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# Simulation and Field Study of Static Var Compensator in High Wind Power Penetration Area using LFA –Western Rajasthan

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**Abstract:** Wind generation is currently the leading form of new renewable generation in the world. The amount of electricity being generated by wind turbines is increasing continuously, day by day and wind power penetration in a power system is spreading in an uncontrollable way. The power generation through wind energy totally dependent on the flow of the wind due to uncertainty and randomness of wind flow, the generation of power is quite fluctuating in nature and large-scale wind farms may cause significant impact to the stability and power system safety. Wind power has significant variation over shorter time periods. With large variations in wind generation, reactive power flows on transmission lines, transmission loss, voltage and power factor are major attributes which having a major impact on power system performance. The shunt connected FACT devices such as a static var compensator (SVC), which is dynamic reactive power compensator whose reactive power output depends upon the system voltage, is adopted for control of bus voltage magnitude and to bring the system near to unity power factor, thus for mitigation of reactive power. This paper presents the finalization of SVC rating in the power system having high wind power generation, the SVC and system performance with the increase of wind power penetration and static /dynamic var mitigation with the change of the location of SVC too far off the main wind bus. For analysis Rajasthan Grid (India), comprising of different voltage level with high wind power penetration in the Western part selected. All analysis is anchored with load flow analysis, by using Mi-Power system analysis software. The method used is quite effective to give the need of reactive power mitigation device applicability, power system strengthening requirement in view of high wind power penetration under actual field conditions.

**Keywords:** Static Var Compensator; Load Flow Analysis; Wind Power; Voltage Stability, Dynamic Stability, Wind Power Penetration.

## I. INTRODUCTION

Wind energy is playing a vital role in world energy markets and wind energy has been focused as a clean and endless energy sources, its penetration level has been increased throughout the globe. It is most attractive and effective renewable source of energy and can be smoothly integrated into the power system by adopting proper control strategies. The wind turbine prime mover, wind, is uncontrollable which makes it different from conventional generation. Therefore, it becomes very important to carry out investigations on the dynamic behavior of wind power generating systems. Power system assumed to be more strengthened capacity wise due to addition of generation of wind power day by day and thus become environmentally friendly by eliminating conventional power pollution creating, bi-products. Also the active power supply mainly depends upon the potential of the wind power produced and wind turbine generator design. The reactive power demand on other hand depends upon conversion devices and recovered power quality fed to the grid.[1] At the same time, long electrical distance from the load center, unpredictable behavior of wind, and the generation of power with wind machine is not firm, and reactive power mitigation and voltage support is required. Reactive power control is important because all wind farm technology do no not have the same capability. The voltage stability in the power system is high on the stack with the increase of wind power penetration in the system and act as a limiting factor for wind power, which can be installed. The voltage quality of a wind turbine may be assessed in terms of the parameters, steady state voltage under continuous production of power, flicker during operation, flicker due to switching and voltage fluctuations. The short circuit power level in a given point in the electrical network represents the system strength of the concern power system.

Reactive power control is important because all wind farm technology do no not have the same capability. The wind farm is usually installed in remote areas; therefore the reactive power has to be transported over long distances resulting in power loss. The wind farm has to provide

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reactive power control in response to voltage variation [2-3]. The reactive power control requirement is related to, characteristic of grid because the influence of injection of reactive power in various voltage levels depends on network short circuit capacity and impedance. The reactive power compensation becomes utmost requirements for wind farm operation and contribution to the power grid, uncompensated reactive power cause stress on the hosting grid as well as casting effects. In general compensation of reactive power of wind farms have the main purpose to keep the voltage of a wind farm at the appropriate level and ensure loss minimization in transferring power to the main grid also to meet with connection requirement related to the grid code and reactive power exchange. The basic device for reactive power compensation is Under Load Tap Changer (ULTC) of the station transformer. If the action of ULTC does not comply grid requirement than other reactive power compensator devices, static capacitors, FACTS devices such as Static Var Compensators (SVC), Unified Power Flow Controller (UPFC), Unified Power Quality Conditioner (UPQC) and Distributed Static Synchronous Compensators (DSTATCOM) aimed at regulating reactive power requirements. A decision on the application VAR compensation technique depends upon the feasibility study taking into account technical requirements and economical consideration [4]. These devices are now suggesting for control of reactive power requirements of wind generators, studies also show their acceptability in voltage stabilization control. This increases the acceptability of wind power penetration even in distribution network world-wide. The shunt connected FACT devices such as SVC, which is dynamic reactive power compensator whose reactive power output depends upon the system voltage. SVC is adopted for control of bus voltage magnitude and to bring the system near to unity power factor.[5] If the power system's reactive load is capacitive, it uses the reactors to consume VARs from the system, decreases the system voltage. Under inductive conditions, the capacitor banks are switched on, and increase system voltage, thus improve the dynamic stability of a power system. Under the condition, variability of wind power generation, SVC [6-7] helps to regulate power system voltage. For proper power system operation with the electrical network connected with wind farms suitable size of SVC is of prime importance. The installation of SVC at a suitable point in the electrical network can improve the power transfer capability and reduce transmission losses by maintaining a smooth voltage profile under different field conditions. The dynamic stability of the grid can also be improved by proper application of SVC in wind power penetration area, and active power oscillations mitigated.

This paper is divided into six sections. In Section II, SVC characteristic presented. Field Conditions, Required SVC Rating and Wind Power Penetration Analysis covered in Section III, whereas in Section IV the Simulation Study and Analysis under Field Conditions presented including the system performance with the increase of wind power and static /dynamic var mitigation with the change of the location of SVC. The detailed results are analyzed and discussed in Section V, Result and Analysis by discussing the various attributes in steady state & fault conditions. The conclusions are drawn in the Section VI, Conclusions.

## II. SVC CHARACTERISTIC

Varieties of designs are available in SVC construction, but the main controllable elements are Thyristor Controlled Reactor, Thyristor Switched Capacitors, Thyristor Switched Reactors and Mechanical Switched Capacitors. Whereas the SVC configurations are, Thyristor Controlled Reactor and Fixed Capacitor SVC, mechanical controlled switched reactor and capacitor SVC and both reactor and capacitor thyristor controlled SVC, [8]. The voltage stability at the connected bus can be maintained by controlling the inductive or capacitive current output. TCR uses firing angle control to decrease/increase the inductive current. The reactive power compensation in electric power system can be achieved by SVC in the different ways.

To mitigate the requirement of reactive power in electrical networks, SVC provides the needed reactive power by the conduction period adjustment of each thruster valve and either absorbs or supply the reactive power to the system. The susceptance of SVC with conduction angle β is given by: -

$$B_{SVC} = (2\beta - \mathrm{Sin}2\beta - \pi\omega^2 LC)/\pi\omega L \qquad (1)$$

Where β= (π-α) indicating firing angle. The reactive power compensation for the system is expressed $Q_{SVC} = B_{SVC} * V^{2.}$ The composite characteristic of SVC is derived by adding the individual characteristics of the components. The voltage-current characteristic of SVC is given in Fig.1. The SVC characteristic, steady state and dynamic, represent the variation of SVC current and SVC bus voltage or reactive power.

The slope of the curve is

$$\frac{\Delta Vcmax}{Icmax} = \frac{\Delta Vlmax}{Ilmax} = \text{slope} \qquad (2)$$

by regulating it, the linear operating range of the SVC can be extended, also implement automatic load sharing between other devices and SVC, maintained and improve the voltage regulation loop stability. The SVC is preferred to use for improvement in stabilization of steady-state and dynamic voltage, continuous control of power factor. It also enable fault ride-through capability of the wind farm, improve power quality, mitigate the flickers arises due to the tower shadow effect, starts and stops of wind turbines etc. The reduction in harmonics and phase imbalance also observed with the application of SVC. The voltage at which SVC neither absorbs nor generate the reactive power is called Vref, generally this voltage is adjusted in range of ±10 to ±15%, The slope represents a change in voltage with the current of SVC and considered as slope the reactance XSL , the response of SVC is given by:-

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$$VT = Vref + I_{SVC}\ XSL \qquad (3)$$

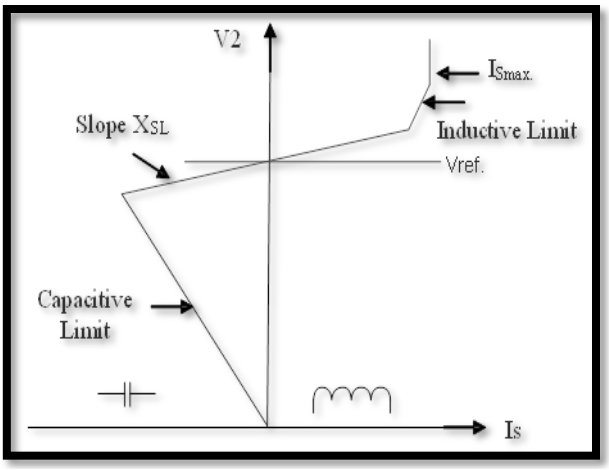


Fig.1. Steady state V-I characteristic of SVC

## III. FIELD CONDITIONS, REQUIRED SVC RATING AND WIND POWER PENETRATION

The power system network considered of Western Rajasthan having a high wind penetration area having total connected wind power 2000 MW in three buses, namely Akal 220 kV, 1600MW, at Amarsagar (Jaisalmer) 220kV 300MW & Amarsagar (Jaisalmer) 132 kV, 100MW, with actual field system network comprising of 29 Bus including wind power connected buses, Generating station, bus, SVC bus and other power transfer buses 400kV (4), 220 kV (10), 132 kV (9), 33kV (1) and 11kV(5). Total 37 Transmission lines of voltage level 400kV, 220 kV and 132KV level, with shunt reactors connected to both ends of 2 numbers 400kV transmission lines [9-10].Wind power is represented as negative load. The 29 bus system under consideration is further connected and part of 657 buses Rajasthan power system. In Table 1,details of load flow parameters given.

