CHAPTER 3

Test Case and Estimation Results

This chapter introduces 10 bus test system and estimation results, testing with measurement noises and estimation with nonlinear equipment such as saturated transformer.

3.1 The Test System

There are two related parts of the test system, the simulation and the estimation parts. First, the simulation part is built in PSCAD/EMTDC program for generating measured values which are set as actual values. This study focuses on transient phenomena that usually occurs which is voltage sag. Voltage sag is determined from fault event defined by fault location, fault type, fault size and fault duration. After that, the selected measurements from these simulation data are fed to TSE algorithm. This algorithm has been written and implemented in MATLAB. TSE algorithm constructs the measurement equation without fault. Figure 3.1 shows the framework of the studies.

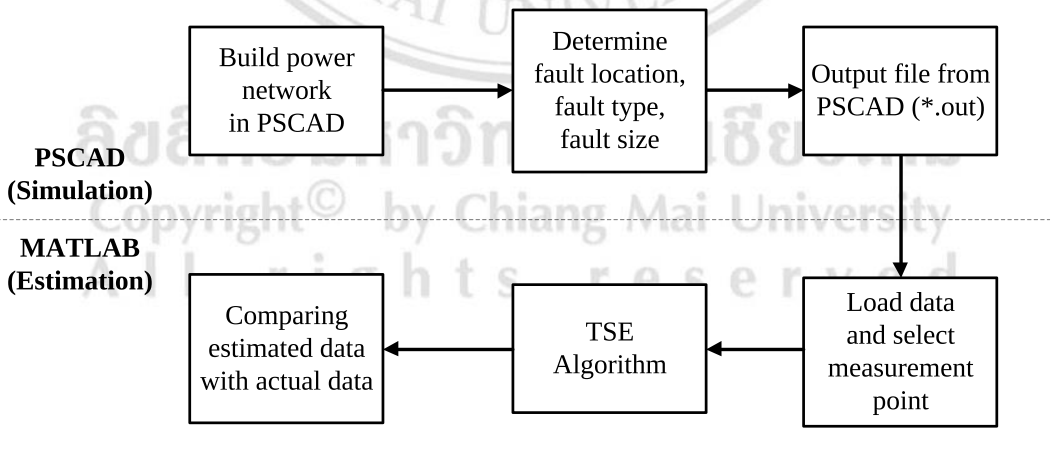

Figure 3.1 Overall frameworks.

Figure 3.2 shows the test case of a 10 bus power system which focuses on characteristic of Bergeron transmission whose the parameters are obtained from [10]. The system for testing a proposed algorithm consists of

1) Two generators connected at bus no.1 and no.2.

2) Four transformers (two windings type) connected in star-delta manner.

3) All of transmission lines are single circuits and these includes traveling wave propagation. The parameters for all Bergeron transmission line models considered in this test system are [10]

$$
\begin{aligned}
r^{(0)} &= 0.29\ \Omega/\text{km}, & r^{(1)} &= 0.048\ \Omega/\text{km} \\
\ell^{(0)} &= 3.23\ \text{mH/km}, & \ell^{(1)} &= 1.012\ \text{mH/km} \\
c^{(0)} &= 7.66\ \text{nF/km}, & c^{(1)} &= 11.86\ \text{nF/km}
\end{aligned}
$$

where superscript (0) and (1) denote zero and positive sequence parameters, respectively. For a completely transposed transmission line, the positive and negative sequence parameters are identical. The inductor, 500 mH, was added to each transmission line at the sending-end to solve the sending-end current state variables.

4) Each linear load at bus no.5-8 is resistance of 1 kΩ in parallel with a capacitance of 0.1 μF, for solving the receiving-end voltage state variables. Load at bus no.9 and no.10 had a resistance of 1 kΩ [10].

5) Fault characteristics are defined only in the simulation part, not model in estimation program. Two different fault patterns, symmetrical line-to-ground (three-phase fault) and asymmetrical line-to-ground (single line to ground fault), are simulated in PSCAD program. Fault sizes are acquired by determining the fault resistance connected to ground, which correspond to retained voltage at 90% to 10%. Fault duration for test system use 50 ms (2.5 cycle for fundamental frequency 50 Hz), which classified to instantaneous sag refer to table 2.1.

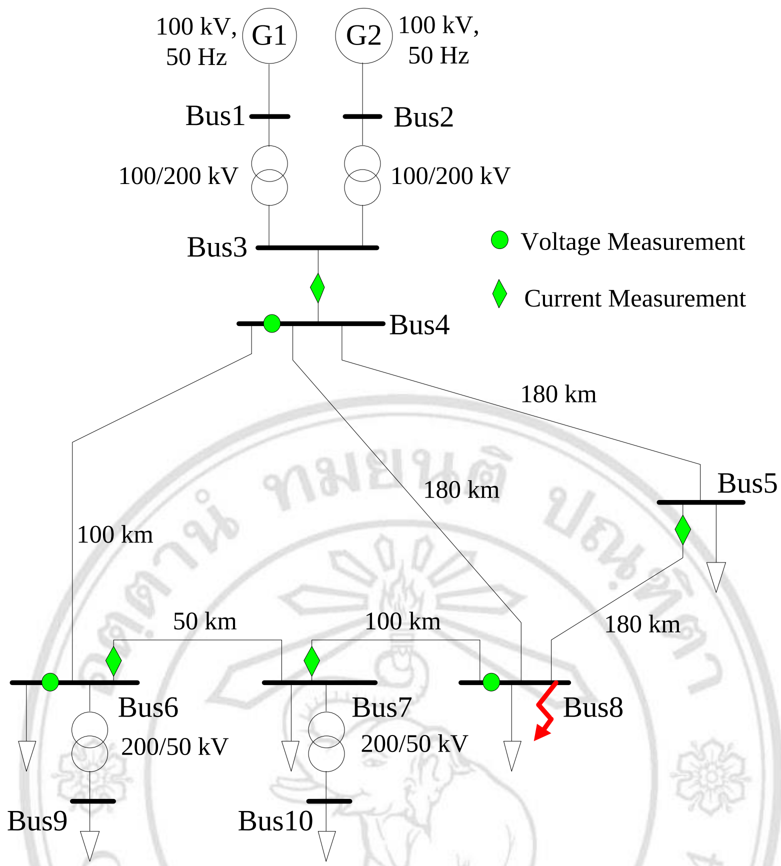

Figure 3.2 Test system.

In this test system, seven measurement values were determined at the selected placement locations. The simulation was tested with a transient that was caused by a fault event for 50 ms at a simulation time of 0.035 sec. The test specified application of the fault resistance at different levels which caused a voltage drop at a selected bus (bus no. 8) which persisted at 90% to 10% (sag magnitude referred to the remaining voltage). Three-phase and single-phase (disturbance at phase A) fault were applied to the proposed algorithm. The estimation was performed using time step,Δt as 10 μs. The proposed algorithm estimated the busbar voltage at the location without voltage measurement as bus no.5 and no.7. Figure 3.3 shows the test system which is built in PSCAD program.

