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Power System State Estimation With and Without Multiple FACTS Devices-SVC

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***Abstract*—In this paper , State estimation of power systems with and without Flexible AC Transmission systems (FACTS) controllers has been presented and discussed in detail. Firing angle model for SVC is proposed to control the voltage at which it is connected. The proposed model take firing angle as a state variable. To validate the effectiveness of the proposed model Weighted Least Square Algorithm(WLS) is used in IEEE-14 bus system and IEEE-30 bus system. Necessary changes are made in Jacobian matrix for incorporating SVC. Incorporation of one or more FACTS devices into power system state estimation algorithm are investigated. After an accurate estimation has been carried out, the system quantities such as voltage and phase angle has been calculated.**

***Index Terms*— State estimation, Static VAR Compensator, Firing Angle, Weighted Least Square(WLS) Algorithm.**

I. INTRODUCTION

With the fast development of power system, especially the increased use of transmission facilities, it is necessary to explore new ways of maximizing power transfer in existing transmission facilities, while at the same time maintaining the acceptable levels of the network reliability and stability. Transmission systems are undergoing continuous changes mainly from the strong increase in interconnected power transfers, opening of the market for delivery of cheaper energy to the customers, and economic and ecological constraints which delay the building of new transmission facilities. The need for more efficient power systems management, and the fast development of power electronics based on new and powerful semiconductor devices, have given rise to innovative technologies, such as FACTS controllers[1].

FACTS devices can be connected in series, in parallel, or in a combination of both. The benefits they offer to the electrical grid are widely referenced in scientific literature. These benefits include improvement of the stability of the grid, control of the flow of active and reactive power on the grid, loss minimization, and increased grid efficiency. FACTS controllers such as Static Synchronous Compensator (STATCOM), Static VAR Compensator (SVC), Thyristor Controlled Series Compensator (TCSC), Static Synchronous Series Compensator (SSSC) and Unified Power Flow controller (UPFC) are able to change the network parameters in a fast and effective way in order to achieve better system performance [1], [2], [3], [4]. These controllers are used for enhancing dynamic performance of power systems in terms of voltage/angle stability while improving the power transfer capability and voltage profile in steady-state conditions [5], [6]. Steady state modelling of SVC and TCSC and other FACTS devices in the power flow analysis using newton raphson algorithm, resulting in better voltage profile [7], [8].

Static VAR Compensator (SVC) is the FACTS controller based on Thyristor-controlled and Thyristor-switched Reactor (TCR and TSR); and Thyristor-switched capacitor (TSC). SVC is a shunt compensator used for voltage regulation which is achieved by controlling the production, absorption and flow of reactive power through the network. According to the IEEE definition, a Static VAR Compensator (SVC) is a shunt connected static VAR generator or absorber whose output is adjusted to exchange capacitive or inductive current to maintain or control specific parameters of the electrical power system (typically, the bus voltage) [2]. It is mainly used for voltage regulation. For voltage control SVC is usually installed at the receiving node of the transmission lines.

This paper focuses on the development of SVC model and its implementation in Weighted Least Square(WLS) algorithm, to control voltage of the bus. Incorporation of FACTS devices in an existing WLS algorithm results in increased complexity of programming due to the following reasons:

- New terms owing to the contributions from the FACTS devices need to be included in the existing power flow equations of the concerned buses. These terms necessitate modification of existing power flow codes.
- New power flow equations related to the FACTS devices come into the picture, which dictate formulation of separate subroutine(s) for computing them.
- The system Jacobian matrix contains entirely new Jacobian sub-blocks exclusively related to the FACTS devices.

Therefore, new codes have to be written for computation of these Jacobian sub-blocks. Comparison with and without FACTS controllers using WLS state estimation Algorithm has been done. Further a Matlab code is developed for the proposed approach and applied to IEEE-14, 30 bus system and the results are tabulated.

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In section (II) of this paper carries the Static VAR Compensator (SVC) concept and modeling, while section (III) demonstrates the Weighted Least Square (WLS) Algorithm. The results and different cases are presented in section (IV).Finally; conclusion is discussed in section (V).

