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Modeling FACTS Devices in Power System State Estimation

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ABSTRACT

In this paper is modeled different types of control devices including various kinds of FACTS devices based on power system states. Also, the impact of each device on the amount of injection active or reactive powers as well as active and reactive power flow will be investigated. Based on the type of these devices which can be in parallel, in series or in series–shunt in power systems, proposed models are considered differently. Accordingly, case studies will be performed for three different types of control devices installed in series, in shunt and in series-shunt fashions. State estimation results based on Weighted Least Square not only confirm the proposed models' effectiveness in accurately state estimating of the system and measurement values but also shows that the estimated values can be obtained from the states of the control devices.

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1. INTRODUCTION

In recent years, the role of power system state estimators in establishing a real-time control system for energy control centers has been recognized by more and more utilities. State estimators are very necessary in establishing a complete, reliable database for power system real-time computer applications [1].

Different algorithms have been presented to estimate the state of power systems. The algorithms are divided into the two major intelligent and mathematic-based methods. In contrast to the mathematical models, intelligent models have a reasonable speed [2-6], however, due to the difficulty in training intelligent models in the different network situations, their accuracy is less than the mathematical models. Consequently, despite the advances in the intelligent models, the mathematical methods are still used in state estimation of power systems.

In mathematical method, the aim of state estimation is to find the estimate x of the true state x which best fits the measurements z related to x through the nonlinear model [7]:

$$z = h(x) + e \tag{1}$$

Where:
z: m-dimensional measurement vector
x: n-dimensional state vector of voltage magnitudes and phase angles
e: m-dimensional error vector
$h(x)$: vector with non-linear functions

The state estimation procedure involves finding the n-dimensional state vector x resulting from e minimization.

For this purpose, several methods have been provided including the weighted least square (WLS), the weighted least absolute value (WLAV), non-quadratic estimators and the least median squares. Among these methods, the first two models have good accuracy [8, 9]. Also, the first model has better speed than the second model and will be used much more [10, 11].

WLS-based state estimation objective function is given as (2) [12].

$$J(x) = [z - h(x)]^T W [z - h(x)] \quad (2)$$

Where $W=R^{-1}_z$ is a diagonal matrix whose elements are the inverse of the covariance matrix of measurements (R_z).

In function expressed in (2), W and Z are constant for a network in a given state, but *h(x)* almost is a nonlinear function and its mathematical model will be different based on measurement type and network structure. Network structure and thus *h(x)* is depend on the installed control devices such as capacitors, reactors, phase shifters and FACTS devices and *h(x)* should be modeled based on device type. In [8] the influence of capacitors, reactors and phase shifters have been studied, and in this work, the impact of different types of FACTS devices in modeling *h(x)* and thus power system state estimation will be investigated.

2. MODELING MEASURMENT FUNCTION

Measurements can be of different types. Existing measurements are usually active and reactive power of lines, injected active and reactive power as well as voltage magnitude of bus-bars measurements, also system states are voltage magnitude and angle of bus-bars, it also should be noted that the voltage of reference bus-bar is considered zero, therefore the state vector can be written:

$$x^T = [V_1 V_2 \ldots V_n \theta_2 \theta_3 \ldots \theta_n] \quad (3)$$

In which:
x: state vector
V_n: voltage magnitude of nth bus-bar
θ_n: voltage angle of n^{th} bus-bar

In a state in which there is no control device in the network, for each of the aforementioned measurements, h(x) can be calculated as follows.

2.1. Injection measurements

Injection active and reactive powers in i^{th} bus are as follow:

$$p_i = \sum_{j=1}^{n} V_i V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) \quad (4)$$

$$Q_i = \sum_{j=1}^{n} V_i V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) \quad (5)$$

Where, θ_{ij}, G_{ij} and B_{ij} are obtained using (6) to (8).

$$\theta_{ij} = \theta_i - \theta_j \quad (6)$$

$$G_{ij} = \mathrm{Re}\,al(Y_{ij}) \quad (7)$$

$$B_{ij} = \mathrm{Im}\,ag(Y_{ij}) \quad (8)$$

Y_{ij} is the network admittance matrix.