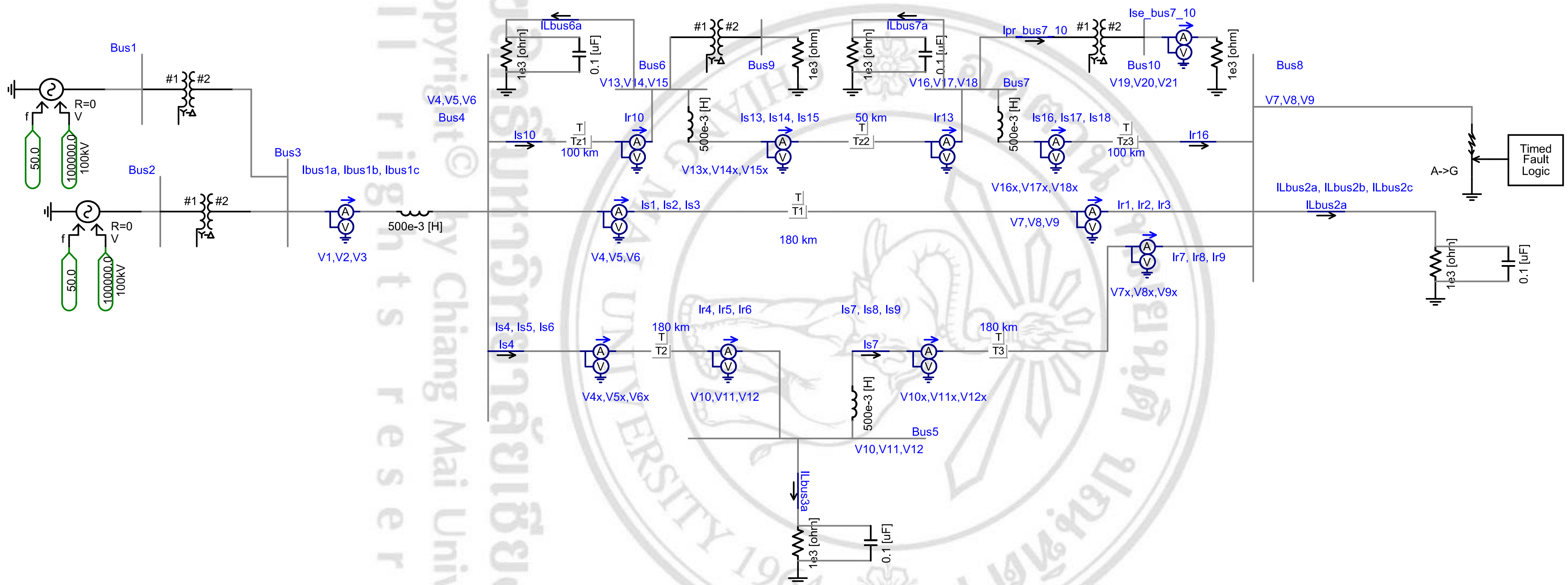

Figure 3.3 Test system in PSCAD.

By consideration of a decision tree for the selection of the appropriate transmission line model in figure 2.1, all of transmission lines have the same parameter value except the distance of each segment. Thus the phase velocity, ϖ of each line is the same.

From equation (2.17) $\varpi = \dfrac{1}{\sqrt{\ell c}}$,

Consider the positive sequence in modal domain.

$$\varpi^{(1)} = \frac{1}{\sqrt{\ell^{(1)} c^{(1)}}} = \frac{1}{\sqrt{\left(1.012\times10^{-3}\right)\left(11.86\times10^{-9}\right)}} = 2.89\times10^{5} \text{ km/sec},$$

which $\varpi^{(1)}$ is phase velocity of transmission line in positive sequence.

The shortest transmission line in the test system is 50 km which is located between bus 6 and 7.

From equation (2.18) $\tau = \dfrac{l}{\varpi}$,

$$\tau^{(1)} = \frac{l}{\varpi^{(1)}} = \frac{50}{2.89\times10^{5}} = 1.73\times10^{-4} \text{ sec} = 173\ \mu\text{s}.$$

This study uses time step, Δt of 10 μs which in decision tree $\tau > \Delta t$, therefore this line can be represented by the Bergeron model and same as other longer line. Negative sequence can use the same calculation as positive sequence.

Similarly, zero sequence can calculate as follows

$$\varpi^{(0)} = \frac{1}{\sqrt{\ell^{(0)} c^{(0)}}} = \frac{1}{\sqrt{\left(3.23\times10^{-3}\right)\left(7.66\times10^{-9}\right)}} = 2\times10^{5} \text{ km/sec},$$

$$\tau^{(0)} = \frac{l}{\varpi^{(0)}} = \frac{50}{2\times10^{5}} = 2.5\times10^{-4} \text{ sec} = 250\ \mu\text{s}.$$

As the result, $\tau > \Delta t$ means that it is suitable to use Bergeron model for this line.

Besides, it can also consider how long transmission line should be used with Bergeron model. For example, considering positive sequences which phase velocity as 2.89×10^5 km/sec and time step as 10 μs are calculated. From equation (2.18), $l = \tau\varpi$, the traveling time represent by time step.

$$l = \left(10\times10^{-6}\right)\left(2.89\times10^{5}\right) = 2.89\ \text{km}.$$

Therefore the transmission line length over 2.89 km can be represented by the Bergeron model.

According to the decision tree in figure 2.1 which is a transmission line model selection, it was found that Bergeron model can be applied to all transmission lines in the proposed power system. It is suitable for represent in component model in state space of transient state estimation algorithm. The results of estimation are show in four parts. There are transient state estimation results, estimation result with noise, estimation result with nonlinear equipment, and the estimation in detail of modal domain.

3.2 Transient State Estimation

The results of the proposed algorithm evaluated with the test system in figure 3.2 are follows; figure 3.4-3.5 show comparisons of voltage waveform and difference values between the actual value and the estimated value (solid and dashed lines) for case of three-phase fault that affected 80% sag magnitude which referred to the remaining voltage. While testing of single-phase fault (disturbance at phase A) is shown in figure 3.6-3.7 (Only 80% sag case are shown).

The results show that both actual and estimated waveforms are similar. Some discrepancies occurred during the fault event at bus no.8 (time at 0.035 – 0.085 sec.) because of a very fast transient in the voltage level. The performance evaluation methods are %RMSE and %MAE from equation (2.38) and (2.39). The time period used for the calculation of this simulation is 0 – 0.11 second.