II. STATIC VAR COMPENSATOR

A. Modeling of SVC

SVC device is a parallel combination of thyristor controlled reactor with a bank of capacitors. It's a shunt connected variable reactance, which either generates or absorbs reactive power in order to regulate the voltage magnitude where it is connected to the AC network. Mainly used for voltage regulation. As an important component for voltage control, it is usually installed at the receiving node of the transmission lines.Fig.1 shows a SVC model with step down transformer.

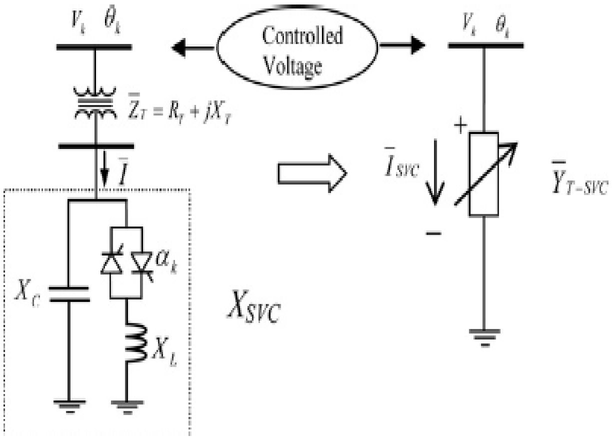

Fig.1 SVC-Transformer representation

In this case, the firing angle $\alpha_{svc}$is adjusted, within limits, to constrain a voltage magnitude $V_k$at a specified value [9]. The total admittance of the combined SVC-transformer set $\bar{Y}_{T-SVC}$, as seen from the high-voltage side of the transformer, consists of the series combination of admittances $\bar{Y}_T$ and $\bar{Y}_{SVC}$:

The total admittance of the combined SVC-Transformer set,

$$\bar{Y}_{T-SVC} = G_{T-SVC} + jB_{T-SVC} \qquad (1)$$

where $G_{T-SVC}$and B_{T-SVC} can be found from the following equations

$$X_{TCR} = \frac{\pi X_L}{2(\pi-\alpha_{SVC})+\sin(2\alpha_{SVC})} \qquad (2)$$

$$X_{EQ} = X_T X_{SVC} \qquad (3)$$

$$X_{SVC}=\frac{X_c X_{TCR}}{X_c-X_{TCR}} \qquad (4)$$

$$G_{T-SVC} =\frac{R_T}{R_T^2+X_{EQ}^2}\; B_{T-SVC} =-\frac{X_{EQ}}{R_T^2+X_{EQ}^2} \qquad (5)$$

The active and reactive powers injected at node k by the single model are,

$$P_k^{T-SVC} = V_k^2 G_{T-SVC};\; Q_k^{T-SVC} = -V_k^2 \qquad (6)$$

At the k^{th}iteration ,the firing angle is upgraded as

$$\alpha_{svc}^{k+1} = \alpha_{svc}^{k} + \Delta\alpha_{svc}^{k}$$

where, $G_{T-SVC}$is the real part of $\bar{Y}_{T-SVC}$ and B_{T-SVC} is the imaginary part of $\bar{Y}_{T-SVC}$

X_{TCR} is the reactance of TCR, X_L and X_c are the inductive and capacitive reactance

X_{EQ}- equivalent reactance, X_T- transformer reactance,

X_{SVC} - SVC reactance, α_{SVC}- firing angle of SVC,

R_T- transformer resistance. V_k- voltage at node k,

P_k^{T-SVC} and $Q_k^{T-SVC}$are active and reactive power injected at node k.

B. SVC V-I Characteristics

Use SVC is a shunt controlled susceptance which injects reactive power into thereby increasing the bus voltage back to its net desired voltage level. If bus voltage increases, the SVC will inject less (or TCR will absorb more) reactive power, and the result will be to achieve the desired bus voltage. The SVC can be operated in two different modes:

(*i*)In voltage regulation mode (the voltage is regulated within limits as explained below).

(*ii*)In VAR control mode (the SVC susceptance is kept constant).