**Table 1 Load flow parameters**

| Particulars | Description |
|---|---|
| Load Flow | Fast De Coupled Technique |
| Base MVA | 100 |
| Real Power Tolerance pu | 0.0001 |
| Reactive Power Tolerance pu | 0.0001 |
| Maximum Number Of Iterations | 100 |
| Circuit Breaker Resistance pu | 0.0000 |
| Circuit Breaker Reactance pu | 0.0001 |
| Transformer R/X Ratio | 0.0500 |
| Nominal System Frequency | 50Hz |
| Zones | 17 |
| Slacks bus | 43 |
| Q Checking Limit | 4 |

In the study, the SVC rating decision for reactive power mitigation with the help of load flow analysis using the Fast De Coupled Technique get carried away along with analysis of the other power system attributes in high wind power penetration area. Mi.-Power software is used with actual field conditions of the Western region of Rajasthan Grid which is high wind power penetration area.

### SVC Rating

In order to work out SVC rating, the worst condition of the system considered. The SVC has both capacitive as well as inductive rating. For a selection of capacitive rating of SVC, the maximum load condition of the area, maximum wind power generation of the area considered along with other factors. Similarly for calculation of minimum rating the minimum load and zero wind power condition are considered along with other factors. A MVAr Virtual Generator (VG) of half the capacity of wind generation and zero active power are connected at main bus. The MVAr absorbed/ supplied by generator in load flow analysis gives the rating of SVC.

### Capacitive rating of SVC

In the present case for working out the capacitive rating of SVC, the maximum load of Rajasthan considered 10,000MW, the maximum wind power of high wind power penetration area 0.75*2000= 1500 MW. The nearby nonrenewable energy generating station in a high wind penetration area is M/S Raj West lignite based thermal power station and Gas based Ramgarh combined cycle power plant. The power factor of these stations considered 0.95 and 1.0 p.u. There is shunt reactor connected in 400kV transmission line, for working out the capacitive rating of SVC, the shunt reactor connected at 400kV Akal is switched off. Fig.2. A virtual generator of rating ± 500MVAr and zero MW connected at 400 kV bus Akal. From the load flow analysis, it is observed that, the generator is feeding 421 MVAr, if SVC is not connected with the above condition, the power system is not converging and it collapses. To bring the system in conversing state, the nearby Generator voltage increased to 1.01 pu and the voltage at Akal is kept at the minimum allowable as per grid code, i.e. 362 kV, under these conditions it is observed that in load low analysis the virtual generator is absorbing 400MVAr.Fig.3. As such the capacitive rating of SVC becomes 400 MVAr.

### Inductive rating of SVC

For deciding the inductive rating of SVC, the condition of minimum load in the system and condition of minimum wind power is considered. The minimum load on the system is 9000 MW and wind power generation considered zero MW. It is assumed that nearby generating power stations viz, Giral Lignite power thermal power station, Raj West power thermal power station and Ramgarh combined cycle gas power station, are operating at maximum voltage i.e. 1.05 per unit. Under these conditions the voltage observed at Akal is 424 kV


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Fig.4.To decide the inductive rating of SVC, again virtual generator of the rating ± 500 MVAr at 400kV Akal bus with active power rating 0 MW is connected. The nearby generating power station voltage is kept 1 per unit. In load flow analysis, it is observed that virtual generator is absorbing 353 MVAr, accordingly, the SVC inductive rating is considered 350 MVAr. Fig.5

In this way, with the help of load flow analysis of the system under consideration, the SVC rating works out (+) 350 MVAr and (-) 400 MVAr. This basic value of SVC rating so obtain, be further modified considering future wind plant growth in the area along with power evacuation network growth and load demand. In the present system looking about 15-20% growth in wind power generation, the capacity of SVC for the further analysis purpose safely considered as ±500MVAr.

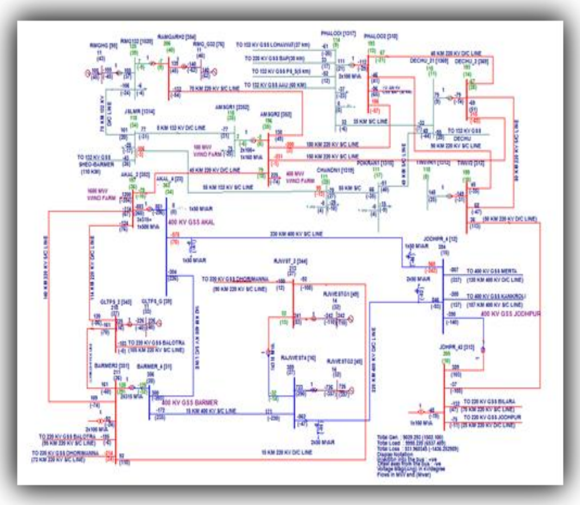

**Fig.2 Power plot with maximum load and wind power generation**

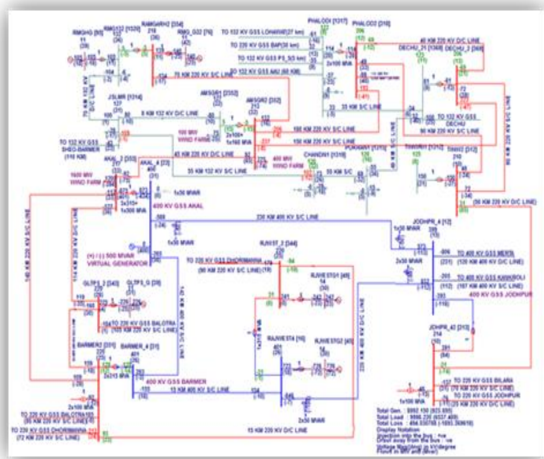

**Fig.3 Power plot with VG ±500MVAr at Akal max. wind and load**

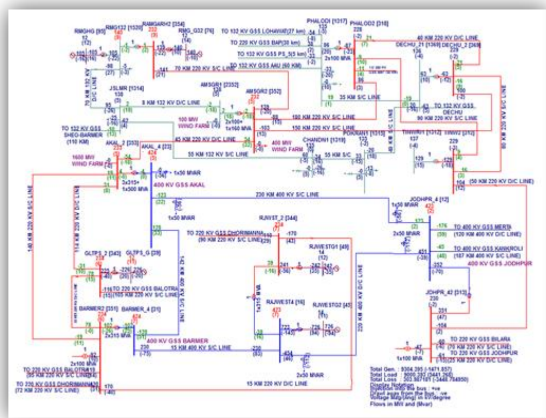

**Fig.4 Power plot with minimum load and wind power generation**

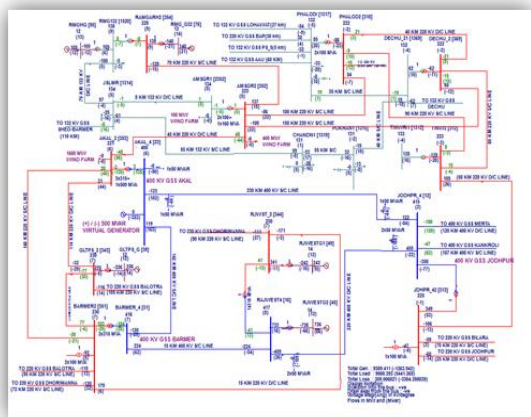

**Fig.5 Power Plot with VG ±500MVAr at Akal at minimum wind power and load**

**Wind Power Penetration Analysis**

Presently, in Western Rajasthan sector the wind power installed is 2000MW. Out of which 1600 MW is connected at 220kV Akal Bus, 300MW at 220 kV Amarsagar and balance 100 MW at 132 kV Amarsagar. For this much wind power penetration, the existing power evacuation system is sufficient [11]. To analyze further, the wind power penetration is required to increase, with the assumption that the SVC of rating ± 500MVAr stand connected to main wind bus i.e. 400kV Akal. It is also assumed that the addition of wind power in the system is as per existing wind power installations Akal and Amarsagar, percentage. During analysis, it is also assumed that conventional power generation in the system remains unchanged. Fig. 6 depicts the base case of wind power generation 2000MW under steady state condition. The SVC is injecting 193 MVAr in the system. The bus voltage at 400kV Akal and Jodhpur 0.985 and 0.991 pu respectively. The reactive power flow in 400 kV Akal-Jodhpur line and 400 kV Akal –Barmer lines are (-) 7 KV and 168MVAr respectively. For analysis the purpose the

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wind power penetration considered increase of 10%, 25% and 50% from the base case of 2000MW wind power plant installation in Western Rajasthan on prorate basis.