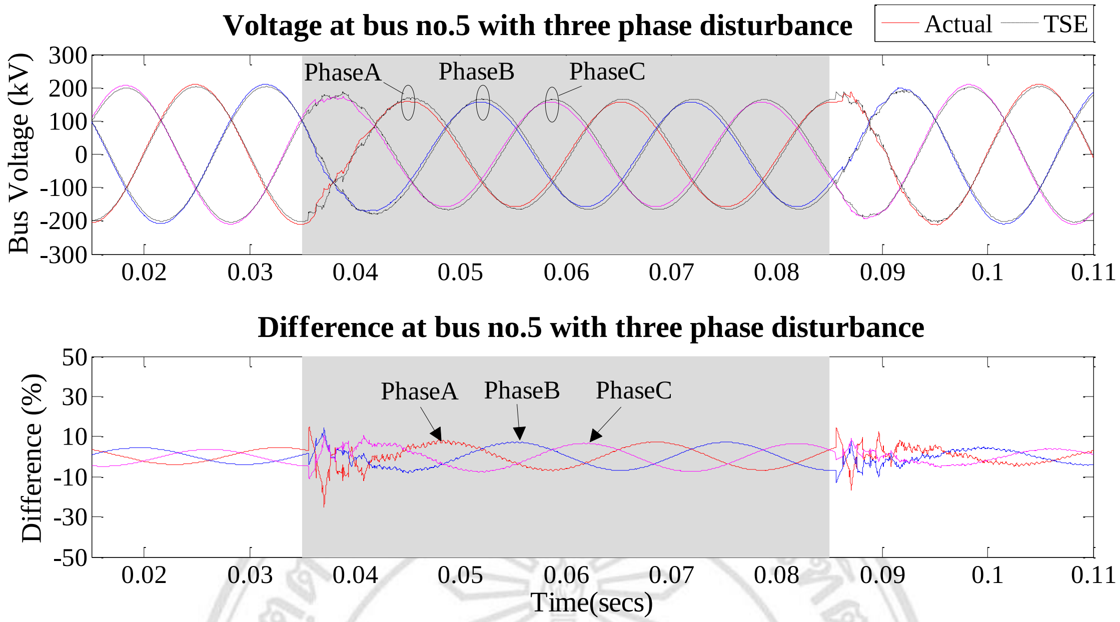

Figure 3.4 Voltage at bus no.5 (three-phase disturbance: 80% sag).

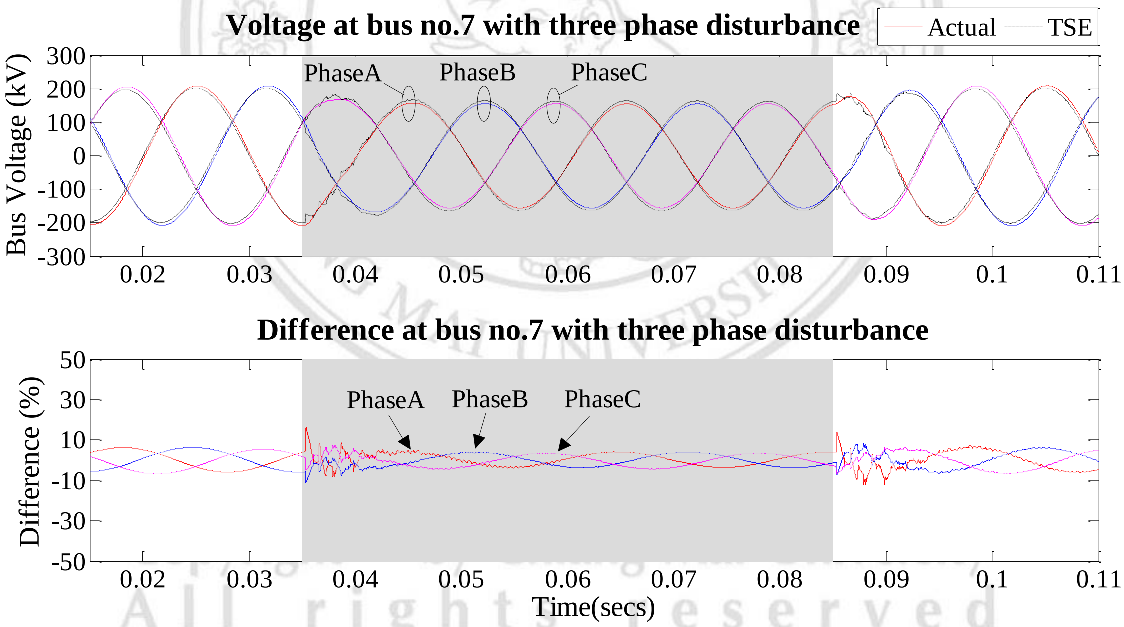

Figure 3.5 Voltage at bus no.7 (three-phase disturbance: 80% sag).

Figure 3.8-3.11 show only percentage of %RMSE at bus no.5 and 7 for both three-phase and single-phase fault testing, respectively, which are corresponding with table 3.1 – 3.4. All figures indicated that TSE can estimate high percentage of sag better than low percentage of sag. The lower percentage of sag means the less remaining voltage which leads to immediate reduction of the value. This affects the estimator that it cannot respond quickly which leads to poorer performance.

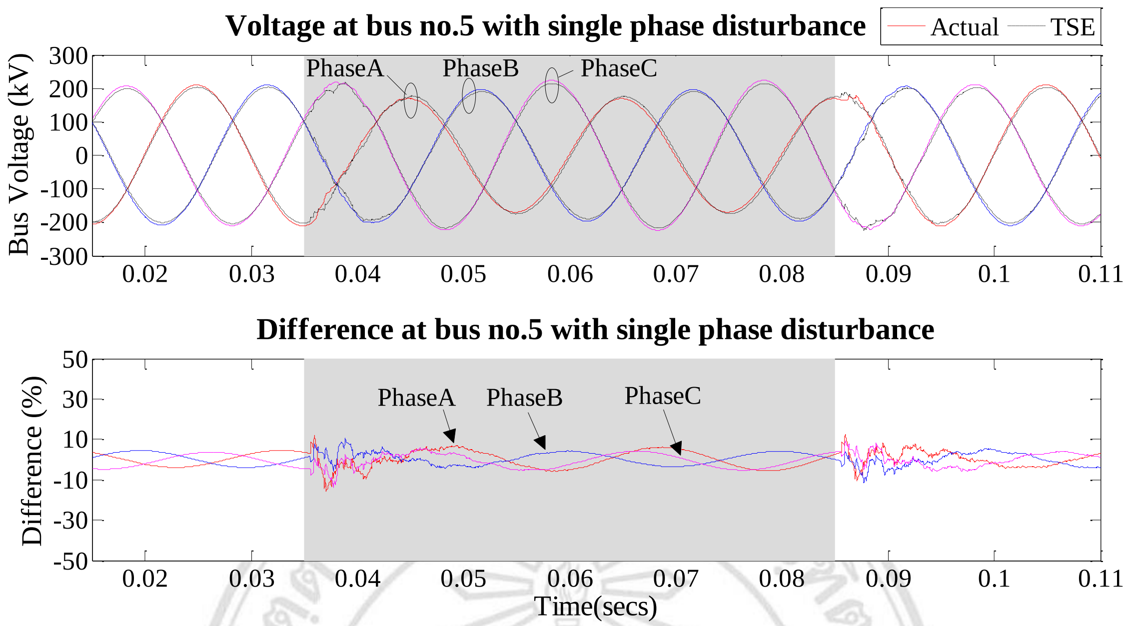

Figure 3.6 Voltage at bus no.5 (single-phase disturbance at phase A: 80% sag).

