Steady State and Dynamic Performance of Shunt FACTS Devices

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Abstract

Nowadays, the electronic switches are the emergent technology to control the power flow and line losses. In this way, the steady state and dynamic stability of the system is enhanced. In this paper, we have considered the Pakistan National Grid network which has a lot of congestion management issues that leads to enrichment in power operational cost. These issues are becoming frequent due to integration of renewable energy resources. This integration is significantly raised because of increased load demand in the system. However, one of the cost-effective solution to this problem is shunt compensation in transmission lines. It increases the transfer capability of transmission lines of existing transmission lines instead of installing new lines in the network. It significantly enhances the stability performances at a lower cost and has shorter installation time. This paper deals with the dynamic modelling of shunt FACTS devices such as SVC, STATCOM in congested QESCO network to alleviate the issues of congestion in this network. This study is carried out in PSS/E tool and comparison of SVC and STATCOM is presented. The simulation results dictated that STATCOM is prior to SVC and it provides the reliable and encouraging results.

Keywords

Flexible AC transmission systems (FACTS), Power system simulation for engineers (PSS/E) tool, Static volt-ampere reactive (VAR) compensator (SVC), Static compensator (STATCOM)

I. Introduction

In an economically stressed situation of the world, the cost-effective methodology of the system is required. In this perspective of electrical industry, uninterruptable power supply to the consumers is today era need so, the new emerging techniques are developed which are economic as well as environment friendly. For this purpose, the renewable energy sources are introduced in the conventional networks such as wind and solar technologies. These emerging technologies played a superficial effect in the existing network according to need. In Pakistan, the environment is very feasible for these wind and solar energy technologies. The coastal area is used for the wind power generation and the desert is used for the solar power generation. Some mega projects of power generation are under construction using these technologies. Due to the old ones conventional networks, the issues of congestion and power stability in transmission lines is raised.

Network or transmission congestion is one of the technical challenges in context of power system operation. The transmission congestion occurs when there is insufficient transmission capacity of simultaneously accommodate all constraints. The constraints such as these limits of lines, voltage profile, thermal limits, overloading and generation integration reduces the quality of transmission.

The literature review revealed that many methodologies are adopted to meet the challenges of congestion. These methods are cost and not cost free means, given in table.

Table1. Remedies of Congestion

Cost-Free Means	•Removal of old lines •Operation of transformer taps / phase shifter •FACTS [1]
Not Cost-Free Means	•Re-dispatching of generation amounts •Prioritization and curtailment of load [2]

Due to the emergent technology of electronic switches, in this paper, we have focused on Flexible AC Transmission System (FACTS) devices for the congestion management and power stability of the network. It controls the power flow by compensating the reactive power and provides the steady state and dynamic stability to the network.

II. Facts Devices

Basic types of FACTS devices

Flexible AC transmission systems are used to control the power system by changing voltage, impedance and angle of the network. The technology developments of FACTS are classified into three generation [3];

1st Generation

The function of the FACTS devices is controlled by the mechanically switched components. The response time of these devices are breaker delay. It gives slow VARs in the system.

2nd Generation

The function of the FACTS devices is controlled by the thyristor-controlled components. The response time of these devices are 2-3 cycles. It provides fast VARs in the system.

3rd Generation

The function of the FACTS devices is controlled by the voltage source convertor (VSC) technology, gate turn off (GTO), insulator gate bipolar transistor (IGBT) and integrated gate commutated transistor (IGCT) switches. The response time of these devices are 1-2 cycles. It delivers fast VARs in the system.

Applications of FACTS Controllers

These controllers are mainly classified into four categories of series, shunt, series-series and series-shunt controllers. It has numerous applications in the power system e.g.;

- Control of power flow
- Increase the loading capacity of lines
- Improve transient stability limit during contingencies
- Reduce the short-circuit power level
- Compensate the reactive power
- Improve dynamic voltage stability
- Control loop power flow
- Damp power oscillation
- Mitigate voltage unbalance due to single-phase loads

III.Basic Mechanism Of Shunt Facts Controller

Shunt FACTS controllers (SVC and STATCOM) are used to control the reactive power according to requirement of the network. It is installed in parallel midway of transmission lines to provide the VAR compensation which is being used as voltage regulation to prevent from voltage instability. In this way, loading capacity, the dynamic and transient stability and power flow of the network is increased.

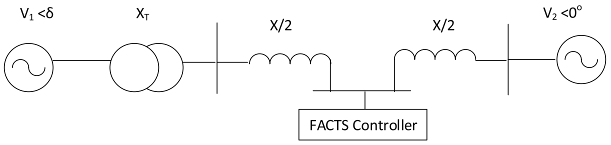


Fig 1. Power system model with shunt FACTS controller [4]

1. Reactive compensation by Shunt FACTS Controller

In usual approximation, power transfer equation becomes;

$$P(t) = \frac{V_1 V_2}{X_d + X_T + X_E} \sin\delta\,(t) \qquad (1)$$

where P is power, V_1 is sending end voltages, V_2 is receiving end voltages, X_d is generator reactance, X_T is transformer reactance, X_E is effective line reactance, δ is angle between sending and receiving ends.