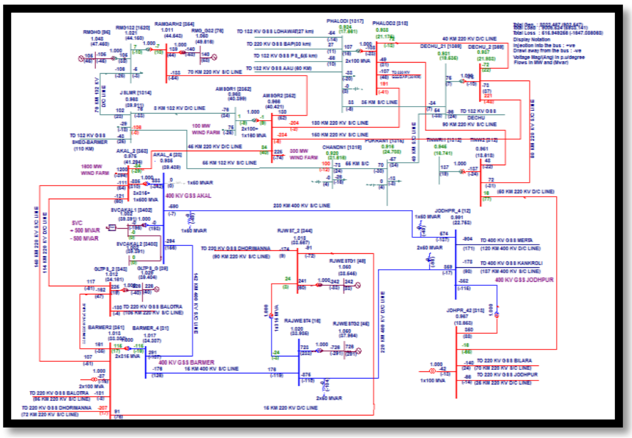

**Fig. 6 2000 MW wind power normal base case**

**10% Increase in wind power penetration (total wind power 2200MW)**

During load flow analysis to analyze the effect of wind power penetration.

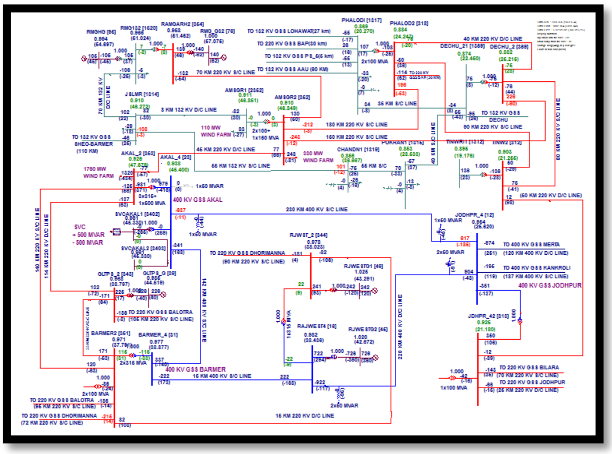

**Fig. 7 Increase in wind power penetration 10%**

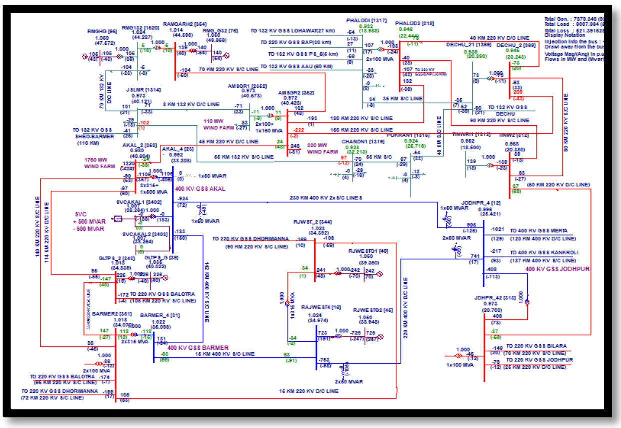

**Fig. 8 Increase in wind power 10% with double circuit 400 kV Akal Jodhpur Line**

The wind power is increased by 10%, with this wind power in coming to Akal 400 kV bus, Amarsagar 220 kV Bus and Amarsagar 132 kV bus this becomes 1760 MW, 330MW and 110MW respectively. In the simulation of the load flow analysis, it is observed that the system converges but transmission lines were heavily loaded, due to increase of 200 MW of wind power.Fig.7. So for the strengthening of the system one more 400kV single circuit added in the network, between Akal and Jodhpur. With the addition of one more single circuit, the system converges. The power plot of 10% wind power penetration is depicted in Fig. 8.

**Increase in wind power penetration 25% (total wind power 2500MW)**

With the 25% increase in wind power penetration, the wind power injection at 400kV Akal bus increased to 2000 MW. Similarly, it becomes 375MW and 125 MW at 220kV and 132 kV Bus at Amarsagar. In load flow simulation, it is observed that power system converges at this level of wind power penetration. The power plot at 25% wind power penetration is depicted in Fig.9. The power flow, in two numbers 400kV single circuit lines, increases to 1028 MW and reaches full capacity of transmission lines. The bus voltage at 400kV Akal become 0.914 pu, similarly at 400kV Jodhpur the bus voltage become 0.929 pu. The SVC is injecting 292 MVAr in the system. The power flow in 400 kV Akal Barmer line is noted 237 MW.

**Increase in wind power penetration 50% (total wind power 3000MW)**

With the 50% increase in wind power penetration, the wind power injection at 400kV Akal bus increased to 2400 MW. Similarly, it becomes 450MW and 150 MW at 220kV and 132 kV Bus at Amarsagar.

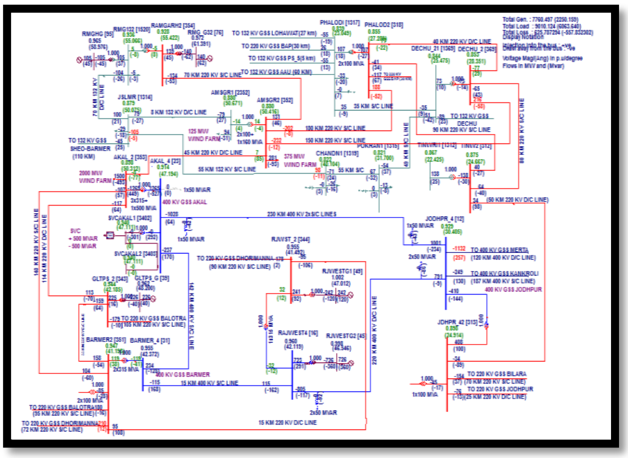

**Fig. 9 Increase in wind power 25% with double circuit 400 kV Akal Jodhpur line**

In the simulation of the load flow analysis, it is observed that system not converging due to overloading of the transmission system/other reasons, even if there is a

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double circuit line between Akal and Jodhpur The power plot of this condition are shown in Fig.10.

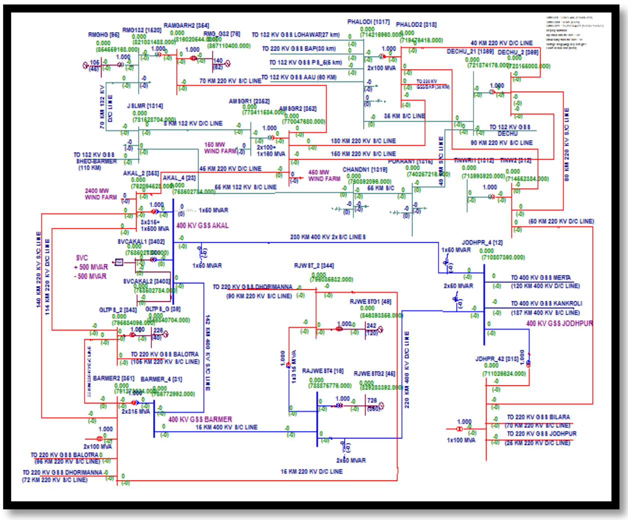

**Fig. 10 Increase in wind power 50% with double circuit 400kV Akal Jodhpur line**

To make the power system converges, the 400 kV transmission systems between Akal and Barmer for analysis purposes. The load flow simulation again conducted after strengthening of 400 kV transmission systems between Akal and Barmer. The power plot of the same is shown in Fig. 11.

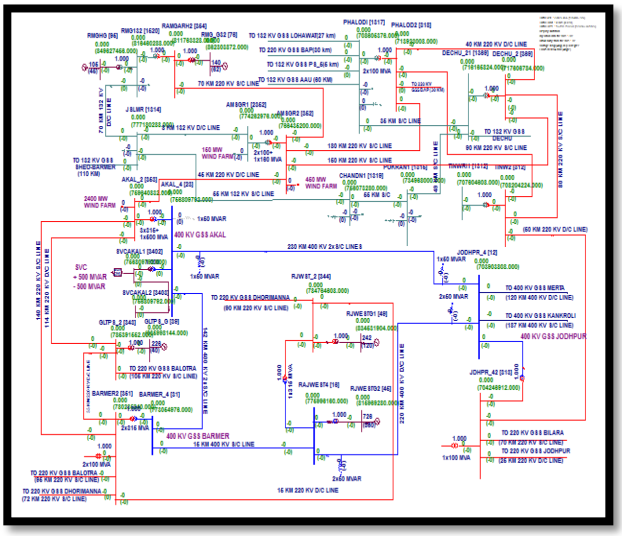

**Fig.11 Increase in wind power 50% with double circuit 400 kV Akal Jodhpur and Akal Barmer line**

It observed that even strengthening of power system by making 400kV Akal-Jodhpur and 400kV Akal –Barmer double circuit, the power system load flow simulation at 150% wind power penetration not converging even if in static mode. Apart from power plot with different wind power penetration, the SVC performance and pu voltage at wind buses and Western Rajasthan 400 kV Bus is given below in Table 2.