2.2. Power flow measurements

Active and reactive powers in *i-j* line are as follow:

$$p_{ij} = V_i^2 g_{ij} - V_i V_j (g_{ij} \cos\theta_{ij} + b_{ij} \sin\theta_{ij}) \tag{9}$$

$$Q_{ij} = -V_i^2 (b_{si} + b_{ij}) - V_i V_j (g_{ij} \sin\theta_{ij} - b_{ij} \cos\theta_{ij}) \tag{10}$$

Where:
g_{ij}: series electrical conductance of transmission line
b_{ij}: series susceptance of transmission line
b_{si}: shunt susceptance of transmission line

2.3. Voltmeter

Voltmeter itself is a state variable. Thus:

$$V_{est} = V_i \tag{11}$$

Where:
V_i: measured voltage magnitude
V_{est}: estimated voltage magnitude

When FACTS devices are utilized in the network, these devices which are in three types of parallel, series and series-shunt can be used to change *h(x)*.

2.4. SVC and STATCOM

SVC and STATCOM act as the capacitor and reactor with the variable impedance or reactive power source.

2.4.1. SVC or STATCOM as fixed impedance installed in the ith bus

By installing a susceptance b_{sh} in the i^{th} bus, the amount of injected reactive power at the bus will be changed as follows:

$$Q_i = \sum_{j=1}^{n} V_i V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) - b_{sh,i} V_i^2 \tag{12}$$

Where $b_{sh,i}$ is the susceptance of SVC or STATCOM installed in i^{th} bus. It should be noted that the sign of b_{sh} is negative for inductive state.

2.4.2. SVC or STATCOM as fixed reactive power installed in the ith bus

By installing a reactive power source, Q_{sh}, in the i^{th} bus, the amount of injected reactive power at the bus will be changed as follows:

$$Q_i = \sum_{j=1}^{n} V_i V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) + Q_{sh,i} \tag{13}$$

In which, $Q_{sh,i}$ is reactive power of SVC or STATCOM installed in i^{th} bus. It should be noted that the sign of Q_{sh} is negative for capacitive state.

2.5. TCSC, GCSC and TSSC

According to the Fig. 1, a GCSC is constructed of a fixed capacitor in shunt with a bidirectional switch, GTO, and it can be seen from Fig. 2 that aTSSC is built of a fixed capacitor in shunt with a bidirectional switch, thyristor, and TCSC structure is depicted in Fig. 3 as a fixed capacitor in shunt with a TCR. Consequently, these three devices, from the viewpoint of the power system, are variable impedance in series with transmission line, and as it can be seen from the (14), it leads to change the line impedance.

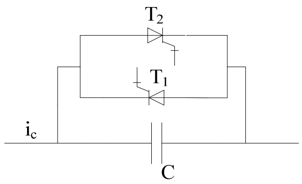

Figure 1. Electrical model of GCSC

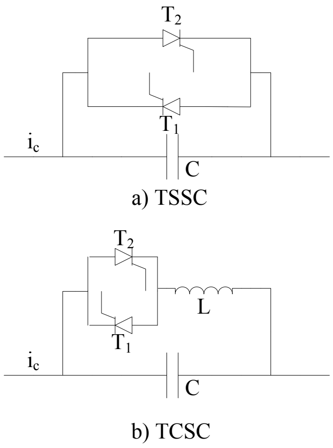

Figure 2. Electrical models of TSSC and TCSC

$$b_{ij}^{new} = b_{ij} + b'' \tag{14}$$

Where:
b": series susceptance of TSSC, TCSC or GCSC
TCSC could be also resulted in changing network admittance matrix and injection powers.

$$Y_{ij}^{new} = Y_{ij} - jb'' \tag{15}$$

$$Y_{ji}^{new} = Y_{ji} - jb'' \tag{16}$$

$$Y_{ii}^{new} = Y_{ii} + jb'' \tag{17}$$

$$Y_{ijj}^{new} = Y_{jj} - jb'' \tag{18}$$

2.6. SSSC

As shown in Fig. 3, SSSC is composed of a voltage source in series with the transmission line. This voltage source injects the voltage with the magnitude and angle, Vq and θq, respectively, which is in same alignment with the transmission line voltage drop, therefore (20) is justified for SSSC.