When the controller is added in the line then the effective line reactance is modulated by susceptance of controller and effective voltage (V_E) becomes;

$$V_E = \frac{V_1}{\frac{X}{2}(B_L(t) - B_C) + 1} \qquad (2)$$

$$V_E = \frac{X}{2} + \frac{\frac{X}{2}}{\frac{X}{2}(B_L(t) - B_C) + 1} \qquad (3)$$

Where $B_L(t)$ is susceptance of inductor while B_C is susceptance of capacitor in the controller.
Thus, the power transfer equation becomes;

$$P(t) = \frac{V_1 V_2}{X_{ds}\,(1-K)} \sin\delta\,(t) \qquad (4)$$

where X_{ds} is the total reactance and the coefficient k defined the degree of compensation.

$$K = \frac{B(t)}{X}\left\{\frac{X}{2}\left(X_a + X_T + \frac{X}{2}\right)\right\} \qquad (5)$$

It has direct relationship to power-angle (P-δ) curve which is controlled by voltage (V), angle between voltages (δ) and impedance (Z). These variables have direct impact on power system performance which is illustrated by given Fig.

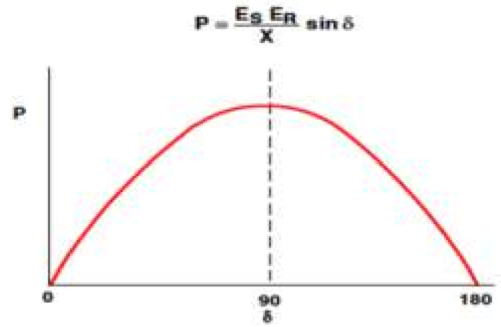


Fig 2. Controllability of power system [5]

From the above relationship, there are two cases;

i. k > 0 if B(t) > 0

In this case, the effective line reactance is reduced then P-δ curve is enlarged. In this way, the stability margin is improved.

ii. k < 0 if B(t) < 0

In this case, the effective line reactance is increased then P-δ curve is reduced. In this way, the stability margin is reduced.

In case of SVC, $B(t) = B_{SVC}(t)$, and in case of STATCOM, $B(t) = B_Q(t)$.

2. Midpoint Regulation

When the controller is added at the midway point, the reactance of line is distributed. In this way, the reactive power exchanges within transmission lines while the real power remains same in the line. Thus, the real and reactive powers are;

$$P = 2\frac{V^2}{X} Sin\frac{\delta}{4} \qquad (6)$$

$$Q = VI\,sin\frac{\delta}{4} = 4\frac{V^2}{x}\left(1 - cos\frac{\delta}{4}\right) \qquad (7)$$

3. Voltage Stability at the End of Line

Reactive shunt compensation is used to provide the voltage regulation at load ends in case of generation, line outage and impaired voltage system. It contributes the voltage support in the system and prevent from voltage instability.

4. Transient Stability Improvement

Shunt compensation is used to control the power flow and enhances the transient stability which is evaluated by equal area criterion. This criterion is illustrated by the power-angle (P-δ) curve that is disturbed by the fault in the system.

5. Power Damping Oscillations

In an undamped system, the minor disturbance can cause a machine angle to oscillate its steady state value. Thus, the shunt compensation is provided to counteract the accelerating and deaccelerating swings in the disturbed system [6].

I. Dynamic Modelling of Shunt Facts Controller

Dynamic Modelling of SVC and STATCOM is illustrated in this section.

1. Dynamic Modelling of SVC

Static VAR compensator is an electrical device to control the voltage by controlling reactive power of the transmission network. It is consisted of FC that acts as harmonic filter to provide the reactive power supply and TCR which is thyristor-controlled reactor series to inductor without gate turn off capability.

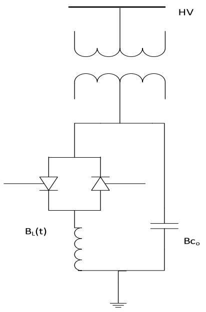


Fig 3. Basic configuration of SVC [8]

The dynamic model can be expressed as [7];

$$B_L(t) = \frac{1}{TB}(-B_L(t)+B_{LO}+K_B\mu_L(t)) \qquad (8)$$

$$B_{SVC}(t) = B_c(t) - B_L(t) \qquad (9)$$

$$\nabla B(t) = B_L(t) - B_{LO}(t) \qquad (10)$$

$$B_{SVC}(t) = B_c(t) - (B_{LO})\Delta B_L(t)) \qquad (11)$$

where $B_L(t)$ is susceptance of TCR, T_B is time constant, K_B is gain of control system, μ_B is input of control system, B_{Lo} is susceptance of TCR at operating point, while the B_{Co} is susceptance of FC and $B_{SVC}(t)$ is the susceptance of SVC.

If the reactive load of the power system is capacitive (leading), SVC consumes the reactive load from the system and lowers the voltage. In case of inductive (lagging) condition, SVC produces the reactive power by switching of capacitor banks and higher the voltage. In this way, the P-δ curve improves.

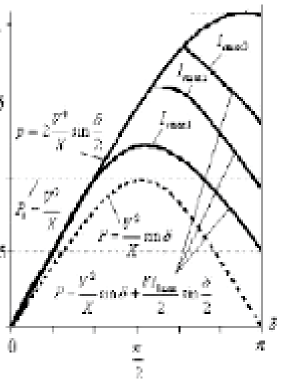


Fig 4. P-δ curve of SVC [8]

SVC are cheaper, reliable and higher capacity. It has no gate turn-off capability. It is used to control the voltage, voltage stability, VAR compensation, damping oscillation, transient and dynamic stabilities.

2. Dynamic Modelling of STATCOM

A shunt connected device to compensate the capacitive or inductive load based on voltage sourced or current sourced converter. It is consisted of thyristor-controlled reactor parallel to capacitor or inductor independent of ac voltages. It has fast switching time due to IGBTs and provides better reactive power support at low ac voltages.