**Table 2 Wind Bus Voltage and SVC performance with increase of wind power penetration**

| Fig. | Bus Voltge pu | | | | SVC MVAr |
|---|---|---|---|---|---|
| | Akal 400kV | Amarsagar 20kV | Amarsagar 32kV | Jodhpur 400kV | |
| 12 | 0.985 | 0.988 | 0.988 | 0.991 | 193 |
| 13 | 0.938 | 0.910 | 0.911 | 0.954 | 289 |
| 14 | 0.992 | 0.972 | 0.973 | 0.998 | 188 |
| 15 | 0.914 | 0.88 | 0.88 | 0.929 | 292 |
| 16 | 0 | 0 | 0 | 0 | 0 |
| 17 | 0 | 0 | 0 | 0 | 0 |

## IV. SIMULATION STUDY AND ANALYSIS UNDER FIELD CONDITIONS

For reactive power control in power system, the basic parameters are voltage and power factor[12]. For analysis either voltage is to be assumed as constant and variable power factor be considered, or the power factor be considered constant and the variation in voltage of GSS and lines is observed, with the change in wind power in the system. Constant power factor can safely be assumed for analysis. With static capacitor, the overall power factor of wind power generation remains in the range of 0.85 to 0.95. For analysis purposes the p.f. assumed 0.90 constant. Generally there are two methods for the placement of SVCs. At first, one SVCs are considered only at the wind injection sites which have the highest contribution to instability modes. The second method for locating new SVC was to place them on the bus which have the highest participation factors to modes of instability regardless if they were a wind injection buses or not. Beside these two methods in this study work the effect on static and dynamic reactive power in the power system by altering SVC Location examined.

The placement of SVC is considered at the highest voltage level bus, i.e. 400 kV Akal and far off same voltage level bus viz. 400 kV Jodhpur and 400kV Barmer under actual field conditions. A complete block diagram of SVC, with TCR and fixed capacitor used for static and dynamic reactive power used for LFS depicted in Fig. 12.


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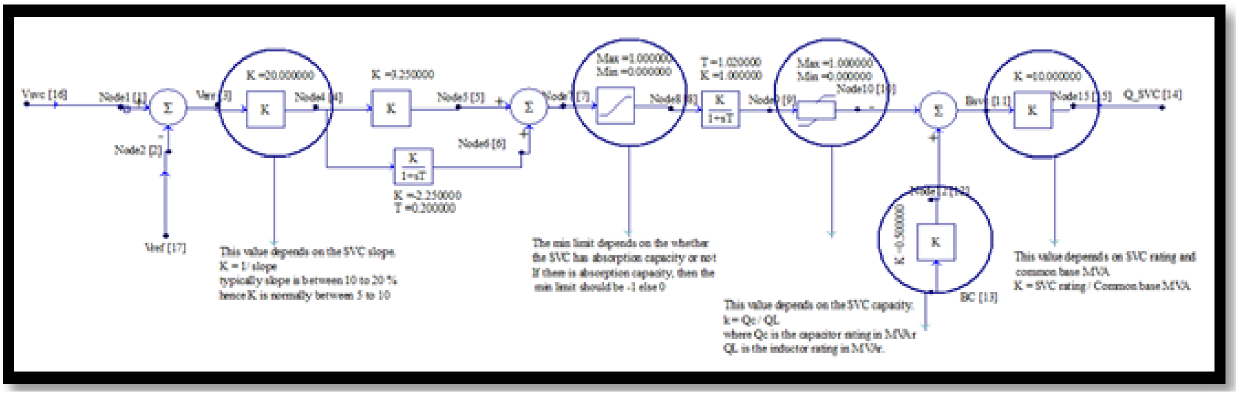


**Fig.12 A complete block diagram of SVC with CR and fixed capacitor used for static and dynamic reactive power used for LFS Static reactive power**

For static reactive power the condition considered comprises of two extreme cases. The first condition is no wind generation/injection in the system. Second condition, comprises of a full wind generation, i.e. 75% of the installed capacity. Under these conditions SVC installation considered at either main wind bus or far off bus. In present case 400 kV treated as main wind bus and 400 kV Jodhpur and Barmer considered as far off bus, The corresponding power plots under on wind and full win conditions are given in Fig.13-18.After analyzing the power plot of no wind power generation at Akal, Jodhpur and Barmer, the various electrical attributes are shown in Table 4 including the total load in the system, SVC MVAR injection in the system, bus voltage reactive power flow, transmission losses etc.[13-14]. It is seen that SVC installation in parent Bus reduces the voltage hike and reduction of transmission losses, along with improvement in attributes, if SVC installed in the main wind bus.

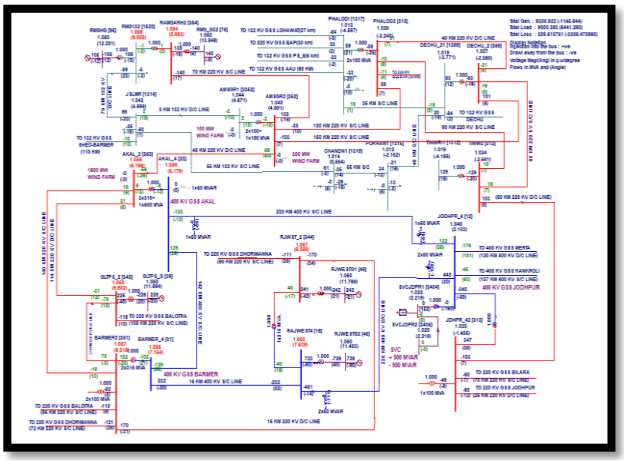

**Fig.14 SVC at Jodhpur with no wind power condition**

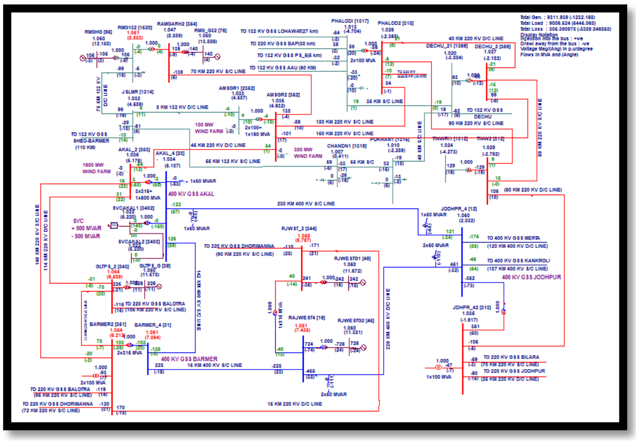

**Fig.13 SVC at Akal with no wind power condition**

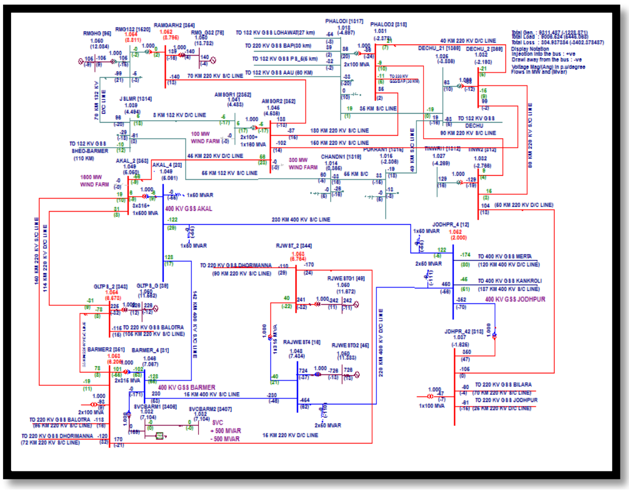

**Fig.15 SVC at Barmer with no wind power condition**

**Table 3 Various Attributes with Wind Power Generation Zero**

| Wind Power Generation Zero | SVC at Akal | SVC at Jodhpur | SVC at Barmer |
|---|---|---|---|
| Total load | 9006 MW | 9006 MW | 9006 MW |
| SVC MVAR injection | (-) 150 MVAR | (-) 160 MVAR | (-) 171MVAR |
| Voltage at 400 kV GSS Akal | 1.034 pu | 1.056 pu | 1.049 pu |

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|---|---|---|---|
| Voltage at 400kV GSS Jodhpur | 1.05 pu | 1.04 pu | 1.062 pu |
| Voltage at 400kV GSS Barmer | 1.061pu | 1.066 pu | 1.048 pu |
| Reactive power flow Akal –Jodhpur 400kV line | (-) 57 MVAR | 12 MVAR | (-) 29MVAR |
| Reactive power flow Akal –Barmer 400 kV line | (-) 89 MVAR | (-) 25 MVAR | (-) 17MVAR |
| Transmission losses | 305.39 MW | 309.51 MW | 304.83 |

The full wind generation considered and power plot under these conditions are depicted in Fig. 22-24. To examine the various electrical attributes such as active and reactive power flow and transmission losses etc.

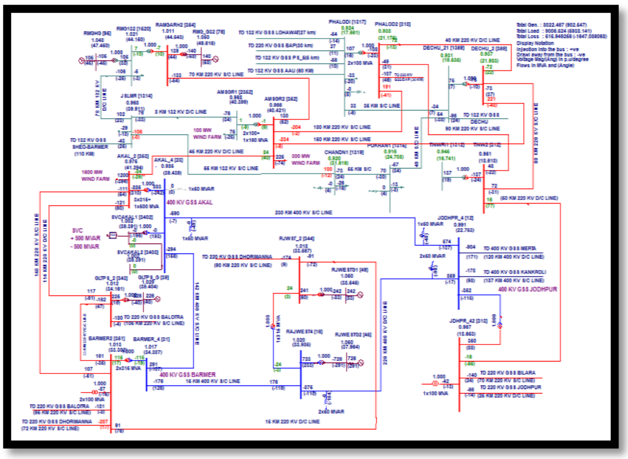

**Fig.16 SVC at Akal with full wind generation condition**

The power plot of full wind power generation condition at Akal/Jodhpur for static reactive power requirement examined, the various electrical attributes is shown in Table 41ncluding the total load on the system, SVC MVAR injection in the power system, bus voltage, reactive power flow, transmission losses etc. It is seen that SVC installation in the parent bus, improve the voltage of the bus and reduction of transmission losses, along with improvement in attributes, if SVC installed in the main wind bus.