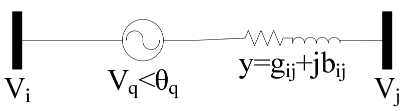

Figure 3. Electrical model of SSSC

$$\hat{V}_i - \hat{V}_j = V_i \angle \theta_i - V_j \angle \theta_j = (V_i \cos\theta_i - V_j \cos\theta_j) + j(V_i \sin\theta_i - V_j \sin\theta_j) \tag{19}$$

$$\theta_q = \tan^{-1}\left(\frac{V_i \sin\theta_i - V_j \sin\theta_j}{V_i \cos\theta_i - V_j \cos\theta_j} \right) \tag{20}$$

Converting the series voltage source into the shunt current source, according to the Fig. 4, the injected power of shunt current source is calculated as follows:

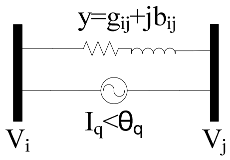

Figure 4. Simplified electrical model of SSSC

$$\hat{I}_q = V_q \angle \theta_q (g_{ij} + j b_{ij}) \tag{21}$$

$$\hat{S}_{ij,SSSC} = \hat{V}_i \hat{I}_q^* = V_i V_q \left[g_{ij} \cos\theta_{iq} + b_{ij} \sin\theta_{iq} \right] + j V_i V_q \left[g_{ij} \sin\theta_{iq} - b_{ij} \cos\theta_{iq} \right] \tag{22}$$

$$P_{ij,SSSC} = V_i V_q \left[g_{ij} \cos\theta_{iq} + b_{ij} \sin\theta_{iq} \right] \tag{23}$$

$$Q_{ij,SSSC} = V_i V_q \left[g_{ij} \sin\theta_{iq} - b_{ij} \cos\theta_{iq} \right] \tag{24}$$

In which:

$$\theta_{iq} = \theta_i - \theta_q \tag{25}$$

It should be noted that:

$$P_{ij}^{new} = P_{ij} + P_{ij,SSSC} \tag{26}$$

$$Q_{ij}^{new} = Q_{ij} + Q_{ij,SSSC} \tag{27}$$

In the same way can be writing:

$$P_{ji,SSSC} = V_j V_q \left[g_{ij} \cos\theta_{jq} + b_{ij} \sin\theta_{jq} \right] \tag{28}$$

$$Q_{ji,SSSC} = V_j V_q \left[g_{ij} \sin\theta_{jq} - b_{ij} \cos\theta_{jq} \right] \tag{29}$$

$$P_{ji}^{new} = P_{ji} + P_{ji,SSSC} \tag{30}$$

$$Q_{ji}^{new} = Q_{ji} + Q_{ji,SSSC} \tag{31}$$

The injection powers may be changed as follows:

$$P_i^{new} = P_i + P_{ij,SSSC} \tag{32}$$

$$Q_i^{new} = Q_i + Q_{ij,SSSC} \tag{33}$$

$$P_j^{new} = P_j + P_{ji,SSSC} \quad (34)$$

$$Q_j^{new} = Q_j + Q_{ji,SSSC} \quad (35)$$

2.7. TCPAR

TCPAR is a phase angle regulator, and as shown in Fig. 5 is placed in series with the transmission line.

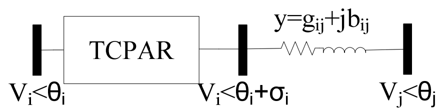

Figure 5. Electrical model of TCPAR

Thus, it is enough to make change in the equations P_{ij}, Q_{ij}, P_{ji}, Q_{ji}, P_i, P_j, Q_i and Q_j use of followed variable.

$$\theta_i^{new} = \theta_i + \Delta\theta \quad (36)$$

2.8. TCVAR

As illustrated in Fig. 6, TCVAR is a voltage regulator placed in series with the transmission line.