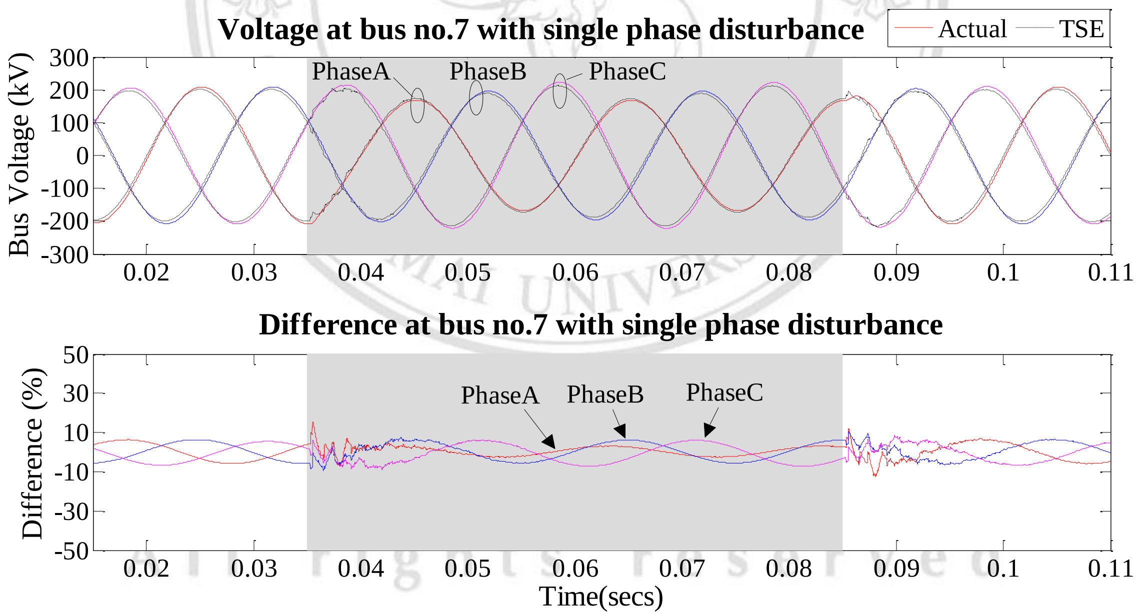

Figure 3.7 Voltage at bus no.7 (single-phase disturbance at phase A: 80% sag).

In addition, %RMSE and %MAE of three-phase fault testing at bus no. 5 has lower error percentage than 10 in case of the voltage sag is not below 40%. Beside bus no.7 has lower error percentage when compared with bus no. 5 because the distance of transmission line between the bus address and the fault location is shorter. The distance affects travelling time according to equation (2.18) and also affects to the calculation of past history current according to equation (2.23) and (2.24) which affects estimator performance. The proposed algorithm can estimate good result but it still depends on transmission line length. The percentage of error from longer line is more than shorter line. However, this error can be reduced by decreasing step size of calculation.

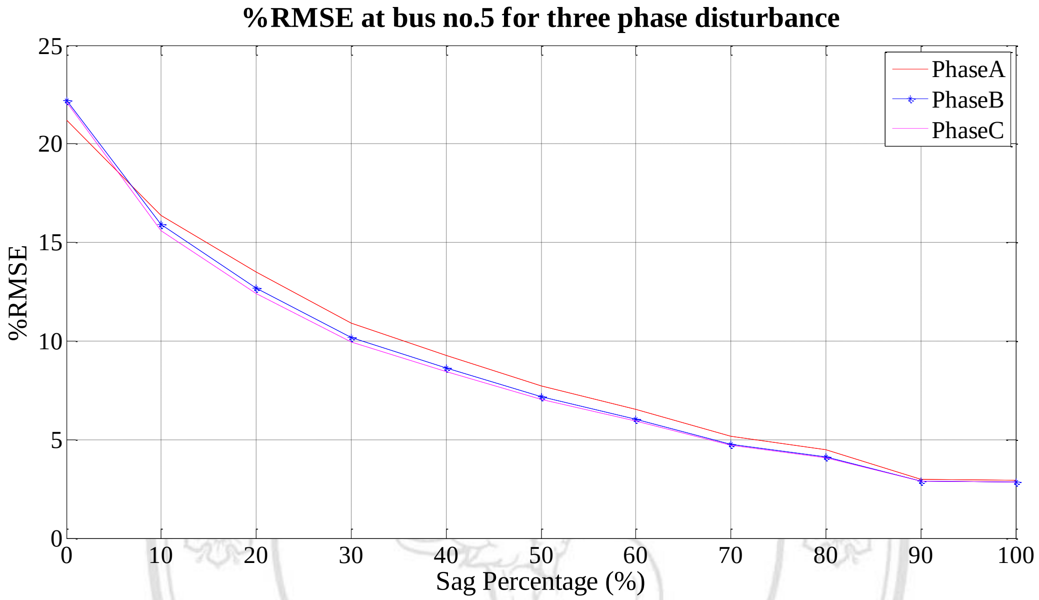

Figure 3.8 %RMSE at bus no.5 for three-phase disturbance.

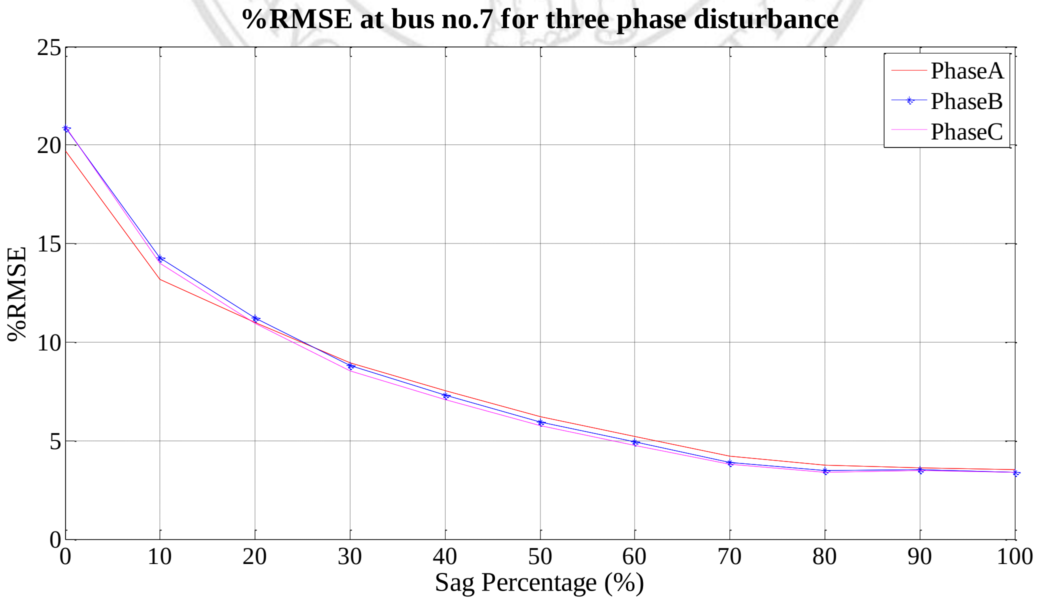

Figure 3.9 %RMSE at bus no.7 for three-phase disturbance.

For single-phase fault testing, it is found that the percentage error is more occurred at the disturbance appeared phase (Phase A for this study) than the others. However, error is not over 10% when the voltage sag is not lower than 40%.