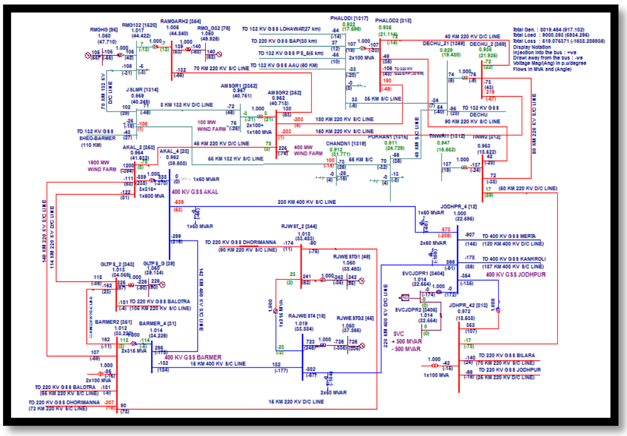

**Fig.17 SVC at Jodhpur with full wind generation condition**

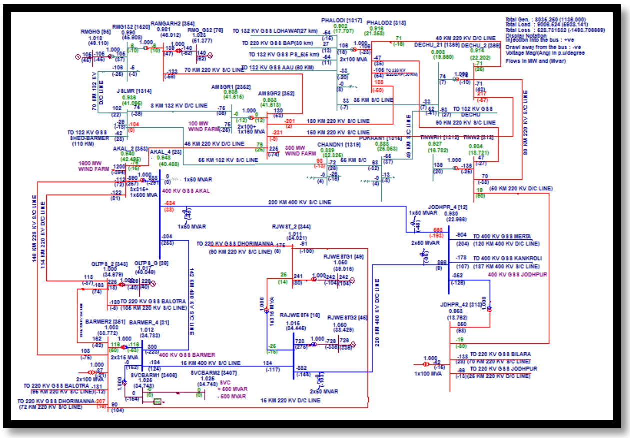

**Fig. 18 SVC at Barmer with full wind generation condition**

**Table 4 Various attributes under full wind power generation with SVC at Akal, Jodhpur and Barmer**

| Full Wind Power Generation | SVC at Akal | SVC at Jodhpur | SVC at Barmer |
|---|---|---|---|
| Total load | 9006 MW | 9006 MW | 9006 MW |
| SVC MVAR injection | 193 MVAR | 172 MVAR | 164 MVAR |
| Voltage at 400 kV GSS Akal | 0.985 pu | 0.962 pu | 0.948 |
| Voltage at 400kV GSS Jodhpur | 0.991 pu | 1.00 pu | 0.98 |
| Voltage at 400kV GSS Barmer | 1.017 | 1.014 | 1.012 |
| Reactive power flow Akal –Jodhpur 400kV line | 7 MVAR | (-) 53 MVAR | (-)38MVAR |
| Reactive power flow Akal –Barmer 400 kV line | (-) 156 MVAR | (-) 216 MVAR | (-) 253MVAR |
| Transmission losses | 515.94 MW | 519.07 MW | 528.73MW |

**Dynamic reactive power**

The analysis of static reactive power reveals that the SVC installation at Barmer increases the transmission losses in range of 10-15 MW which is not a desirable condition for SVC installation as such for analysis of dynamic reactive power the installation of SVC at Barmer not is not justified [15-18]. For dynamic reactive power analysis the condition created are, the addition of 25% of wind generation at wind buses from zero MW, in the interval of

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5sec. 50% after 10 sec. and 75% after 15 sec. of the installed capacity of wind power generation. The effect of altering the location of SVC at 400 KV Akal bus w.r.t. SVC at 400 KV GSS Jodhpur, corresponding to 400 KV bus voltages, voltage of the wind buses, voltage of M/s Raj West bus, flow of current, reactive power and active power in 400kV transmission lines, reactive power flow in 220 KV transmission line and swing curve of M/s Raj West LTPP and Ramgarh GLTPP are shown in Fig.19-24. To analyze the effect of disturbance LLLG fault created at far end 400 KV GSS Barmer and its effect on the voltage and power flow with SVC installed at Akal and Jodhpur considered and are depicted in Fig.25-27.The SVC Q flow and swing performances of power plants are shown in Fig. 28 and Fig.29


**Fig.19 Voltage at 400KV GSS with SVC location change**

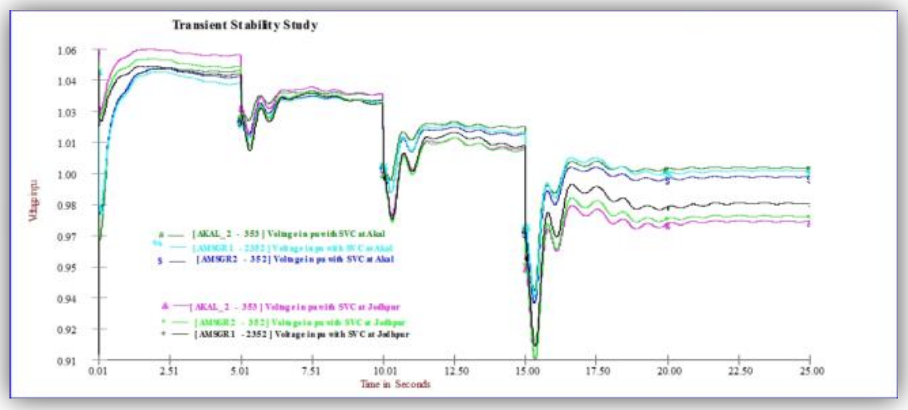


**Fig. 20 Wind bus voltages with SVC at Akal and Jodhpur**

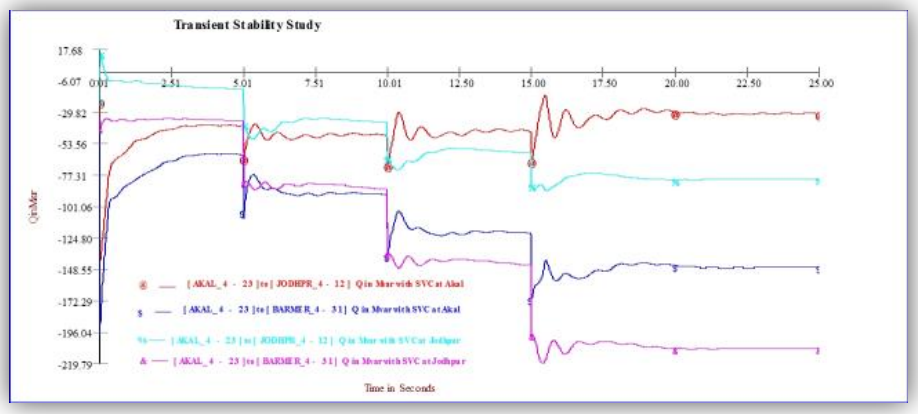


**Fig. 21 Reactive power flow variation in 400kV lines with change of location**

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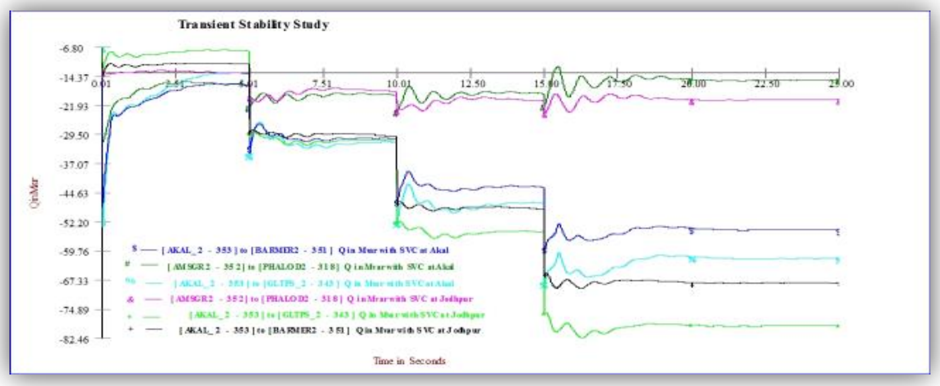