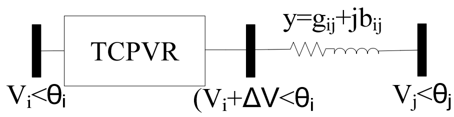

Figure 6. Electrical model of TCVAR

Thus to calculate the injection and transmitted powers, variable change is utilized.

$$V_i^{new} = V_i + \Delta V \quad (37)$$

2.9. UPFC

UPFC, as depicted in Fig. 7 consists of a series voltage source and a shunt current source with the condition that the injected active power of series voltage source and the shunt current source is same. Modeling the voltage source is identical to the SSSC modeling with the difference that the condition of (20) is eliminated and replaced by this condition.

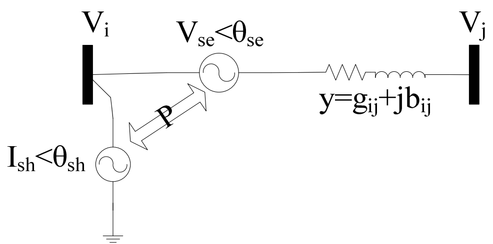

Figure 7. Electrical model of UPFC

$$P_{ij,UPFC} = P_{ij,SSSC} \quad (38)$$

$$Q_{ij,UPFC} = Q_{ij,SSSC} \quad (39)$$

$$P_{ji,UPFC} = P_{ji,SSSC} \quad (40)$$

$$Q_{ji,UPFC} = Q_{ji,SSSC} \quad (41)$$

$$P_{ij}^{new} = P_{ij} + P_{ij,UPFC} \quad (42)$$

$$Q_{ij}^{new} = Q_{ij} + Q_{ij,UPFC} \quad (43)$$

$$P_{ji}^{new} = P_{ji} + P_{ji,UPFC} \quad (44)$$

$$Q_{ji}^{new} = Q_{ji} + Q_{ji,UPFC} \quad (45)$$

Shunt current source changes only the injection power of i^{th} bus.

$$\hat{S}_{i,sh} = V_i I_{sh}^* = V_i I_{sh}\left[\cos\theta_{i,sh} + j\sin\theta_{i,sh}\right] \quad (46)$$

$$P_{i,sh} = V_i I_{sh} \cos\theta_{i,sh} \quad (47)$$

$$Q_{i,sh} = V_i I_{sh} \sin\theta_{i,sh} \quad (48)$$

It is important to note that according to the aforementioned condition $P_{i,sh}$ and P_{ij} should be equal, thus injected active power of i^{th} bus is exactly equal to the injected active power, $P_{i,sh}$. Injected reactive power of i^{th} bus as well as injected active and reactive power of j^{th} bus will be changed according to the following equation, too.

$$P_i^{new} = P_i + P_{i,sh} \quad (49)$$

$$Q_i^{new} = Q_i + Q_{ij,UPFC} + Q_{i,sh} \quad (50)$$

$$P_j^{new} = P_j + P_{ji,UPFC} \quad (51)$$

$$Q_j^{new} = Q_j + Q_{ji,UPFC} \quad (52)$$

2.10. IPFC

IPFC is almost the same as SSSC and UPFC except that as it can be seen from Fig. 8, it has two voltage sources in series with two or more circuit's transmission lines; and the summed injected active power by the voltage sources are zero.

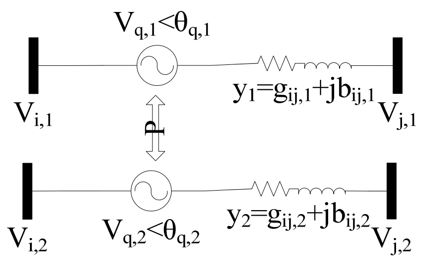

Figure 8. Electrical model of IPFC for the two circuit's transmission lines

Thus, injected and transmitted powers through each line are changing like the SSSC if the condition of (20) will be removed and replaced by the condition of previous paragraph.