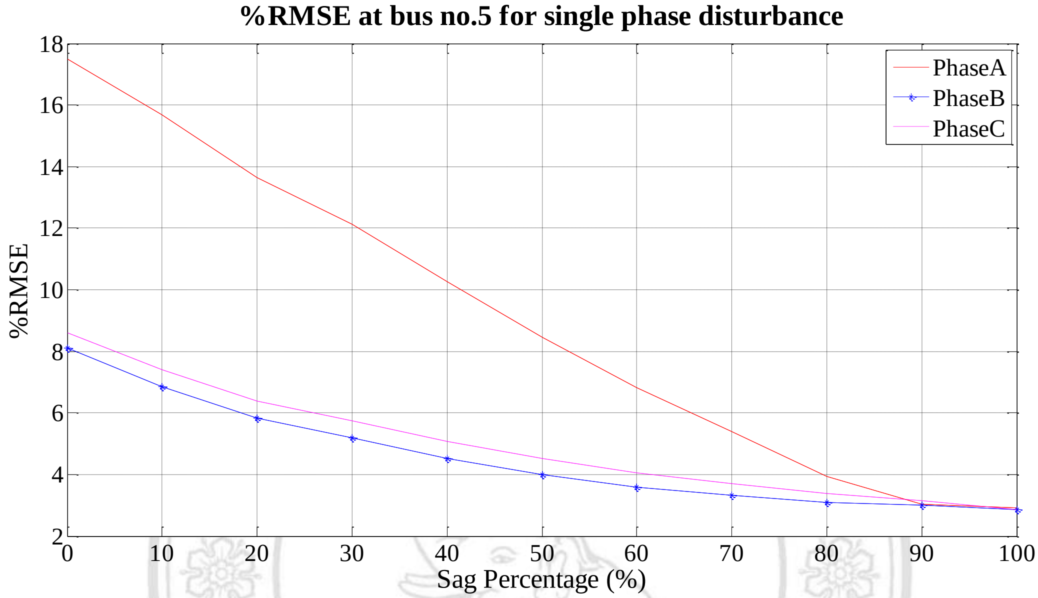

Figure 3.10 %RMSE at bus no.5 for single-phase disturbance.

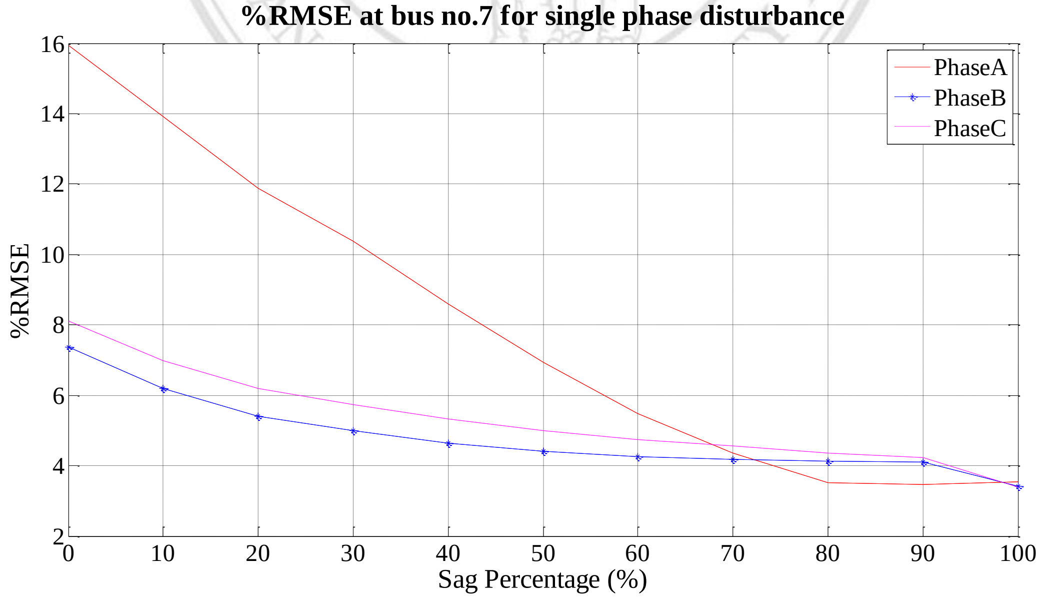

Figure 3.11 %RMSE at bus no.7 for single-phase disturbance.

Table 3.1-3.4 show the evaluation of TSE at bus no.5 and no.7 for three-phase and single-phase fault, respectively. These tables indicated that TSE gives better estimation at high percentage of sag better than low percentage of sag.

Table 3.1 Evaluation at bus no.5 for three-phase disturbance.

Voltage Sag	Phase A		Phase B		Phase C	
(%)	%RMSE	%MAE	%RMSE	%MAE	%RMSE	%MAE
100% (no sag)	2.9179	2.5416	2.8601	2.5209	2.8555	2.5412
90%	2.9634	2.5764	2.8834	2.5367	2.8769	2.5573
80%	4.4726	3.6567	4.1432	3.5124	4.0972	3.5460
70%	5.1661	4.1166	4.7741	3.9592	4.7085	3.9756
60%	6.5266	4.9838	6.0392	4.8192	5.9331	4.7932
50%	7.7172	5.7139	7.1607	5.5614	7.0190	5.4850
40%	9.2699	6.6357	8.6298	6.5120	8.4449	6.3591
30%	10.9091	7.5688	10.1819	7.4801	9.9590	7.2457
20%	13.5040	8.9541	12.6929	8.9136	12.4254	8.5621
10%	16.3759	10.3187	15.8965	10.5893	15.5961	10.1743
0% (Interruption)	21.2054	12.7900	22.2124	14.3879	22.0984	14.2189

Table 3.2 Evaluation at bus no.7 for three-phase disturbance.

Voltage Sag	Phase A		Phase B		Phase C	
(%)	%RMSE	%MAE	%RMSE	%MAE	%RMSE	%MAE
100% (no sag)	3.5399	3.0490	3.4066	2.9435	3.3987	2.9089
90%	3.6277	3.1553	3.5094	3.0611	3.5060	3.0253
80%	3.7767	3.1923	3.4922	3.0180	3.4004	2.8973
70%	4.2104	3.5933	3.9081	3.4210	3.7866	3.2796
60%	5.2346	4.4013	4.9354	4.2486	4.7682	4.0766
50%	6.2175	5.0933	5.9438	4.9738	5.7464	4.7729
40%	7.5386	5.9612	7.3203	5.9012	7.0934	5.6575
30%	8.9265	6.8160	8.8010	6.8480	8.5525	6.5509
20%	11.0173	8.0394	11.2040	8.2743	10.9319	7.9097
10%	13.1901	9.1790	14.2700	9.9017	13.9927	9.5122
0% (Interruption)	19.6825	12.4394	20.8797	13.7511	20.9237	13.6893

Table 3.3 Evaluation at bus no.5 for single-phase disturbance (Phase A disturbance).

Voltage Sag	Phase A		Phase B		Phase C	
(%)	%RMSE	%MAE	%RMSE	%MAE	%RMSE	%MAE
100% (no sag)	2.9179	2.5416	2.8601	2.5209	2.8555	2.5412
90%	3.0390	2.6427	3.0118	2.6349	3.1576	2.7951
80%	3.9288	3.2891	3.1007	2.6373	3.3763	2.9250
70%	5.3913	4.2827	3.3164	2.7241	3.7066	3.1224
60%	6.8213	5.2144	3.5964	2.8319	4.0607	3.3109
50%	8.4573	6.2466	3.9940	2.9702	4.5147	3.5293
40%	10.2507	7.3500	4.5225	3.1375	5.0791	3.7806
30%	12.1282	8.4716	5.1866	3.3425	5.7583	4.0665
20%	13.6532	9.3556	5.8242	3.5366	6.3941	4.3225
10%	15.6690	10.4845	6.8516	3.8802	7.4013	4.7398
0% (Interruption)	17.4972	11.4670	8.0933	4.4837	8.6045	5.3035

Table 3.4 Evaluation at bus no.7 for single-phase disturbance (Phase A disturbance).