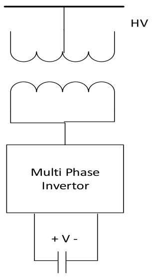


Fig 5. Basic configuration of STATCOM [8]

The dynamic model of STATCOM is expressed as [7];

$$B_Q(t) = \frac{i_Q(t)}{V_Q(t)} \qquad (12)$$

$$i_Q(t) = \frac{1}{T_Q}(-i_Q(t)+i_{QO}+K_Q\mu_Q(t)) \qquad (13)$$

Where $B_Q(t)$ is susceptance of STATCOM, $I_Q(t)$ is reactive current, $V_Q(t)$ is the voltage to which STATCOM is connected, K_Q is gain of control system, μ_Q is input of control system, $I_{Qo}(t)$ reactive output current at operating point of STATCOM.

The reactive power from the STATCOM is deceases linearly with the ac voltage due to direct proportions. The reactive current is possibly controlled by δ, by which convertor output voltage leads by bus voltage. The positive value of δ leads to inductive region while the negative value leads to capacitive region. In this way, the P-δ curve improves.

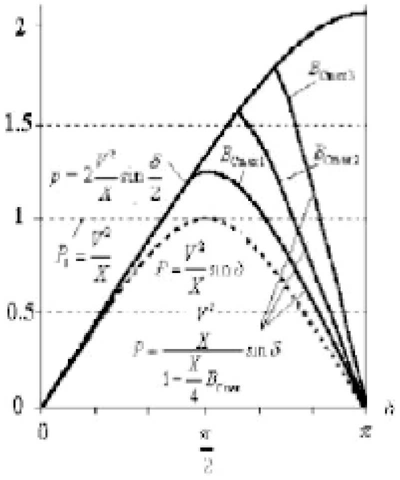


Fig 6. P-δ curve of STATCOM [8]

It have higher losses and expansive device. It is used to control the voltage, voltage stability, VAR compensation, damping oscillation.

V. Dynamic Modelling of Shunt Facts Controller In PSS/E

Dynamic modelling of SVC and STATCOM in PSS/E tool is expressed as;

1. Dynamic Modelling of SVC in PSS/E

SVC is the shunt controller without any controlling switch. In this paper, CSVGN1 model of SVC is implemented which has 300 MVAR rating. It provides the reactive power in case of inductive load and consumes reactive power in case of capacitive load. The SCR switch is controlled by the auxiliary signal. It controls the voltage and provides transient and dynamic stability [9-10].

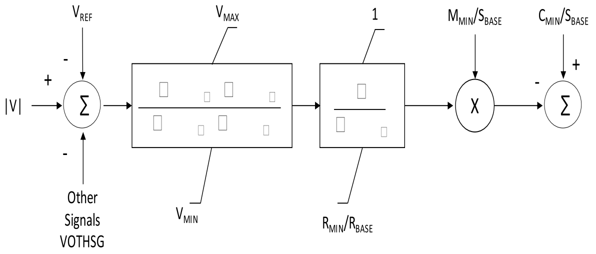


Fig 7. Control diagram of SVC [11]

The description of constants, used in control diagram, are given in Table 2.

Table 2. Parameters of SVC

No.	Value	Parameters
1	0	PGEN
2	0	QGEN
3	-9999	PMAX
4	450	PMIN
5	450	QMAX
6	-50	QMIN
7	500	MBASE
8	9999	XSOURSE

2. Dynamic Modelling of STATCOM in PSS/E

Static condenser (STATCON) or static compensator (STATCOM) is a shunt capacitor that is voltage source convertor with thyristor-controlled switch. It is used to control the reactive power that has direct relation with the voltage. The voltage is synthesized behind the convertor transformer reactance. For the reactive control, the synthesized voltage is kept in phase with the terminal voltage. In ideal condition, the capacitor remains charged because there is no exchange of active power with the network. In practical network, the convertor has losses and a trend of discharging of capacitor is followed. For charging of capacitor, the voltage is controlled and lag by the terminal voltage, thus the active power flow between the system and condenser is maintained. In this way, the voltage of the capacitor is controlled which determine the internal voltage that control the reactive power exchange with the network.

In this paper, CSTCNT models of STATCOM is modeled which has 150 MVAR rating. It delivers the reactive power whereas the active power is considered as negligible. STATCOM is modeled as FACTS device and has no active output power. [9-10].

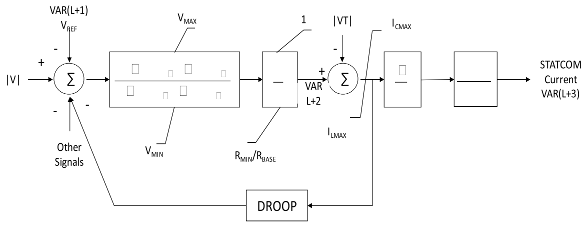


Fig 8. Control diagram of STATCOM (CSTCNT) [11]

The description of constants, used in control diagram, re given in Table 3.

Table 3. Parameters of STATCOM

No.	Value	Parameters
1	1	DEVIE MODLE
2	0	TERMINAL BUS
3	NORMAL	CONTROL MODE
4	0	P SET-POINT
5	0	Q SET-POINT
6	1.02	VS END-SETPOINT
7	64	SHUNT MAX
8	100	RMPCT
9	0	BRIDGE MAX
10	1.1	V TERM MAX
11	0.9	V TERM MIN
12	1	V SERIES MAX
13	64	I SERIES MAX
14	0.05	DUMMY SERIES X
15	VS ENDING	V SERIES REFERENCE

VI.Test Case Scenerio

Pakistan National Grid network is comprised of numerous generators, busses, lines, transformers, and variety of loads. As the old existing network, the system becomes more overloaded due to generation integration and increased demand of power. In this way, the issues of stability, loss and congestion are raised. For this purpose, new transmission lines are needed to meet the criteria of demanded power. The proposed strategies of new transmission lines are not the right way to meet this challenge. Thus, many methodologies are adopted to mitigate these issues. In this paper, we have focused on FACTS devices to address these issues of stability and congestion.

