	93.61	100.41
Reactive Power Loss (MVAr)	26.30	24.88	23.34	21.71	3.27
% Loss Reduction Over Base Case		5.40	11.25	17.45	87.57

The FACTS devices' effect on the spot price is seen in Fig. 7. The spot price for active power in $/MWh is calculated by

(23). As can be seen in Fig. 7, the price is reduced using FACTS.

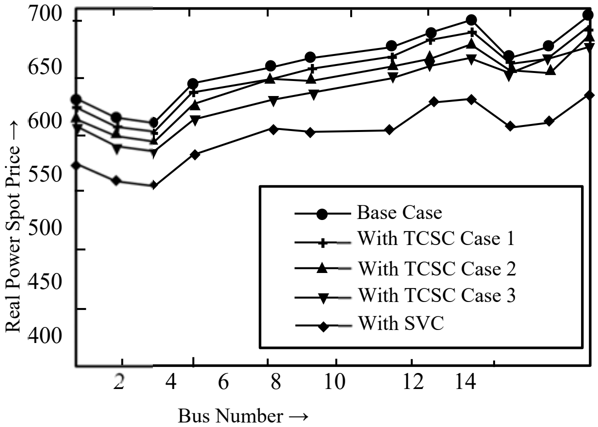

Fig. 7 Comparison of spot prices

Generation cost of reactive power at the generator buses is zero; the generators are not running on maximum capacity; hence they can increase the reactive power generation without any additional cost. Load buses with a power factor greater than 0.97 and at the SVC bus are found to have a reactive power spot price of zero. It is also found that reactive power spot price follows the same trend as active power spot price. In Table V, the FACTS cost allocation among the load buses is found.

TABLE V
FACTS COST ALLOCATION IN ¢/MVARH

Bus No.	TCSC in Line 20			SVC at Bus 9
	Case 1	Case 2	Case 3	
6	0.1341	0.2679	0.463	3.223
7	0.3793	0.7578	1.1492	5.9060
8	-	-	-	-
9	0.2063	0.4121	0.6247	4.3510
10	0.0726	0.1448	0.2193	1.1220
11	0.0977	0.1948	0.2949	1.5090
12	0.0812	0.1638	0.2480	1.2690
13	0.0726	0.1448	0.2193	1.1220
14	0.1252	0.2498	0.9782	0.9260

It is argued that the reduction in generation cost, seen by using the OPF, shows that the gains of using FACTS devices ARE enough to justify this cost. There is a great change in transmission prices for a system including FACTS, compared to one without.

V. CONCLUSION

This paper has described the general functionality of FACTS devices, as well as shown an example of how FACTS can be used to improve the grid stability and decrease transmission pricing, hence maximizing social welfare. It is discussed how FACTS can help to increase transmissible power, transient stability, and voltage and frequency stability.

From the example, derived from modified IEEE 14 bus system [5], it is shown that FACTS devices can help with greatly reducing losses of both active and reactive power. The reduction of reactive power losses is more than 5% for all cases tried. There is also a decrease in generation cost, which is of great benefit for a deregulated power market. FACTS devices also impact the spot prices, which are reduced.

When building/rebuilding a power system, the need for FACTS should be taken into consideration at an early stage of the development.

APPENDIX

A. Loss Coefficients

$$\alpha_{jk} = \frac{R_{jk}}{|V_j||V_k|}\cos(\delta_j - \delta_k)$$

$$\beta_{jk} = \frac{R_{jk}}{|V_j||V_k|}\sin(\delta_j - \delta_k)$$

$$\gamma_{jk} = \frac{X_{jk}}{|V_j||V_k|}\cos(\delta_j - \delta_k)$$

$$\xi_{jk} = \frac{X_{jk}}{|V_j||V_k|}\cos(\delta_j - \delta_k)$$

B. Generator Cost Characteristics

TABLE VI
GENERATOR COST CHARACTERISTICS

Generator No.	a_i ($/MWh/puMW)	b_i ($/MWh)	c_i ($/h)
1	1	8.5	5
2	3.4	25.5	9

C. Compensation and Costs of FACTS Devices

TABLE VII
COMPENSATION PERCENTAGE AND COSTS OF FACTS DEVICES

	% compensation	Setting (X_c)	Cost (US $/year)
Case 1	20	0.0696	9570
Case 2	40	0.1392	19 140
Case 3	60	0.2088	28 710

REFERENCES

[1] EWEA, "Wind in Power: 2012 European Statistics", February 2013.
[2] EWEA, "Pure Power – Wind Energy Scenarios up to 2030", 2008.
[3] Bharat Singh, S.N. Singh, "Wind Power Interconnection into the Power System: A Review of Grid Code Requirements", The Electricity Journal, Volume 22, Issue 5, pp. 54-63, June 2009.
[4] E. Muljadi, C.P. Butterfield, J. Chacon, H. Romanowitz, "Power Quality Aspects in a Wind Power Plant," IEEE Power Engineering Society General Meeting, 2006.
[5] S.C. Srivastava, R.K. Verma, "Impacts of FACTS Devices on Transmission Pricing in a De-regulated Electricity Market", International Conference on Electric Utility Deregulation and Restructuring and Power Technologies 2000, pp. 642 – 648, London 2000.
[6] S. Chanana, A. Kumar, "Effect of Optimally Located FACTS Devices on Active and Reactive Power Price in Deregulated Electricity Markets", Power India Conference 2006 IEEE, New Delhi, 2006.
[7] G. Li, M. Zhou, and Y. Gao, "Determination of Total Transfer Capability Incorporating FACTS Devices in Power Markets," in Proc of IEEE PEDS Conf., pp. 1327-1332, 2005.
[8] damczyk, A.; Teodorescu, R.; Mukerjee, R.N.; Rodriguez, P" ;.Overview of FACTS devices for wind power plants directly connected to the transmission network", International Symposium on Industrial Electronics, pp. 3742 – 3748, 2010.
[9] Hingorani, N.; Gyugyi, L "Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems" Wiley-IEEE Press, 2000.
[10] M.A. Kamarposhti, and M Alinezhad "Comparison of SVC and

STATCOM in Static Voltage Stability Margin Enhancement" World Academy of Science, Engineering and Technology 26 2009.
[11] M.E. Baran, S. Teleke, L. Anderson, S. Bhattacharya, A. Huang, S. Atcitty, "STATCOM with Energy Storage for Smoothing Intermittent Wind Farm Power", *IEEE/PES*, 2008.
[12] N. G. Hingorani, "FACTS Technology - State of the Art, Current Challenges and the Future Prospects," *2007 IEEE Power Engineering Society General Meeting*, 2007, pp. 1-4, doi: 10.1109/PES.2007.386032.

Abdulrahman M Alsuhaibani received his B.Sc (Honors) in Electrical Engineering from King Fahd University Of Petroleum And Minerals, Saudi Arabi in 2012; M.Sc. Electric Power Engineering from Chalmers University of Technology, Sweden 2014. Abdulrahman worked as Research & Development Engineer at ABB FACTS Sweden for one year. He joined Saudi Aramco in 2015 as an Electrical Engineer in the Power Systems Engineering Department.
Abdualrahman.alsuhaibani@aramco.com

Martin Macken obtained his M.Sc. in Electric Power Engineering from Chalmers University of Technology, Sweden, in 2014. Martin has since worked in the automotive industry, specializing in topics related to automotive functional and system safety.
martinmacken82@gmail.com