Voltage Sag	Phase A		Phase B		Phase C	
(%)	%RMSE	%MAE	%RMSE	%MAE	%RMSE	%MAE
100% (no sag)	3.5399	3.0490	3.4066	2.9435	3.3987	2.9089
90%	3.4787	2.9648	4.1067	3.6280	4.2364	3.6980
80%	3.5049	2.8803	4.1186	3.6205	4.3713	3.8099
70%	4.3567	3.6466	4.1731	3.6353	4.5547	3.9559
60%	5.4906	4.5037	4.2608	3.6711	4.7466	4.0944
50%	6.9283	5.4776	4.4086	3.7323	4.9968	4.2598
40%	8.5858	6.5328	4.6428	3.8221	5.3233	4.4501
30%	10.3778	7.6261	4.9974	3.9420	5.7486	4.6660
20%	11.8737	8.5075	5.4027	4.0730	6.1878	4.8600
10%	13.9325	9.6840	6.1931	4.3512	6.9830	5.2116
0% (Interruption)	15.9451	10.7790	7.3595	4.8595	8.1028	5.7394

3.3 Estimation with Measurement Noise

Generally, measurement noises affect the performance of estimation algorithms. This study added the normally distributed measurement noises of 1%, 2% and 3% to all of the measurement data. This testing applied to both three-phase and single-phase (disturbance appeared on phase A.) faults at bus no.8. In practice, if the measurement noises are higher, they can be reduced by a pre-filtering process [27-28]. Figure 3.12-3.13 show the comparison of voltage waveforms and difference values at bus no.5 and no.7, between the actual value and the estimated value for three-phase fault that affected 80% of the sag cases with 1% measurement noise. While the test results of single-phase disturbances, are shown in figure 3.14-3.15.

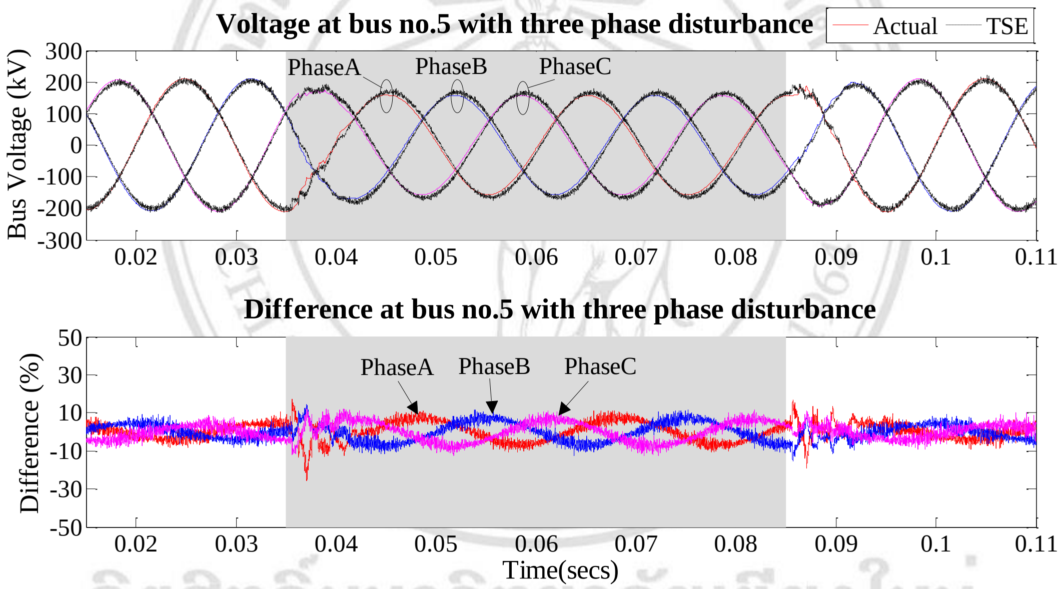

Figure 3.12 Voltage at bus no.5 (three-phase disturbance, 80% sag with a 1% measurement noise).

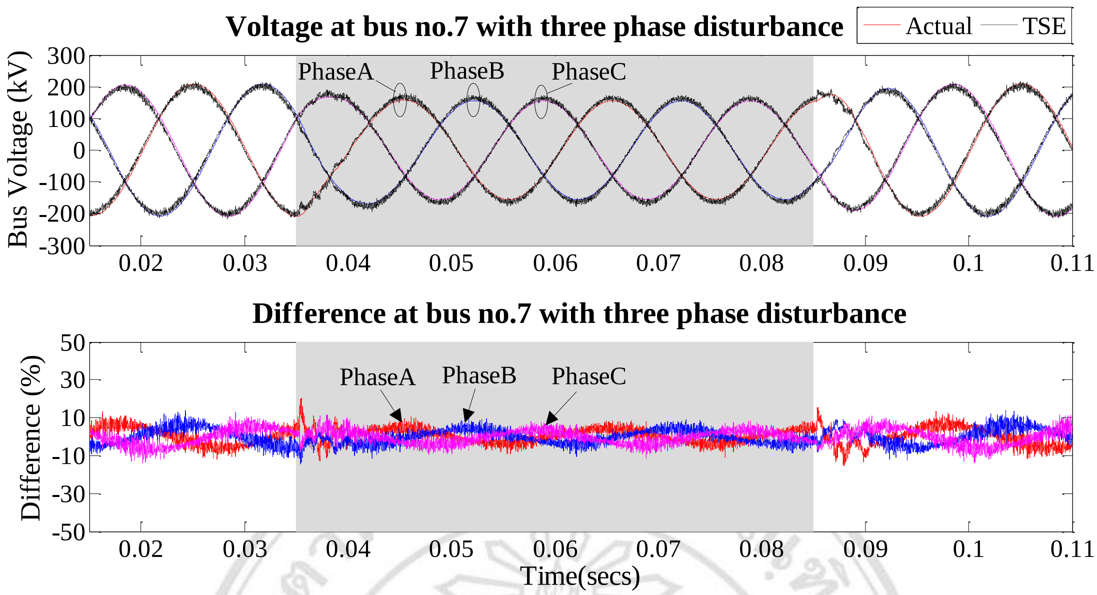

Figure 3.13 Voltage at bus no.7 (three-phase disturbance, 80% sag with a 1% measurement noise).