3. CASE STUDY

For case studies, IEEE 14-bus system is selected. As shown in Fig. 9, this system has a variety of line power flow measurements, voltage magnitude measurements and power injection measurements.

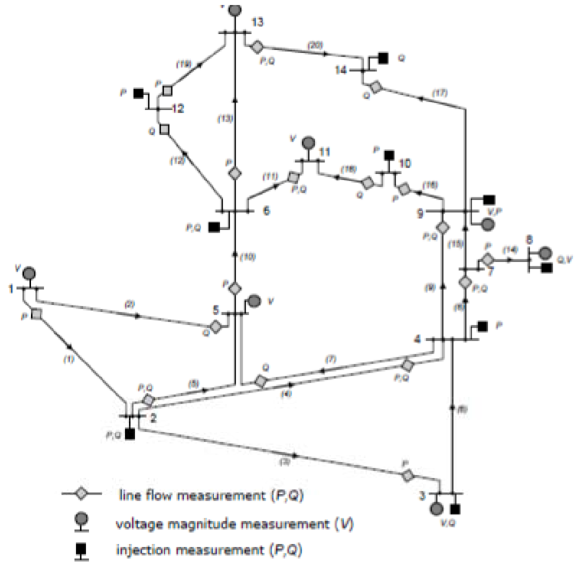

Figure 9. IEEE 14-bus system

In the first mode, it is assumed that there are no control devices in the network. WLS state estimation results are be obtained and given in Table 1.

Table 1.State estimation in the normal mode for IEEE 14-bus system

Measurements	Actual data (pu)	Measured data (pu)	Estimated data (pu)	Measurements	Actual data (pu)	Measured data (pu)	Estimated data (pu)
V_1	1.0600	1.1108	1.0600	$Q_{10,11}$	-0.0162	-0.0161	0.0298
V_3	1.0100	1.0220	1.0100	$Q_{13,14}$	0.0175	0.0182	0.0154
V_4	1.0180	1.0636	1.0180	$Q_{5,1}$	0.0223	0.0224	0.0243
V_5	1.0200	1.0071	1.0200	$Q_{4,2}$	0.0302	0.0289	0.0316
V_8	1.0900	1.0603	1.0900	$Q_{5,4}$	-0.1420	-0.1462	-0.1383
V_9	1.0560	1.0632	1.0560	$Q_{7,4}$	0.1138	0.1169	0.1146
V_{11}	1.0570	1.0634	1.0470	$Q_{9,4}$	0.0173	0.0173	0.0168
V_{13}	1.0500	1.0270	1.0500	$Q_{11,6}$	-0.0344	-0.0328	-0.0767
$P_{1,2}$	1.5688	1.6272	1.5695	$Q_{12,6}$	-0.0235	-0.0246	-0.0242
$P_{2,5}$	0.4152	0.4296	0.4141	$Q_{14,9}$	-0.0336	-0.0327	-0.0324
$P_{4,5}$	-0.6116	-0.6207	-0.6118	P_2	0.1830	0.1903	0.1795
$P_{5,6}$	0.4409	0.4508	0.4408	P_4	-0.4780	-0.4755	-0.4760
$P_{6,13}$	0.1775	0.1734	0.1785	P_6	-0.1120	-0.1071	-0.0905
$P_{7,8}$	0	0	0	P_7	0	0	-0.0008
$P_{12,13}$	0.0161	0.0155	0.0166	P_9	-0.2950	-0.2911	-0.2946
$P_{13,14}$	0.0564	0.0573	0.0554	P_{10}	-0.0900	-0.0901	-0.0709
$P_{3,2}$	-0.7091	-0.6975	-0.7085	P_{12}	-0.0610	-0.0603	-0.0607
$P_{4,2}$	-0.5445	-0.5509	-0.5435	Q_2	0.3086	0.2932	0.3047
$P_{7,4}$	-0.2807	-0.2884	-0.2811	Q_3	0.0608	0.0621	0.0588
$P_{9,4}$	-0.1608	-0.1645	-0.1608	Q_4	0.0390	0.0384	0.0381
$P_{11,6}$	-0.0730	-0.0747	-0.0924	Q_6	0.0523	0.0531	0.0970
$P_{10,9}$	-0.0521	-0.0498	-0.0527	Q_9	-0.1660	-0.1605	-0.1713
$Q_{2,5}$	0.0117	0.0114	0.0091	Q_{14}	-0.0500	-0.0506	-0.0468