**Fig. 22 Reactive power flow variation in 220kV lines with change of location of SVC**

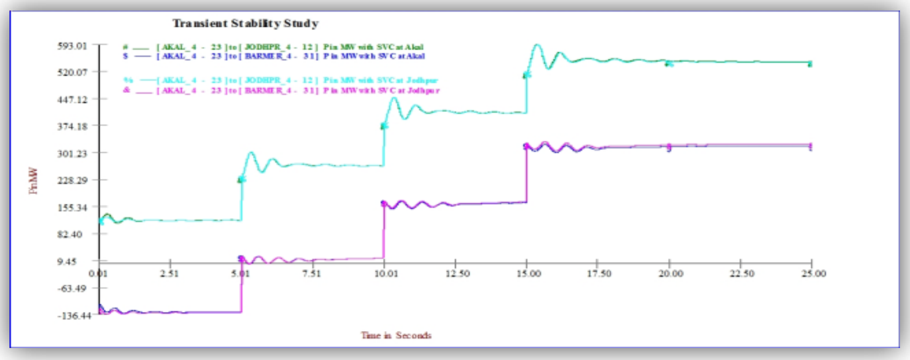


**Fig. 23 Active power flow in 400 kV lines with change of location of SVC**

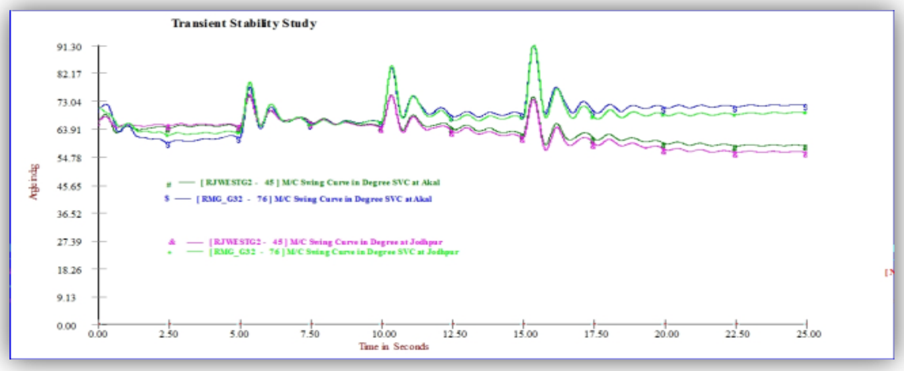


**Fig.24 Swing curve of M/s Raj West & Ramgarh PP with change of location of SVC**

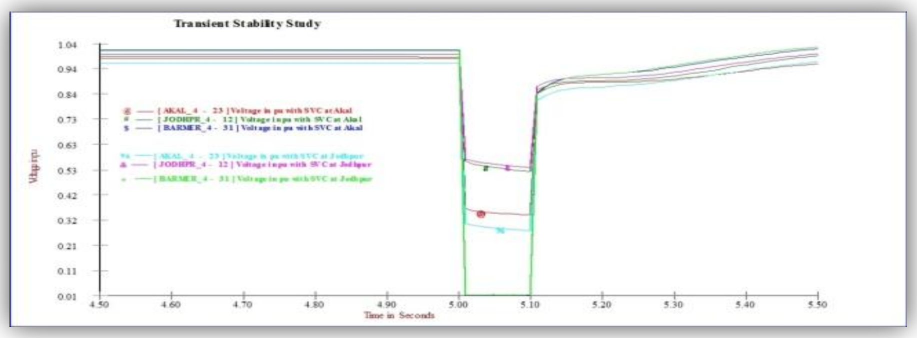


**Fig. 25 Voltages at 400 kV GSS with LLLG fault condition**

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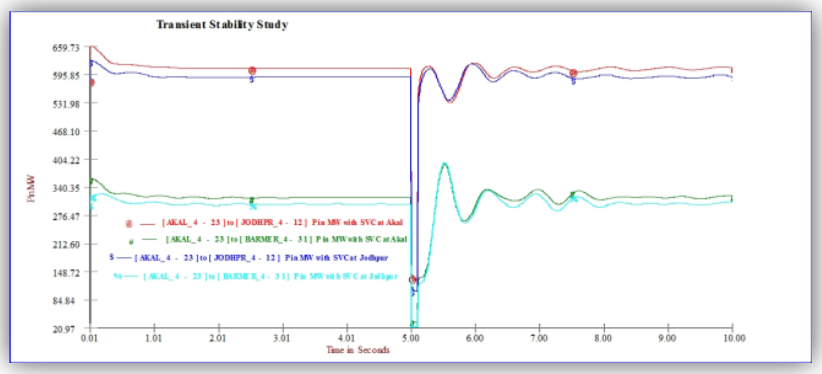


**Fig. 26 Active power flow in 400 kV lines with LLLG fault condition**

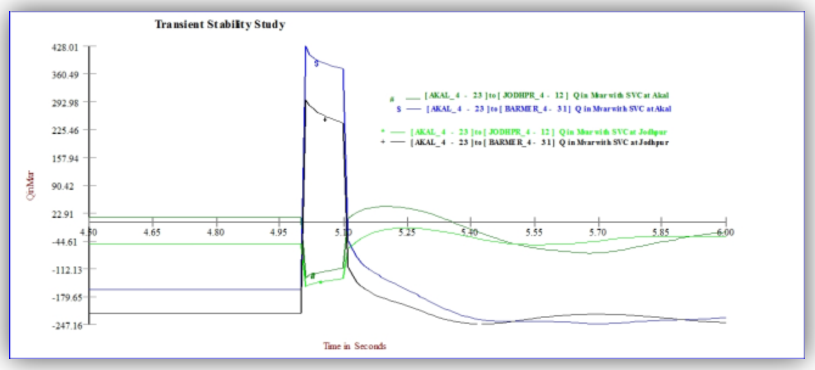


**Fig.27 Reactive power flow in 400 kV lines with LLLG fault condition**

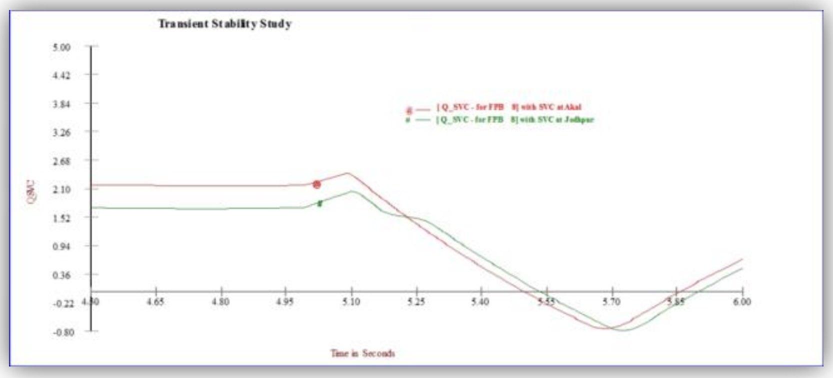


**Fig. 28 SVC Q flow with LLLG fault condition**

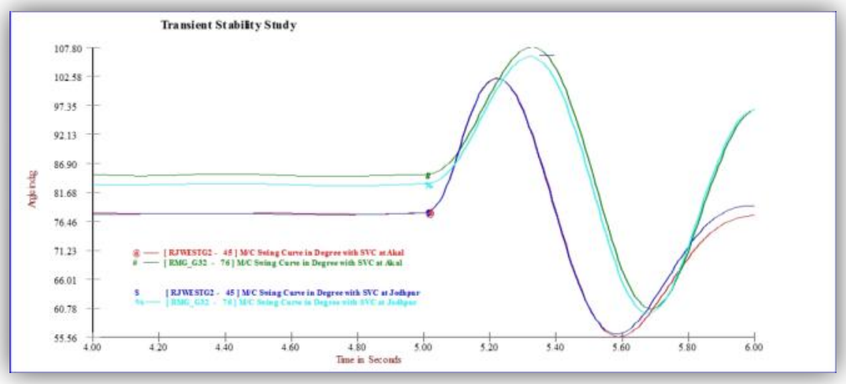


**Fig. 29 Swing performance of power plants with LLLG fault condition**

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## V RESULT ANALYSIS AND DISCUSSION

Using the concept of virtual generator on main wind bus the necessary capacity of SVC decided. Load flow analysis with Mi-Power software topology, using modelled SVC in actual field condition and real time data of Western Rajasthan the SVC rating works out (+) 350 MVAr and (-) 400 MVAr. further modified considering future wind plant growth15-20%. As such the SVC of rating ±500MVAr, if introduce into Rajasthan power system will successfully mitigate the requirement reactive power of the wind farm and also maintain the system voltage within limit ad retired per grid code.

In case of increase of wind power penetration in Western Rajasthan from 10% to 50% of present wind power installation it is observed that the Fig.6-11, SVC is maintaining bus voltages, feeding reactive power in the system and maintaining voltage stability in the system. With the increase of wind power penetration SVC injection of reactive power increases, but it is observed that with the increase of wind power penetration even 10% of its present level, the transmission system needs to be reviewed and strengthen at different voltage levels along with detailed analysis of voltage stability, static and dynamic var requirements as in static mode power system is not converging with 50% increase of wind power penetration as compared to present existing wind power although the power evacuation system form main wind bus strengthen upto the level of wind power penetration. The main reason beyond it is that the system under study is 29 bus systems of Western Rajasthan the system is further connected to the 657 Bus power system of Rajasthan Grid, with increase of wind power penetration the transmission system connected further to Jodhpur and Barmer needs strengthening to evacuate extra 1000 MW power. The SVC connected at the main wind bus of capacity ±500MVA is feeding/ absorbing reactive power as per need of the power system. The wind power penetration is affecting present grid available, the proper planning of power evacuation system and study of static and dynamic reactive power required**.** The location of SVC is very important and play major role in the mitigation of reactive power and voltage management of power system, transmission lines and bus. Analysis has been carried out to work out various attributes in steady state conditions with the change of location of ± 500MVAr, under the power system condition of nil wind power generation and 75% wind power generation and injection in power system. The SVC installation treated on the 400kV main wind bus and far off 400kV bus at Jodhpur and Barmer Fig.19-24 and Table3-4. The results are analyzed and bus voltage under steady state conditions at different 400 kV GSS due to change of location of SVC at no wind power condition is shown in Fig.30. Reactive power injection by SVC, reactive power flow in 400 kV lines & transmission losses due to change of location of reactive power injection by SVC, reactive power flow in 400 kV lines & transmission losses due to change of location of SVC at no wind power generation is shown in Fig.31. Bus voltage under steady state conditions at different 400 kV GSS and reactive power injection by SVC, reactive power flow in 400 kV lines & transmission losses due to change of location of SVC at full wind power condition are shown at Fig.32-33 respectively**.**

The results depicted in Fig.38 indicates that at bus where the SVC is installed the bus voltage under no wind power condition remain under control as compared to other GSS bus voltage under steady state condition. The voltage rise observed in other GSS. Similar effects are observed if the location of SVC is changed. The reactive power injection by SVC under no wind power condition is in ascending order between Akal.Jodhpur and Barmer Fig.39. The transmission losses are more or less same, but slightly higher with the change of location of SVC to Jodhpur. Similarly the flow of reactive power is from Akal to Jodhpur in 400kV Akal-Jodhpur transmission line if SVC is installed at Jodhpur.