For a test case, the network of National Grid of Pakistan is modeled in PSS/E tool considering all parameters of the system. This network has large integration of renewable energy sources such as 784 MW of wind energy and 400 MW of solar energy. These renewable energy sources are also modelled, to see the impact of these energy sources in the network which are shown in Figs. 9-10.

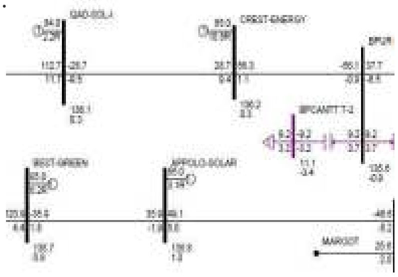


Fig 9. Solar power plants in Pakistan National Grid

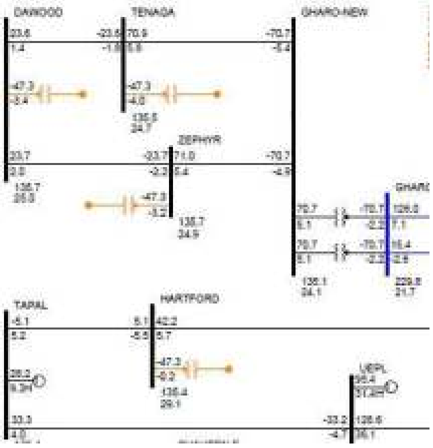


Fig 10. Wind power plants in Pakistan National Grid

This above generation integration as well as load demand and disturbed stability profiles made the high ration congestion issues in the system. The stability analysis is analyzed using PSS/E tool and identified the most critical regions in the network. So, after the critical observations, QESCO network is selected as a test case in this paper. We have observed that the lines of this region are over loaded which are clearly viewed in PSS/E tool, as shown in red and pink color which showed the heavily loaded lines and highly unstable busses respectively.

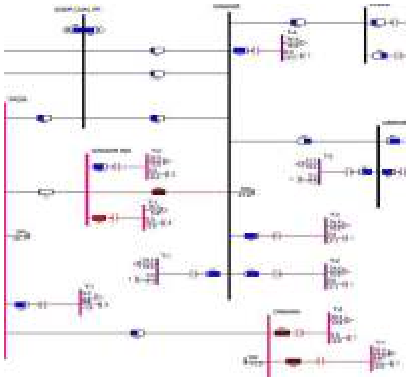


Fig 11. Loading of lines

In case of contingency, when the line is tripped due to fault or switching from Gwadar to Gwadar Coal then the lines are more heavily loaded and does not maintain their stable state as shown in red color.

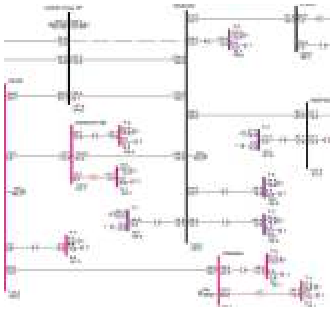


Fig 12. Loading of lines in case of line tripping

VII. Stability Studies

The condition of being stable even after the disturbance in the network is the major need of the power system. The disturbance is due to the switching, faults and outage of the lines or equipment. These disturbances have a great impact on the voltage, frequency, and rotor angle profiles. Power system stability is mainly classified into rotor angle, frequency and voltage stability and further classified into short and long-term phenomenon.

Methodology of Stability Study

The system of being stable even after the disturbance, the following disturbances is studied;

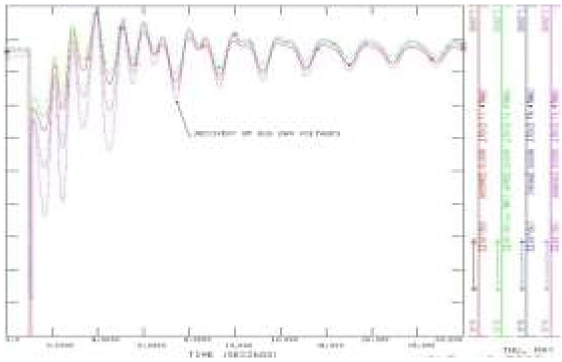
- The severe three-phase balanced fault as per Grid Code of National Electric Power Regulatory Authority (NEPRA) is occurred on the bus bar at critical locations. It remains for the 5 cycles.
- The three-phase fault will be backed up in 9 cycles after fault initiation.
- Contingency is applied for unbalancing of system and remains for 20 cycles.

In this scenario, the waveforms of voltage, frequency, power flows and rotor angle of given bus and nearby busses are plotted against the time axis in PSS/E to perceive the effect of disturbance in the network.

- The voltage waveforms of Gwadar bus bar and nearby busses are plotted in red, green, blue and pink colors.
- The frequency waveform of Gwadar bus bar is plotted in red color.
- The power flows waveform of Gwadar bus bars are plotted in red and green colors.
- The rotor angle waveform of Gwadar bus bar is plotted in red color compared to rotor angle of Tarbela generator.

a. Voltage Waveform

At the time of fault, the reactive power of the system becomes unbalanced and results in disturbed voltage profile of the bus bars. This disturbed voltage profile does not maintain the stable state even after the fault clearance.



b. Frequency Waveform

At the time of fault, the frequency of Gwadar bus bar has more excursions in the system and exceed the rated boundary of plot book due to no restoration in system generation and load in the system. It does not approach the stable state in 20 cycles after the fault clearance.