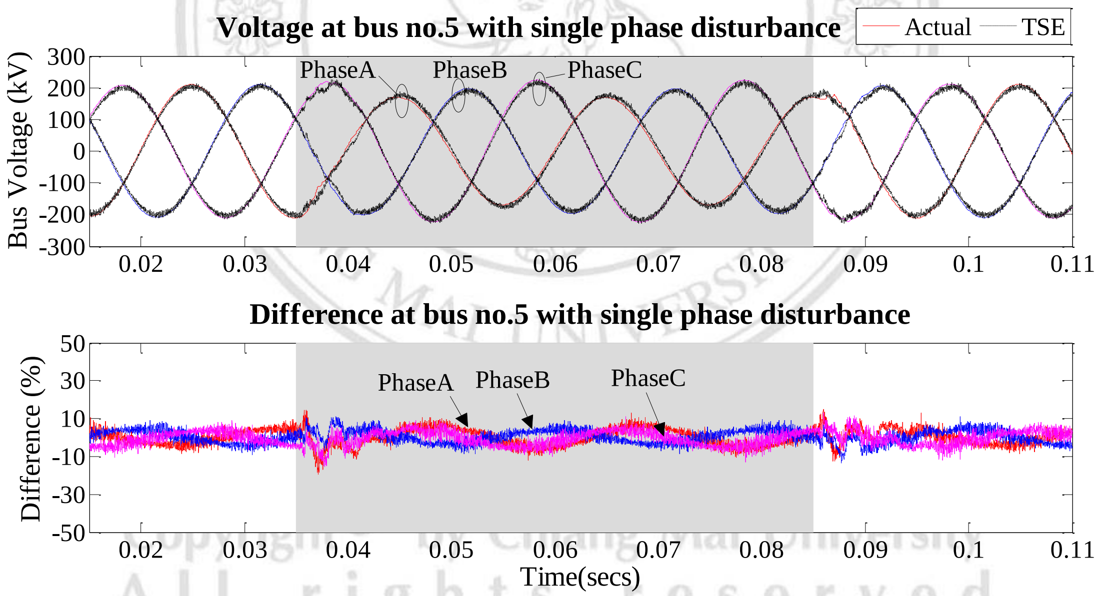

Figure 3.14 Voltage at bus no.5 (single-phase disturbance: 80% sag with a 1% measurement noise).

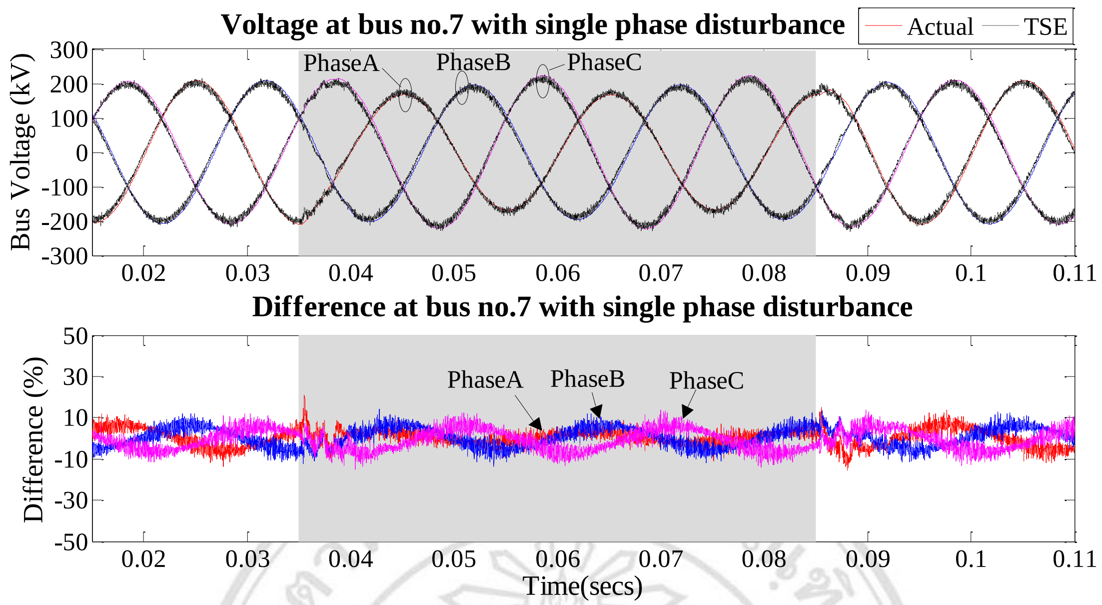

Figure 3.15 Voltage at bus no.7 (single-phase disturbance: 80% sag with a 1% measurement noise).

Figure 3.16-3.19 show %RMSE of bus voltage at bus no.5 and 7 for both three-phase and single-phase fault testing with various noise levels. The results indicate that the measurement noise reduced the accuracy of the proposed algorithm, but provided a good estimation for measurement noise between 1%-3%.

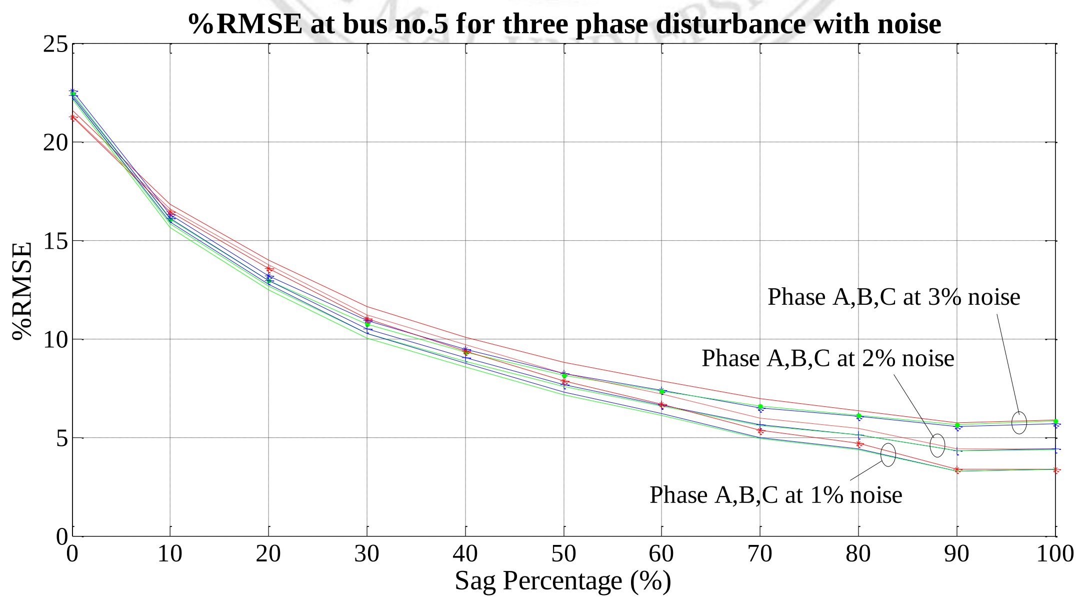

Figure 3.16 %RMSE at bus no.5 for three-phase disturbance with measurement noise.

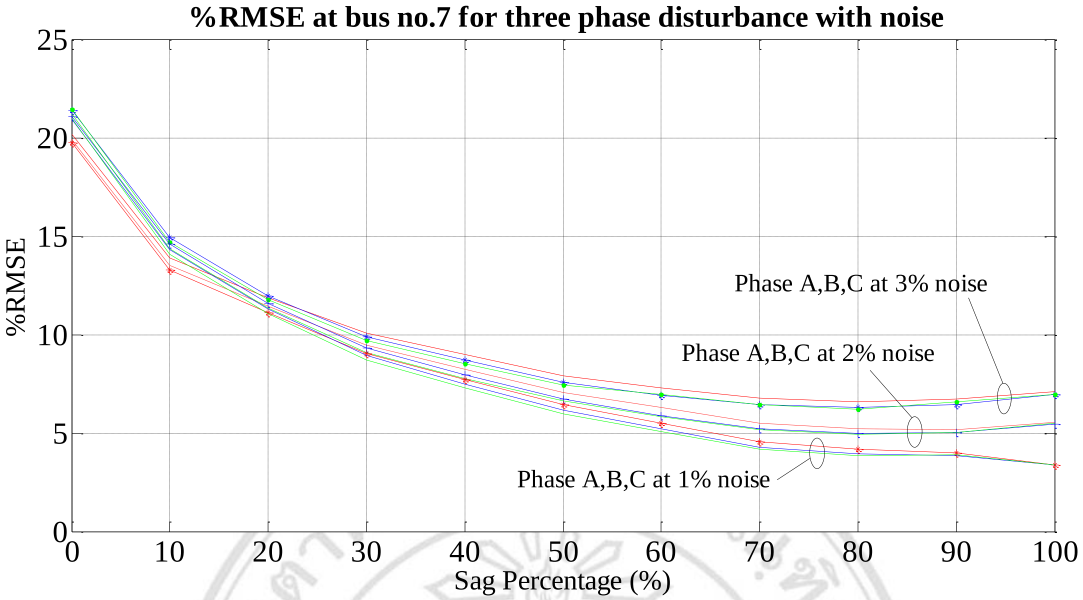

Figure 3.17 %RMSE at bus no.7 for three-phase disturbance with measurement noise.