In the next step, it is assumed that a parallel device having capacitive impedance of 0.2 pu to be installed in bus-14. In this mode the device is modeled according (13) as a reactive power source. The WLS state estimation results are given in Table 2.

Table 2.State estimation regarding a shunt device for IEEE 14-bus system

[9] Measurements	[10] Actual data (pu)	[11] Measured data (pu)	[12] Estimated data (pu)	[13] Measurements	[14] Actual data (pu)	[15] Measured data (pu)	[16] Estimated data (pu)
V_1	1.0600	1.0600	1.0601	$Q_{13,14}$	-0.0883	-0.0883	-0.0884
V_3	1.0100	1.0100	1.0101	$Q_{5,1}$	0.0294	0.0294	0.0291
V_4	1.0200	1.0200	1.0201	$Q_{4,2}$	0.0443	0.0443	0.0441
V_5	1.0210	1.0210	1.0211	$Q_{5,4}$	-0.1640	-0.1640	-0.1640
V_8	1.0900	1.0900	1.0900	$Q_{7,4}$	0.1419	0.1419	0.1419
V_9	1.0710	1.0710	1.0712	$Q_{9,4}$	0.0425	0.0425	0.0422
V_{11}	1.0630	1.0630	1.0632	$Q_{11,6}$	-0.0025	-0.0025	-0.0027
V_{13}	1.0610	1.0610	1.0608	$Q_{12,6}$	-0.0024	-0.0024	-0.0025
$P_{1,2}$	1.5696	1.5696	1.5692	$Q_{14,9}$	0.0926	0.0926	0.0924
$P_{2,5}$	0.4144	0.4144	0.4142	P_2	0.1830	0.1830	0.1829
$P_{4,5}$	-0.6217	-0.6217	-0.6217	P_4	-0.4780	-0.4780	-0.4780
$P_{5,6}$	0.4306	0.4306	0.4303	P_6	-0.1120	-0.1120	-0.1120
$P_{6,13}$	0.1763	0.1763	0.1761	P_7	0	0	0.0001
$P_{7,8}$	0	0	-0.0003	P_9	-0.2950	-0.2950	-0.2949
$P_{12,13}$	0.0120	0.0120	0.0119	P_{10}	-0.0900	-0.0900	-0.0899
$P_{13,14}$	0.0514	0.0514	0.0512	P_{12}	-0.0610	-0.0610	-0.0610
$P_{3,2}$	-0.7088	-0.7088	-0.7088	Q_2	0.2863	0.2863	0.2863
$P_{4,2}$	-0.5463	-0.5463	-0.5461	Q_3	0.0469	0.0469	0.0468
$P_{7,4}$	-0.2878	-0.2878	-0.2875	Q_4	0.0390	0.0390	0.0390
$P_{9,4}$	-0.1654	-0.1654	-0.1652	Q_6	-0.0946	-0.0946	-0.0947
$P_{11,6}$	-0.0684	-0.0684	-0.0683	Q_9	-0.1660	-0.1660	-0.1661
$P_{10,9}$	-0.0567	-0.0567	-0.0567	Q_{14}	-0.0500	-0.0500	-0.0500
$Q_{2,5}$	0.0029	0.0029	0.0030	$b_{sh,14}$	0.2	-	0.1999
$Q_{10,11}$	0.0158	0.0158	0.0159				

To verify the effectiveness of series devices modeling, it is assumed that a series device with the impedance of 0.0296 p.u. to be installed in line 1-2. In this case, this device changes the impedance of the transmission line according to (14). The WLS state estimation results are shown in Table 3.