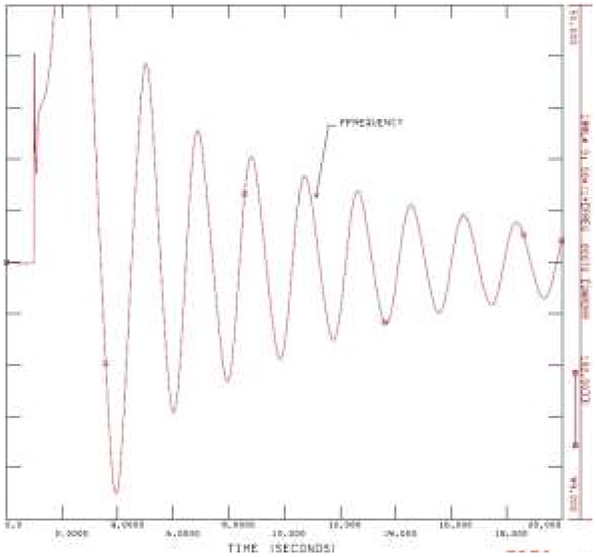


Fig 13 (b). Frequency waveform

c. Power Flow Waveform

The one circuit of Gwadar to Gwadar Coal is switched thus the flow is carried out from the another circuit that is parallel to it. At the time of fault, the loss in active power causes of drooping MW flow whereas increase in reactive power causes of increasing MVAR flow. Both MW and MVAR power flows do not approach the stable state within the 20 cycles.

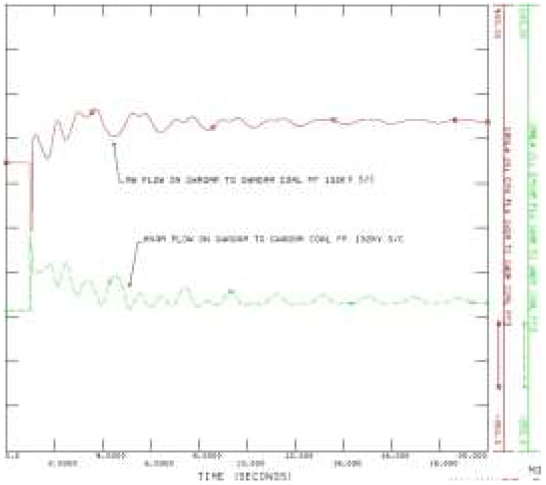


Fig 13 (c). Power flow waveform

d. Angle Waveform

At the time of fault, the loss of synchronism between electromagnetic and mechanical torques causes of disturbed rotor angle profile of generator. It does not approach the stable state even after the fault clearance.

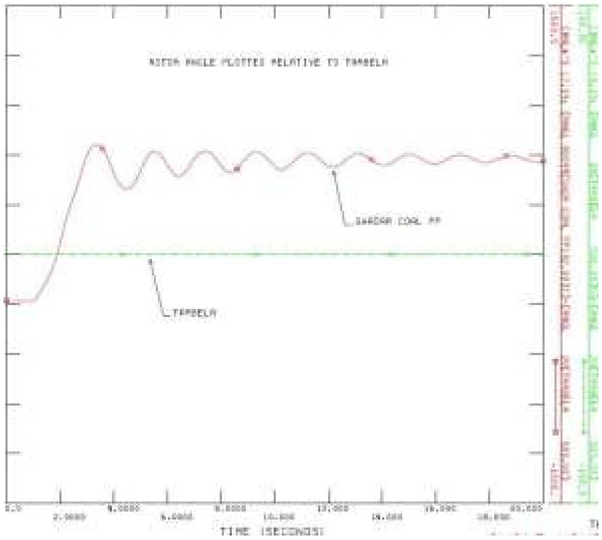


Fig 13 (d). Angle waveform

VII. Implementation of Facts Devices

Congestion includes both MW and MVAR loading. The traditional solution to MW loading is the installation of a new circuit while the solution to MVAR loading is usually installation of capacitors. However, these are not feasible or reliable solutions due to either high cost (in case of stringing new circuits) or due to nonexistent support during fault conditions (in case adding capacitors).

In the selected critical region, Gwadar is located in a remote region as far as the electrical network is concerned. There is no local generation, so it needs to draw power from the National Grid, which passes hundreds of kilometers away from Gwadar. The long transmission lines needed to transport this power need to carry high amounts of reactive power, which causes significant MVAR loading in the network. Again, the traditional solution to this scenario is the addition of transmission lines. However, this is an expensive solution, especially since hundreds of kilometers worth of transmission towers, insulators and conductors are involved. So, SVC and STATCOM are proposed for providing MVARs in the system.

In case of poor damping or oscillations in system recovery after the disturbance is cleared in the simulations. The remedial solutions are proposed to install the FACTS devices and establish the proposed solutions through simulations.

In this paper, we have selected the Gwadar bus bar of QESCO network for the implementation of shunt compensation in the system which is the most significant and critical bus bar of the network.

A. Stability Studies with SVC

The loading of the lines are relieved by installation of SVC. Therefore, no one line is presented in red color which is shown in given figure.