From V-I curve of SVC, From Fig.2,

$$V=V_{ref}+X_s I\ ;$$

In regulation range ($-B_{Cmax}$< B <B_{Cmin})

$V= \frac{I}{B_{Cmax}}$;SVC is fully capacitive (B=B_{Cmax})

$V=\frac{I}{B_{lmax}}$; SVC is fully inductive (B= B_{lmax})

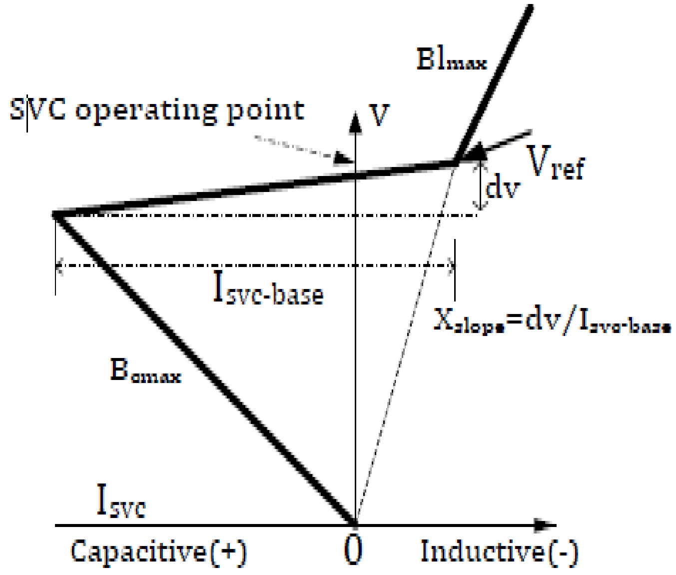

Fig 2. Steady-state V-I characteristics of SVC

III. WLS STATE ESTIMATION ALGORITHM

A. WLS Algorithm without FACTS Devices

WLS State Estimation involves the iterative solution of the normal equations given by the following equation ,

$$G(x^k)\Delta x^k = H^T(x^k)R^{-1}\,[z - h(x^k)]$$

The iterative solution algorithm for WLS state estimation problem can be outlined as follows:

1. Read the network data ; measurements and their standard deviations.
2. Set iteration count k=0 ; Initialize the state vector x^k , typically as a flat start.
3. Knowing the measurement equations, compute the measurement Jacobian matrix H(x^k).
4.Calculate the gain matrix, G(x^k) using
G(x^k) = $H^T(x^k)R^{-1}$ H(x^k).
5. Calculate the right hand side vector t^k, given by $t^k = H^T(x^k)R^{-1}\,[z - h(x^k)]$
6.Decompose G(x^k) and solve
G(x^k)Δx^k = $H^T(x^k)R^{-1}\,[z - h(x^k)]$ for Δx^k
Update $x^{k+1} = x^k + \Delta x^k$
7.Test for convergence , max $|\Delta x^k| \leq \varepsilon$?
8.If no, set k=k+1; go to step 3. Else Stop.

B. WLS Algorithm with facts controllers

Changes are made with WLS algorithm.

1.Read the system input data; line data, bus data, generator and load data.
2.Modified admittance matrix Y bus when svc added to node k.
3.Combining the SVC power equations with network equation,
4.The conventional jacobian matrix are formed due to the inclusion of SVC. The inclusion of these variables increases the dimensions of the jacobian matrix.
5. Increase in size of gain matrix.
6. Then steps are followed WLS state estimation algorithm.

C. Jacobian matrix formation with FACTS controller

Here Firing Angle of SVC $\alpha_{svc}$is taken as an additional state variable which it is added to the Jacobian matrix. If we are incorporating a single SVC, then one state variable added to the jacobian matrix with respect to the injection bus. If we are incorporating Three SVCs, then three state variables are added to the jacobian matrix.