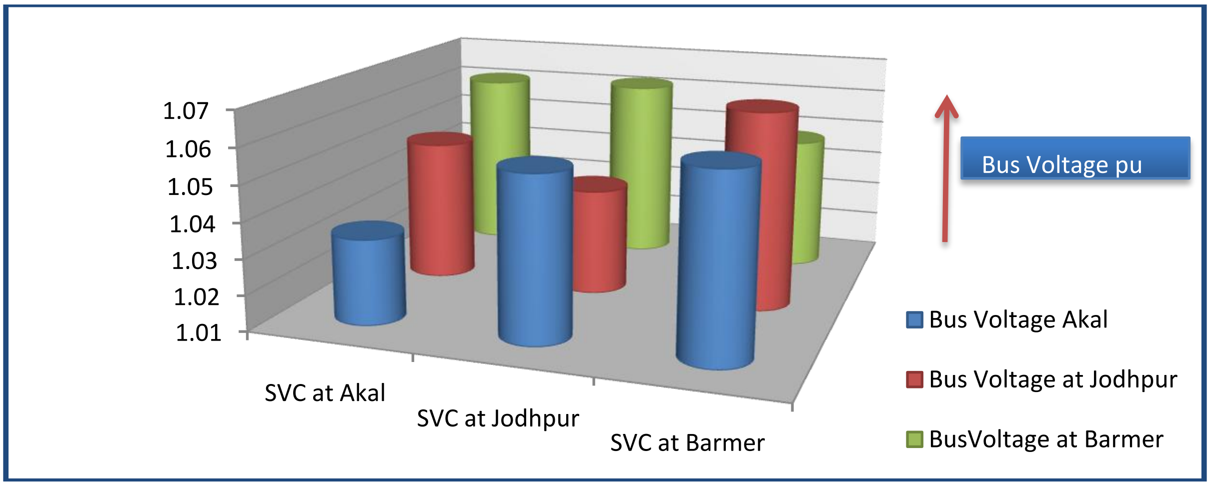


**Fig.30 Bus voltage under steady state conditions at different 400 KV GSS due to change of location of SVC at no wind power condition**

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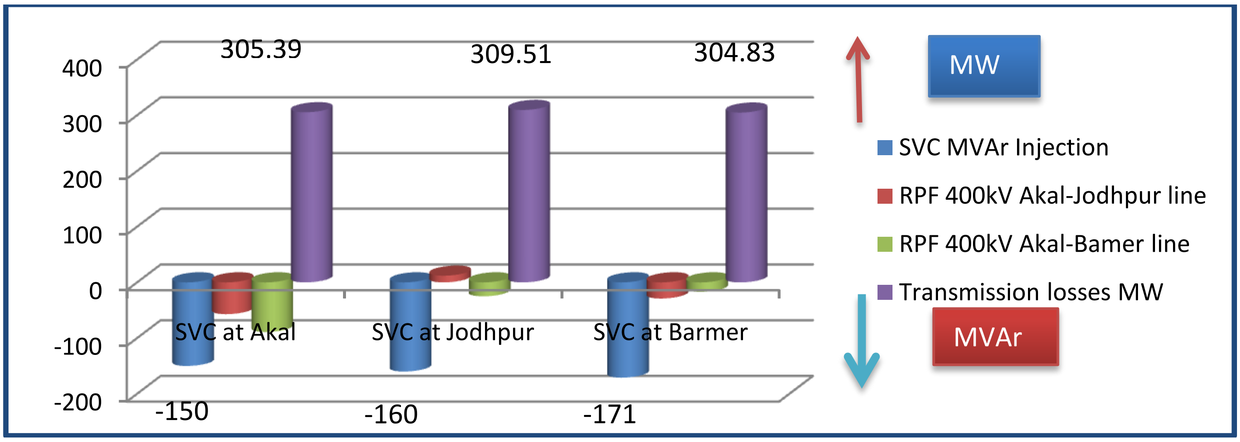


**Fig.31 Reactive power injection by SVC, reactive power flow in 400 kV Lines & transmission losses due to change of location of SVC at no wind power condition**

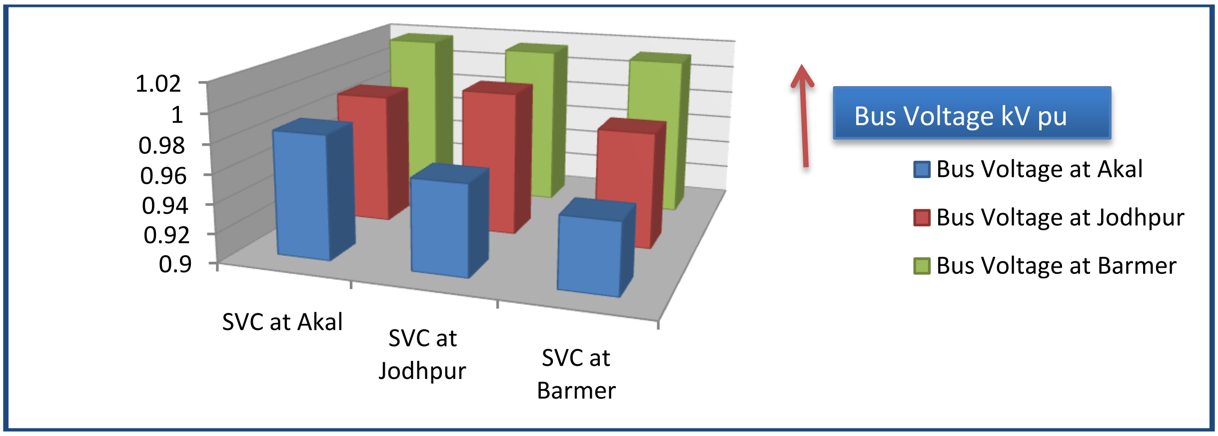


**Fig.32 Bus voltage under steady state conditions at different 400 kV GSS due to change of location of SVC at full wind power condition**

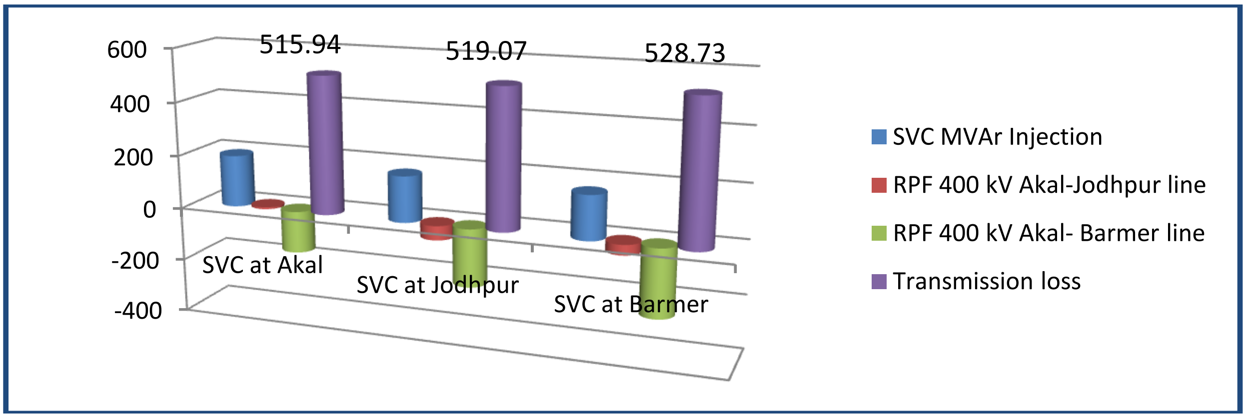


**Fig.33. Reactive Power Injection by SVC, Reactive Power Flow in 400 kV Lines & Transmission Losses Due to change of location of SVC at full wind power condition**

Under the condition of the full wind power generation with steady state condition Fig.32, the bus voltage falls down at the buses where the SVC are not installed, which in turn indicate that SVC is mitigating the reactive power and improving the bus voltage. Under full wind power condition Fig.33, it is observed that there are increases in transmission losses by about 13MW in the power system if the SVC is installed at Barmer. The SVC is injecting more reactive power when it is installed in main wind bus as compared to another location.