Table 3.State estimation regarding a series device for IEEE 14-bus system

[17] Measurements	[18] Actual data (pu)	[19] Measured data (pu)	[20] Estimated data (pu)	[21] Measurements	[22] Actual data (pu)	[23] Measured data (pu)	[24] Estimated data (pu)
V_1	1.0600	1.0600	1.0599	$Q_{13,14}$	0.0179	0.0179	0.0176
V_3	1.0100	1.0100	1.0099	$Q_{5,1}$	-0.0182	-0.0182	-0.0183
V_4	1.0180	1.0180	1.0175	$Q_{4,2}$	0.0460	0.0460	0.0460
V_5	1.0200	1.0200	1.0195	$Q_{5,4}$	-0.1231	-0.1231	-0.1228
V_8	1.0900	1.0900	1.0900	$Q_{7,4}$	0.1142	0.1142	0.1138
V_9	1.0560	1.0560	1.0558	$Q_{9,4}$	0.0177	0.0177	0.0174
V_{11}	1.0570	1.0570	1.0566	$Q_{11,6}$	-0.0351	-0.0351	-0.0346
V_{13}	1.0500	1.0500	1.0499	$Q_{12,6}$	-0.0237	-0.0237	-0.0251
$P_{1,2}$	1.6876	1.6876	1.6876	$Q_{14,9}$	-0.0332	-0.0332	-0.0334
$P_{2,5}$	0.4668	0.4668	0.4668	P_2	0.1830	0.1830	0.1829
$P_{4,5}$	-0.5613	-0.5613	-0.5611	P_4	-0.4780	-0.4780	-0.4781
$P_{5,6}$	0.4375	0.4375	0.4377	P_6	-0.1120	-0.1120	-0.1122
$P_{6,13}$	0.1764	0.1764	0.1766	P_7	0	0	0.0000
$P_{7,8}$	0	0	-0.0004	P_9	-0.2950	-0.2950	-0.2951
$P_{12,13}$	0.0159	0.0159	0.0156	P_{10}	-0.0900	-0.0900	-0.0898
$P_{13,14}$	0.0552	0.0552	0.0544	P_{12}	-0.0610	-0.0610	-0.0612
$P_{3,2}$	-0.7262	-0.7262	-0.7261	Q_2	0.5736	0.5736	0.5736
$P_{4,2}$	-0.5805	-0.5805	-0.5805	Q_3	0.0599	0.0599	0.0601

17 Mea surements	18 A ctual data (pu)	19 M easured data (pu)	20 E stimated data (pu)	21 Mea surements	22 A ctual data (pu)	23 M easured data (pu)	24 E stimated data (pu)
$P_{7,4}$	-0.2828	-0.2828	-0.2826	Q_4	0.0390	0.0390	0.0392
$P_{9,4}$	-0.1620	-0.1620	-0.1620	Q_6	0.0522	0.0522	0.0519
$P_{11,6}$	-0.0709	-0.0709	-0.0708	Q_9	-0.1660	-0.1660	-0.1660
$P_{10,9}$	-0.0542	-0.0542	-0.0546	Q_{14}	-0.0500	-0.0500	-0.0500
$Q_{2,5}$	-0.0022	-0.0022	-0.0023	$b_{se,1,2}$	0.0296	-	0.0296
$Q_{10,11}$	-0.0168	-0.0168	-0.0167				

For the parallel-series devices, it is assumed that a UPFC with $V_{se} = 0.0158 <95.49\ ^o$ and $I_{sh}=0.408<-29.34^o$ to be installed in line 1-2. UPFC, in this mode, is modeled based on (38) to (52) and WLS state estimation is done. The results are obtained as given in Table 4.