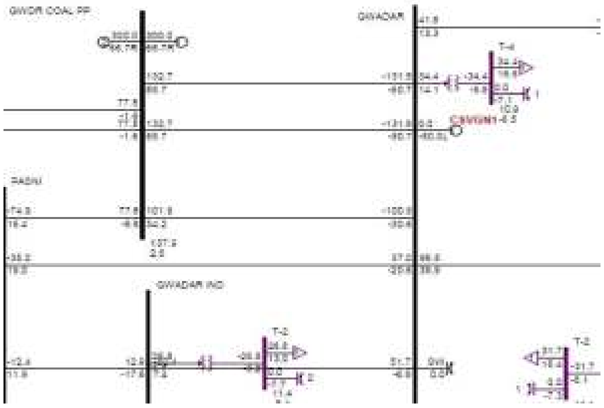


Fig 14. QESCO network with SVC

a. Voltage Waveform with SVC

With the installation of SVC, the reactive power of the system comes to be balanced state, results in the voltages of Gwadar, Pasni, Turbat and Gwadar Coal bus bars are collapse at the time of fault but they are recovered sooner in 8 cycles.

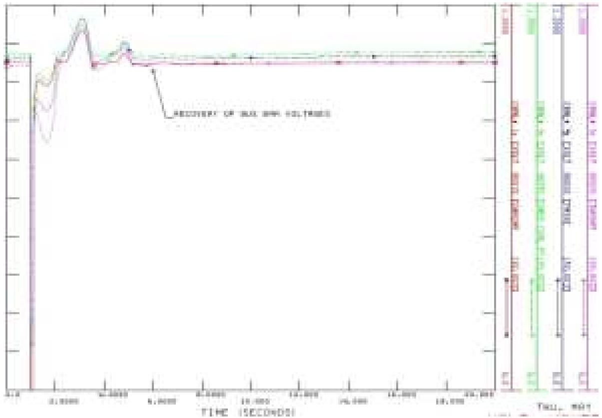


Fig 15 (a). Voltage waveform with SVC

b. Frequency Waveform with SVC

With the installation of SVC, the frequency reaches its peak value within its plot book, at the time of fault. Then it is recovered after 4 peaks within 8 cycles due to restoration in system generation and load.

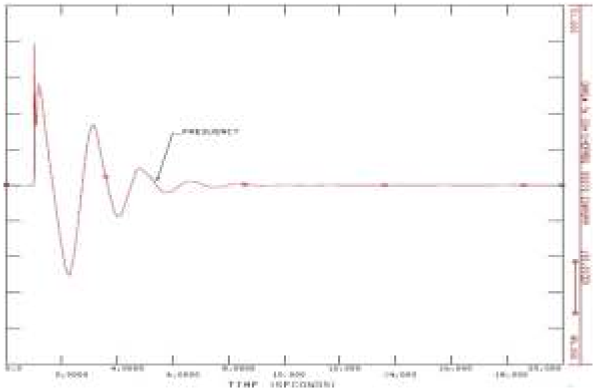


Fig 15 (b). Frequency waveform with SVC

c. Power Flow Waveform with SVC

The one circuit of Gwadar to Gwadar Coal is switched thus the flow is carried out from the another circuit that is parallel to it. At the time of fault, the MW flow is drops out and its oscillation remains for 6 cycles whereas the MVAR flow reaches its peak value and approached the stable state within the 8 cycles.

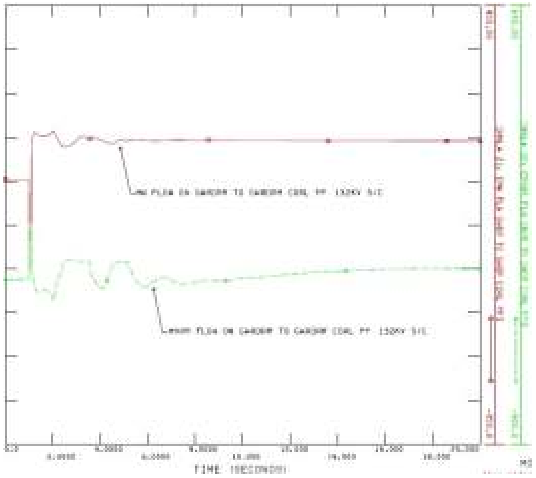


Fig 15 (c). Power flow waveform with SVC

d. Angle Waveform with SVC

With the installation of SVC, rotor angle reaches its maximum peak and being synchronized within 8 cycles after the fault clearance.

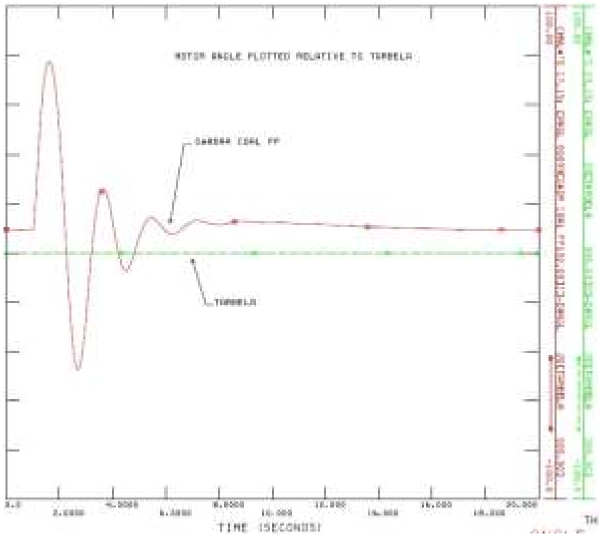


Fig 15 (d). Angle waveform with SVC

e. SVC Output Waveform

SVC provides the current when the system stability drops due to fault occurrence. At the time of fault, SVC delivers current in the system until the system achieved its stable state.