The dynamic condition created in a power system by the sudden addition of wind power in step of 25% in interval of 5 second up to a level of 75% of wind power installation. The various bus voltages, flow of active and reactive power, current flow in major transmission lines, etc, examined Fig.5.29-36 and Table 5.5. The bus voltage

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& voltage dip are analyzed with the sudden addition of wind power, with SVC installed at Akal are shown in Fig. 34. Similarly the bus voltage before the addition of wind power, voltage dips arises due to wind power addition and voltage after wind power addition with SVC installation at Jodhpur are shown in Fig.35. Flow of reactive power in 400 & 220 kV Transmission lines with the change of location of SVC installation is depicted in Fig.36. The bus voltage at Akal, Jodhpur and at Barmer experience lesser dip with the addition of wind power in step of 25% in interval of 5 seconds when SVC is installed at main wind bus at Akal as compared to when the SVC is installed at JodhpurFig.34-35. The flow of reactive power in 400kV Akal Jodhpur transmission line also increases high from (-) 30MVAr to (-) 148 MVAr Fig.36. This increase of reactive power flow is observed in both the other cases of SVC installation at Jodhpur and Barmer,it is all due to mitigation of reactive power demands with the sudden increase of wind power generation met by the installed SVC.

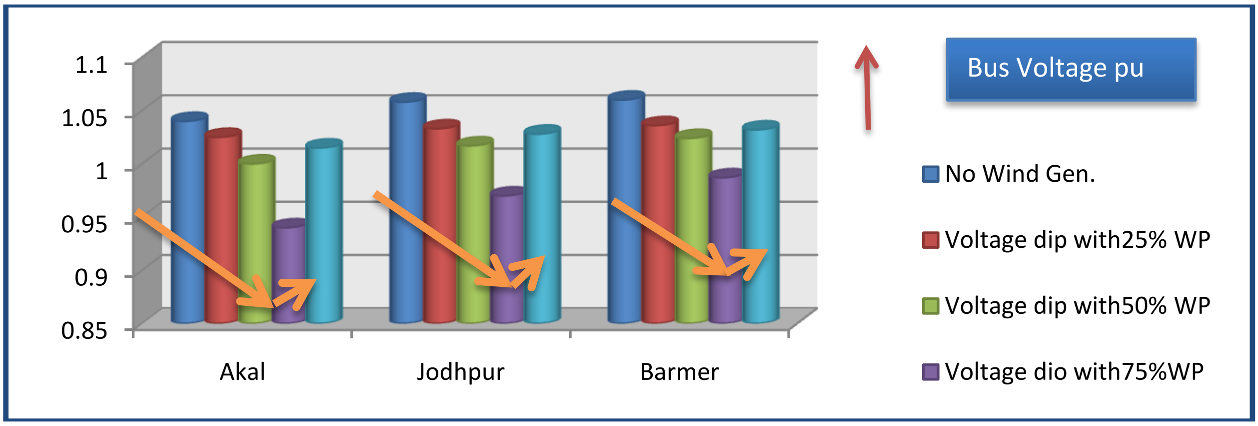


**Fig.34. Bus Voltage & Voltage dip with the addition of WP with SVC installed at Akal**

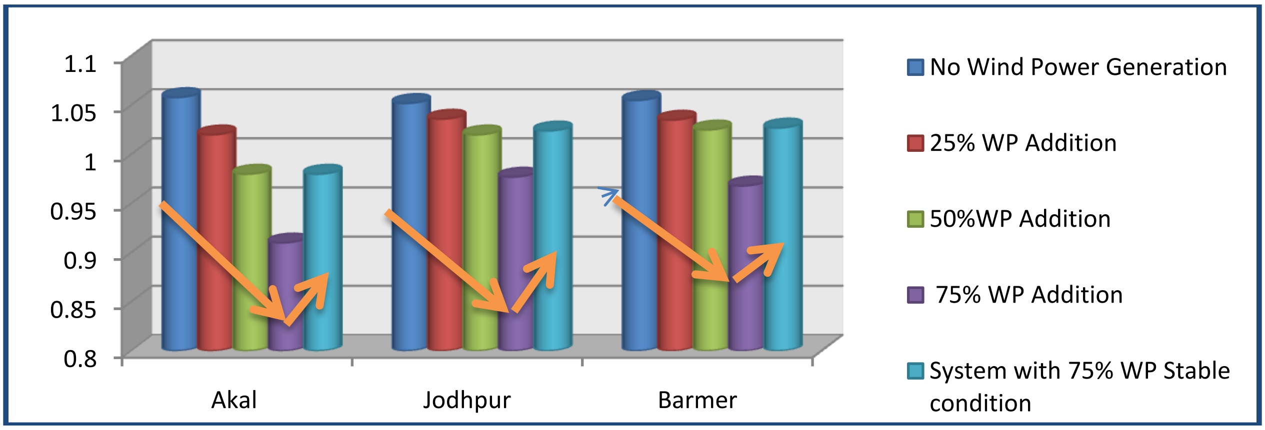


**Fig.35. Bus Voltage & Voltage dip with the addition of WP with SVC installed in Jodhpur**


**Fig.36. Flow of reactive power in 400&220 kV Transmission lines with SVC installation at Akal and Jodhpur**

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The transient behavior analysis during the disturbance, LLLG fault created at far end 400 KV GSS Barmer at the instant 5second with clearance after 0.1 second and its effect on the voltage, active and reactive power flow on transmission line with SVC installed at Akal and Jodhpur analyzed and are depicted in Fig.33-35. Flow of active and reactive power in 400 kV Akal- Jodhpur and Akal- Barmer Transmission line under LLLG Fault at 400kVBarmer Bus with SVC installed at Akal and Jodhpur depicted in Fig.37.

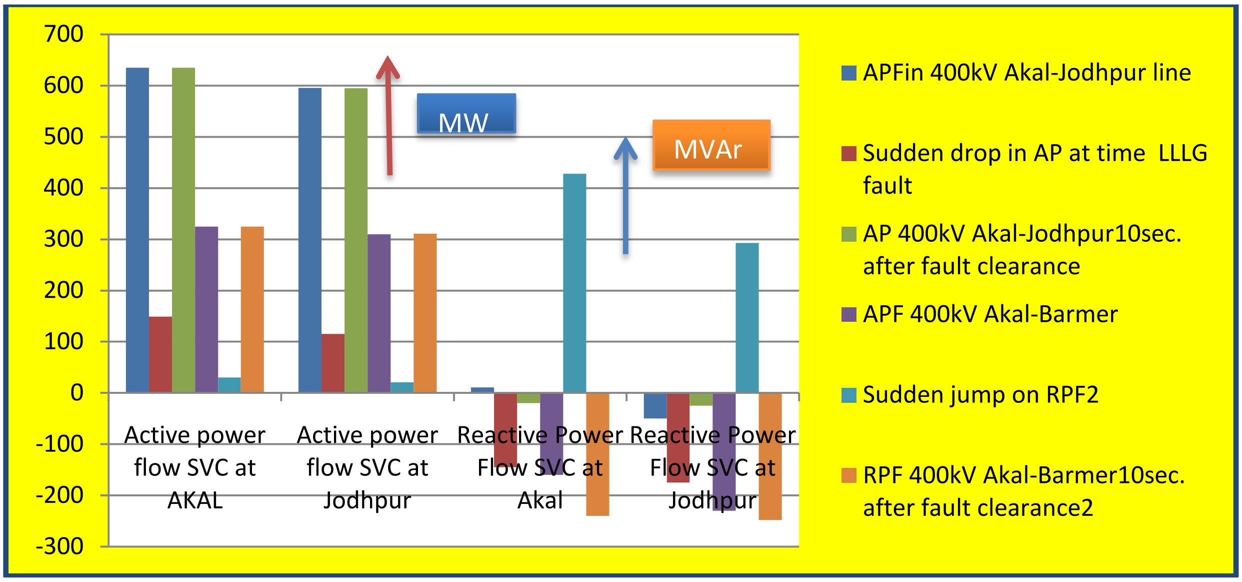


**Fig.37 Flow of active and reactive power in 400 kV Akal- Jodhpur and Akal- Barmer Transmission line under LLLG Fault at 400kVBarmer Bus**

Under the LLLG fault condition, it is observed that the active power flow restored to near about its original value and not much effect observed of LLLG fault. But in case of reactive power flow in the particular case of Akal Barmer transmission line, irrespective of installation of SVC, the voltage and reactive power support are provided by SVC in the power system by injecting reactive power in the power system and meeting the demand of dynamic reactive power.

## VII. CONCLUSION

Modelled SVC is used in LFA, based on this approach, rating of SVC for reactive power mitigation and voltage management worked out, Mi-Power software is used. The LFA gives the range of reactive power for the particular power system, with the use of virtual generator, accounting extreme conditions, which facilitate the capacity decision of SVC, in the wind power area. With the LFA it is also examined that SVC support power system against the increase of wind power penetration up to some extent, after which the strengthening of a power system needs review. Transmission system required to strengthen at all levels. It also needs, the review of operating reserves, demand side management and study for proper installation of reactive power mitigating equipment's with static and dynamic var requirement analysis as all these factors having voltage and system stability.

The static Var Compensator, support in mitigating voltage and reactive power requirement of wind farms. It avoids the tripping of transmission lines due to overvoltage condition by absorbing reactive power. The SVC support the bus voltage in steady state and transient conditions, by supporting static and dynamic var. The proper size and location of SVC is important in its role of voltage and reactive power mitigation. In the case of Western Rajasthan Grid, which having high wind power penetration area the installation of ± 500MVAr capacity SVC is required to be installed at main wind bus at Akal. Which will cover even the further wind power penetration up to 25% of existing wind power plant installation, beyond this the existing transmission system needs deep review at all voltage levels.

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