Table 4.State estimation regarding a UPFC for IEEE 14-bus system

25 Mea surements	26 A ctual data (pu)	27 M easured data (pu)	28 E stimated data (pu)	29 Mea surements	30 A ctual data (pu)	31 M easured data (pu)	32 E stimated data (pu)
V_1	1.0600	1.0600	1.0599	$Q_{5,1}$	0.0562	0.0562	0.0564
V_3	1.0100	1.0100	1.0101	$Q_{4,2}$	0.0621	0.0621	0.0628
V_4	1.0260	1.0260	1.0258	$Q_{5,4}$	-0.2451	-0.2451	-0.2449
V_5	1.0250	1.0250	1.0250	$Q_{7,4}$	0.0927	0.0927	0.0926
V_8	1.0900	1.0900	1.0900	$Q_{9,4}$	0.0099	0.0099	0.0098
V_9	1.0600	1.0600	1.0601	$Q_{11,6}$	-0.0303	-0.0303	-0.0302
V_{11}	1.0590	1.0590	1.0588	$Q_{12,6}$	-0.0233	-0.0233	-0.0224
V_{13}	1.0510	1.0510	1.0510	$Q_{14,9}$	-0.0358	-0.0358	-0.0359
$P_{1,2}$	1.5421	1.5421	1.5424	P_2	0.1830	0.1830	0.1830
$P_{2,5}$	0.4468	0.4468	0.4474	P_4	-0.4780	-0.4780	-0.4779
$P_{4,5}$	-0.6849	-0.6849	-0.6851	P_6	-0.1120	-0.1120	-0.1120
$P_{5,6}$	0.4213	0.4213	0.4221	P_7	0	0	0.0003
$P_{6,13}$	0.1713	0.1713	0.1717	P_9	-0.2950	-0.2950	-0.2950
$P_{7,8}$	0	0	0.0002	P_{10}	-0.0900	-0.0900	-0.0897
$P_{12,13}$	0.0145	0.0145	0.0148	P_{12}	-0.0610	-0.0610	-0.0612
$P_{13,14}$	0.0488	0.0488	0.0497	Q_2	0.2211	0.2211	0.2215
$P_{3,2}$	-0.6892	-0.6892	-0.6888	Q_3	0.0135	0.0135	0.0136
$P_{4,2}$	-0.5109	-0.5109	-0.5111	Q_4	0.2390	0.2390	0.2392
$P_{7,4}$	-0.2928	-0.2928	-0.2935	Q_6	0.0179	0.0179	0.0180
$P_{9,4}$	-0.1680	-0.1680	-0.1684	Q_9	-0.1660	-0.1660	-0.1661
$P_{11,6}$	-0.0614	-0.0614	-0.0614	Q_{14}	-0.0500	-0.0500	-0.0501
$P_{10,9}$	-0.0636	-0.0636	-0.0635	$\|V_{se,4,5}\|$	0.0158	-	0.0158
$Q_{2,5}$	-0.0289	-0.0289	-0.0287	$<V_{se,4,5}$	95.49º	-	95.49º
$Q_{10,11}$	-0.0122	-0.0122	-0.0126	$\|I_{sh,4}\|$	0.408	-	0.408
$Q_{13,14}$	0.0150	0.0150	0.0150	$< I_{sh,4}$	-29.34º	-	-29.34º

It was seen that, all the proposed models are able to model different types of control devices such as FACTS devices. Modeling these devices not only could estimate the correct values of measurements but also is able to estimate these devices' states according to Tables 2, 3 and 4.

4. CONCLUSION

Today, several types of control devices such as FACTS devices are used in power systems. These devices may be influenced state estimation in power systems, which the correct state estimation of system required modeling installed control devices in the system. In this paper, different types of control devices such as parallel, series and series-shunt FACTS devices were modeled for power system state estimation. To demonstrate the effectiveness of the proposed models, a shunt, a series and a series-shunt devices were considered on the IEEE 14-bus system separately and state estimation were done based on WLS. The results have shown that the proposed models not only could effectively lead in proper state estimation of measurements values and system states but also is able to present the estimated states of the control devices.

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