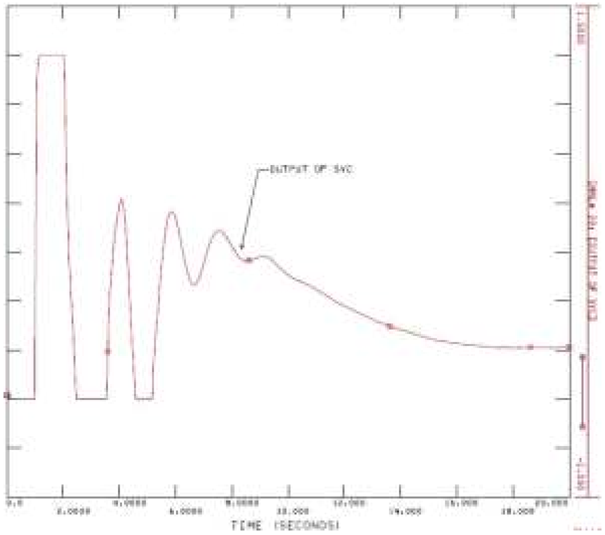


Fig 15 (e). Output waveform of SVC

B. Stability Studies with STATCOM

The loading of the lines are relieved by installation of STATCOM which is shown in given figure.

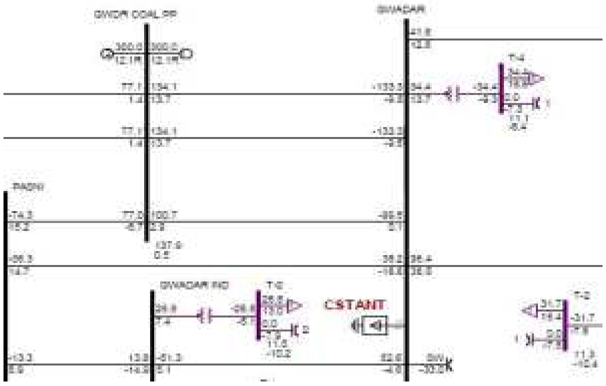


Fig 16. QESCO Network with STATCOM(CSTCNT)

a. Voltage Waveform with STATCOM

The voltages of all bus bars near the faulted bus recover soon after fault clearance with the help of STATCOM, it provides reactive power balancing in the network within 6.5 cycles.

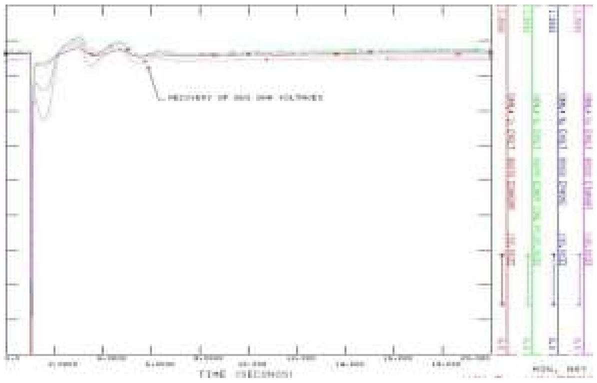


Fig 17 (a). Voltage waveform with STATCOM

b. Frequency Waveform with STATCOM

With the installation of STATCOM, the frequency reaches its peak value within its plot book, at the time of fault. Then it is recovered after 4 peaks within 6.5 cycles due to restoration of system generation and load.

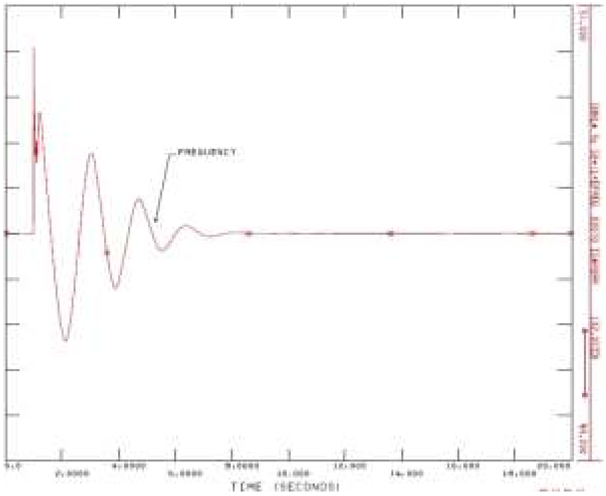


Fig17 (b). Frequency waveform with STATCOM

c. Power FlowWaveform with STATCOM

At the time of fault, the MW flow is drops out and its oscillation remains for 4 cycles whereas the MVAR flow reaches its peak value and approached the stable state within the 6 cycles.

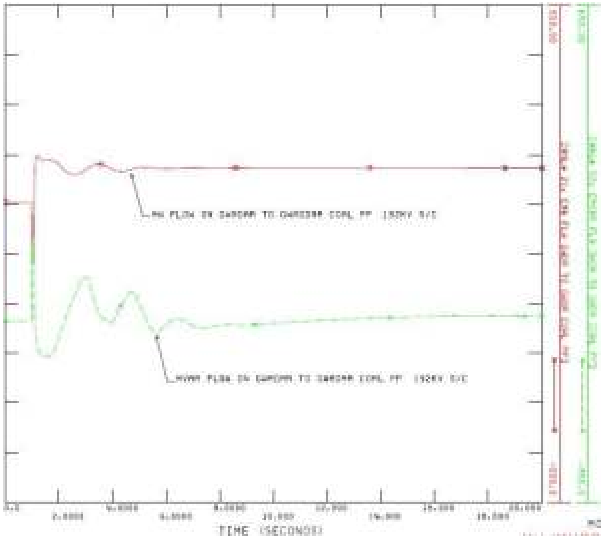


Fig 17 (c). Power Flow waveform with STATCOM

d. Angle Waveform with STATCOM

The first swing has a value within the boundry of plot area. With the installation of STATCOM, the synchronism between electromagnetic and mechanical torques attained within the 8 cycles.