For IEEE-14 bus system,
(i) 14bus without SVC
No. of state variables =27
No. of measurements z=47
h=47x27, g=27x27.
(ii) 14bus with one SVC connected
No. of state variables =28
No. of measurements z=42
h=42x28, g=28x28.
(ii) 14bus with three SVCs connected,
No. of state variables =30
No. of measurements z=47
h=47x30, g=30x30.
For IEEE-30 bus system,
(i) 30 bus without SVC
No. of state variables =59
No. of measurements z=93
h=93x59, g=59x59.
(ii) 30 bus with Three SVCs connected,
No. of state variables =62
No. of measurements z=93
h=93x62, g=62x62.

x^ is the state variable vector, z is vector of measurements.

$$H_{old} = \begin{bmatrix} \frac{x^\wedge}{z} & \Theta & V \\ RealPowerFlow & H_{11} & H_{12} \\ RealPowerInjection & H_{21} & H_{22} \\ ReactivePowerFlow & H_{31} & H_{32} \\ ReactivePowerInjection & H_{41} & H_{42} \\ VoltageMagnitude & H_{51} & H_{52} \end{bmatrix} \tag{7}$$

Changes made when SVC is added, increase in state variable and changes in gain and corresponding residual matrix. An extra column (α_{svc})is added to the jacobian matrix with respect to the real and reactive power injection. All the other terms in the α_{svc} column will become zero. Since we are taking the transformer resistance to R_T be zero, P_K^{T-SVC} will also equal to zero. First derivative of real and reactive power injections of SVC with respect to the state variable are,

$$P_K^{T-SVC} = 0 \tag{8}$$

$$Q_{svc} = -\frac{V_k}{X_L X_C}\left[X_L - \frac{X_C}{\pi}\left[2(\pi - \alpha_{svc}) + \sin(2\alpha_{svc})\right]\right] \tag{9}$$

$$\frac{\partial Q_{svc}}{\partial V_k} = -\frac{2V_k}{X_L X_C}\left[X_L - \frac{X_C}{\pi}\left[2(\pi - \alpha_{svc}) + \sin(2\alpha_{svc})\right]\right] \tag{10}$$

$$\frac{\partial Q_{svc}}{\partial \alpha_{svc}} = \frac{2V_k^2}{\pi X_L}[\cos(2\alpha_{svc}) - 1 \tag{11}$$

$$H_{new} = \begin{bmatrix} \frac{x^\wedge}{z} & \Theta & V & \alpha_{svc} \\ RealPowerFlow & H_{11} & H_{12} & H_{13} \\ RealPowerInjection & H_{21} & H_{22} & H_{23} \\ ReactivePowerFlow & H_{31} & H_{32} & H_{33} \\ ReactivePowerInjection & H_{41} & H_{42} & H_{43} \\ VoltageMagnitude & H_{51} & H_{52} & H_{53} \end{bmatrix} \tag{12}$$

$$H_{21new} = H_{21old} + H_{21svc}$$
$$H_{22new} = H_{22old} + H_{22svc}$$
$$H_{41new} = H_{41old} + H_{41svc}$$
$$H_{42new} = H_{42old} + H_{42svc}$$

IV. RESULT AND DISCUSSION

IEEE 14bus and 30-bus test system is used to assess the effectiveness of SVC model developed in this paper. Four cases are considered, one SVC is connected at bus 10 and three SVCs are connected at bus 7,10 and 14 in IEEE 14-bus system and, three SVCs are connected at bus 11,15 and 24.

CASE I:

Table-I gives the state estimation of IEEE-14 bus system without FACTS devices and with FACTS devices (SVC) connected at buses 10. Initial Firing angle is set to be 130˚ which lies on the capacitive region. $X_c$andX_L values are chosen as 1.07pu and 0.288pu. The firing angle can vary from 90˚≤ α_{svc}≤180˚. The specified voltage calculated is 1.0405.

Table-I
IEEE-14 bus system with SVC connected at bus 10

Bus No.	Without SVC		With SVC connected at bus 10	
	V(pu)	Phase Angle	V(pu)	PhaseAngle
1	1.0500	0.0000	1.0592	0.0000
2	1.0313	-5.4327	1.0425	-4.9358
3	0.9979	-12.0144	1.0146	-11.2071
4	0.9896	-11.5493	1.0080	-10.7945
5	0.9934	-10.0134	1.0114	-9.2910
6	1.0356	-16.5087	1.0622	-15.4374
7	1.0259	-14.5229	1.0427	-13.5734
8	1.0623	-14.4965	1.0774	-13.5428
9	1.0105	-16.1555	1.0282	-15.0784
10	1.0020	-16.8402	1.0405	-16.3545
11	0.9961	-17.6053	1.0316	-16.6659
12	1.0158	-17.6226	1.0435	-16.4443
13	1.0104	-17.5188	1.0385	-16.3530
14	0.9985	-17.0632	1.0208	-15.9321

CASE II:

Table-II gives the state estimation of IEEE-14 bus system with FACTS devices (SVC) connected at buses 7, 10 and 14. Initial Firing angle is set to be 90˚ which lies on the capacitive region. $X_c$andX_L values are chosen as 2.07 and 1.28. SVC absorbs 13. 2 MVAR from bus 10 and injects 24.6 MVAR to bus 14 in order to keep the voltage magnitude at 1 pu, with final firing angle of 153˚.