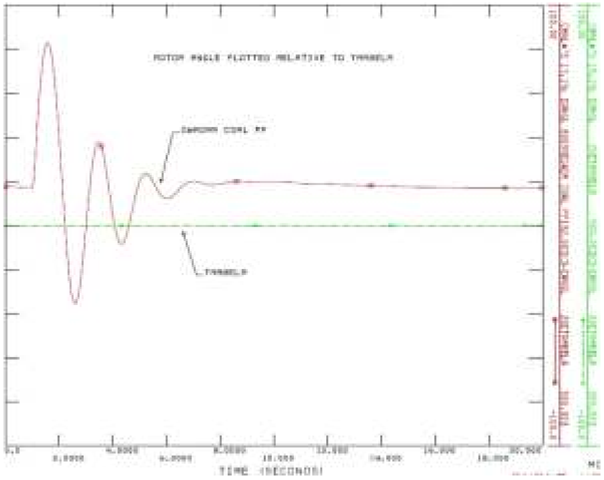


Fig 17 (d). Angle waveform with STATCOM

e. STATCOM Output current waveform

STATCOM provides the current when the sytem stability drops due to fault occurrence. After the fault cleraence, STATCOM delivers current untill the system achieved its stable state.

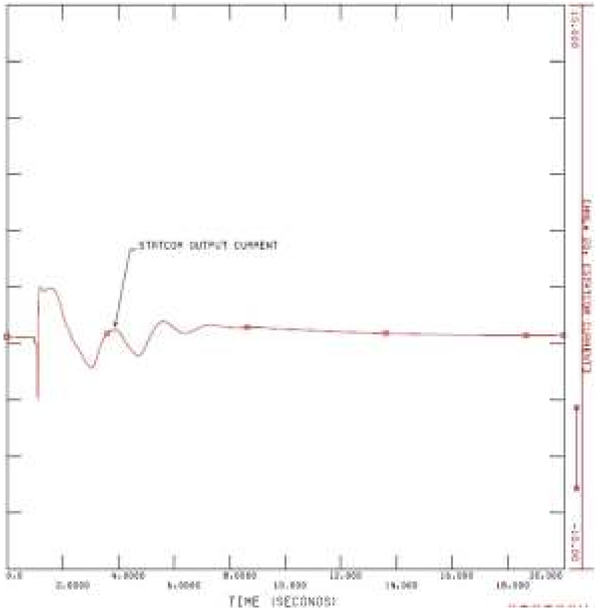


Fig 17 (e). Output waveform of STATCOM

IX. Comparison of SVC and STATCOM

In this paper, two shunt FACTS devices are presented which has its own pros and cons. The dynamic modelling and simulation result that STATCOM is prior to SVC.

STATCOM provides the first swing stability enhancement by controlling the reactive power in the transmission lines.
It has fast switching time due to IGBTs switches.
It improved the phase angle and voltage magnitude.
It has reduced size and need low MVAR rating.
It is slightly costly [12-13].

Table 4. Comparison of SVC and STATCOM

FACTS	Load Flow Control	Voltage Control	Transient Stability	Dynamic Stability	Cost / Kvar ($)
SVC	✓	✓✓✓	✓	✓✓	40-70
STAT-COM	✓✓	✓✓✓	✓✓	✓✓✓	55-70

X. Results and Discussion

The issues of congestion become more frequent due to disturbed voltage profile, generation integration and load demand. These issues are generally observed in QESCO which is selected after the critical study of Pakistan National Grid in PSS/E tool that is highly unstable and over loaded. In PSS/E tool, the simulations are performed which showed that without the insertion of FACTS, voltage, frequency, load flows and angle profiles are disturbed due to unbalanced reactive power, sub-synchronous reactance and loss of synchronism.

As a remedial solution to these disturbed profiles is to insert the shunt FACTS device on Gwadar bus bar. In this paper, SVC and STATCOM is installed in the network. It provides the reactive power compensation and causes of reactive power balancing, restoration between generation and load with less losses, load balancing and synchronism between electromagnetic and mechanical torque. Thus, the voltage, frequency, load flows and angle profiles are maintained and in this way, the capability of transmission lines is increased. The steady state, dynamic and transient stability of the system is enhanced and losses are reduced in the network. It also provides the cost effective solution as compared to laid a new transmission line in the network. When a new transmission line is laid, it includes the material cost (tower, conductor, insulator strings, overhead line and spacers), installation cost (tower, conductor, insulator strings, overhead line and spacers), right of way cost, line bay cost, civil works cost and engineering cost for constructing the lines. These costs are much larger than the cost of FACTS devices. That is why, we preferred these devices specially STATCOM due to superior quality as compared to SVC, for relieving the issues of stability and congestion.

XI. Conclusions

In this paper, power flow and dynamic stability enhancement using shunt FACTS devices is presented. For an analysis, QESCO network of Pakistan National Grid is selected for the installation of FACTS devices. This system is modelled in PSS/E tool and simulation results indicated that system is not being stable without the reactive line compensation. Therefore, the reactive compensation has been applied using shunt devices to support the system. The plotted results show that the voltage, frequency, and power flows of the circuit settled within the rated capacities and enhanced the transfer capability of lines. Significantly, the dynamic stability analysis shows that the reliability of existing National Grid is enhanced with the shunt compensation using SVC and STATCOM. It improves the dynamic stability by providing the reactance in lines and also increases the power flow capacity of TLs. In this way, it provides the reactive power support to the system.

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