Table-II
IEEE-14 bus system with SVC connected at buses 7, 10, 14

Bus No.	Three SVCs connected at bus 7,10 and 14	
	Voltage	Phase Angle
1	1.0630	0.0000
2	1.0463	-4.9002
3	1.0186	-11.1253
4	1.0119	-10.7169
5	1.0154	-9.2193
6	0.9955	-15.6237
7	1.0000	-13.5383
8	1.0790	-13.5152
9	1.0277	-15.0625
10	1.0000	-15.8144
11	0.9704	-16.7216
12	0.9756	-16.7729
13	0.9703	-16.6692
14	1.0000	-16.2457

CASE III:

Table-III gives the state estimation of IEEE-30 bus system with FACTS devices (SVC) connected at buses 11, 15 and 24. Initial Firing angle is set to be 90˚ which lies on the capacitive region. $X_c$andX_L values are chosen as 2.07 and 1.28. SVC injects11.71 MVAR to bus 15 and 8.82 MVAR to bus 24 in order to keep the voltage magnitude at 1 pu, with final firing angle of 143˚.

Table-III
IEEE-30 bus system with SVC connected at buses 11,15,24

Bus No	Without SVC		SVC at bus 11,15,24	
	V(pu)	Phase Angle	V(pu)	Phase Angle
1	0.9865	0.0000	0.9948	0.0000
2	0.9700	-6.2635	0.9910	-5.8146
3	0.9474	-8.8420	0.9690	-8.2363
4	0.9384	-10.9021	0.9615	-10.0701
5	0.9335	-16.4941	0.9566	-15.0023
6	0.9395	-12.9975	0.9622	-11.9257
7	0.9287	-15.0443	0.9502	-13.7010
8	0.9449	-13.9608	0.9667	-12.7741
9	0.9667	-16.4813	0.9858	-15.1492
10	0.9472	-18.3445	0.9677	-16.8450
11	1.0093	-16.4813	1.0000	-15.1492
12	0.9746	-17.6918	0.9916	-16.2908
13	0.9954	-17.6918	1.0123	-16.2908
14	0.9959	-18.7137	0.9739	-17.2280
15	0.9491	-18.7299	1.0000	-17.2566
16	0.9555	-18.2800	0.9747	-16.8044
17	0.9441	-18.5714	0.9644	-17.0480
18	0.9352	-19.4195	0.9555	-17.8347
19	0.9306	-19.6063	0.9513	-17.9674
20	0.9339	-19.3581	0.9545	-17.7498
21	0.9328	-18.9821	0.9539	-17.4040
22	0.9372	-18.7111	0.9577	-17.1607
23	0.9331	-18.9957	0.9540	-17.4141
24	0.9231	-19.0788	1.0000	-17.4556
25	0.9270	-18.7784	0.9500	-17.1536
26	0.9070	-19.2593	0.9324	-17.5501
27	0.9395	-18.2962	0.9617	-16.7165
28	0.9398	-13.7910	0.9622	-12.6318
29	0.9177	-19.7604	0.9424	-17.9807
30	0.9051	-20.8172	0.9311	-18.8598

V. CONCLUSION

In this paper, SVC firing angle model is developed and discussed in detail. SVC firing angle model is considered in which it injects and absorbs reactive power thereby increasing the voltage profile by achieving the desired voltage at a specified bus. The firing angle can vary within certain limits in order to achieve the desired voltage profile. MATLAB coding has been carried out for IEEE 14-bus and 30-bus system in order to show the effectiveness and robustness of the proposed model in State Estimation using WLS Algorithm. The implemented model has been taken for different case studies.

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