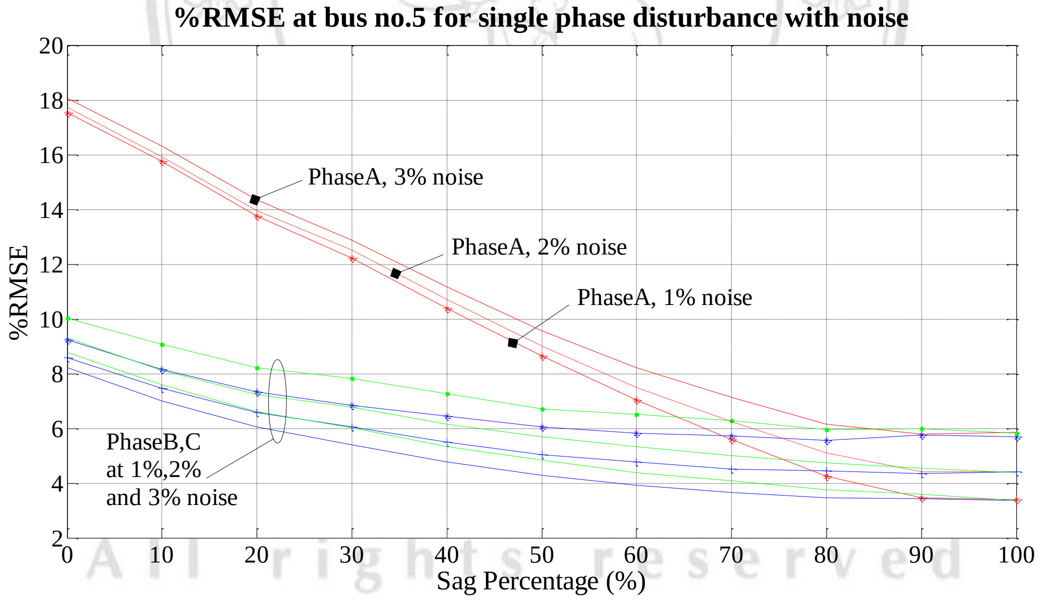

Figure 3.18 %RMSE at bus no.5 for single-phase disturbance with measurement noise.

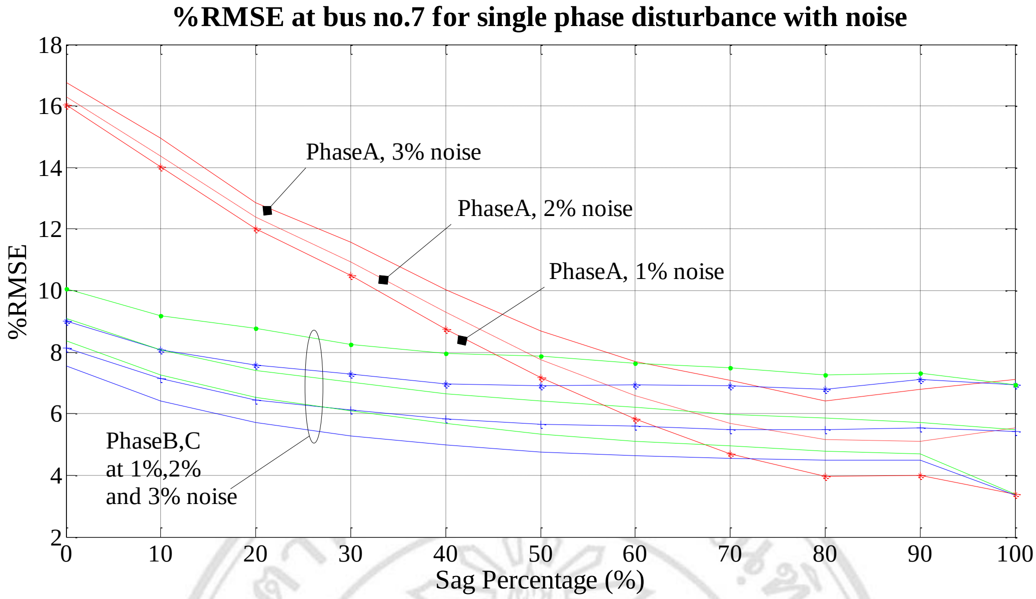

Figure 3.19 %RMSE at bus no.7 for single-phase disturbance with measurement noise.

Both table 3.5 and 3.6 are summarize the results of %RMSE and %MAE at bus no.5 and 7 with 1%, 2% and 3% measurement noise for three-phase fault. Similarly, the evaluation for single-phase fault case is shown in table 3.7 and 3.8.

Table 3.5 Evaluation at bus no.5 for three-phase disturbance with measurement noise.

Voltage Sag (%)	Percentage Root Mean Square Error (%RMSE)								
	Phase A			Phase B			Phase C		
	noise 1%	noise 2%	noise 3%	noise 1%	noise 2%	noise 3%	noise 1%	noise 2%	noise 3%
100% (no sag)	3.3820	4.4108	5.8495	3.3686	4.4071	5.6779	3.3768	4.3636	5.8149
90%	3.3815	4.4043	5.7255	3.2783	4.2946	5.5200	3.2925	4.3122	5.6135
80%	4.7121	5.4420	6.3632	4.4147	5.1299	6.0656	4.3795	5.1042	6.0888
70%	5.3772	5.9879	6.9698	4.9849	5.6267	6.4947	4.9431	5.5867	6.5719
60%	6.6801	7.1816	7.8537	6.2204	6.6273	7.3674	6.1107	6.5904	7.3363
50%	7.8483	8.2346	8.7911	7.2891	7.6643	8.2146	7.1620	7.5561	8.1487
40%	9.3740	9.6803	10.0864	8.7324	9.0152	9.4390	8.5596	8.8506	9.3328
30%	10.9977	11.2249	11.6351	10.2601	10.4743	10.9255	10.0470	10.2785	10.7141
20%	13.5771	13.7277	13.9903	12.7690	12.9325	13.1972	12.4931	12.6716	12.9368
10%	16.4186	16.5733	16.8062	15.9309	16.0953	16.3042	15.6306	15.8293	16.0420
0% (Interruption)	21.2407	21.3176	21.5931	22.2320	22.3513	22.5479	22.1286	22.2454	22.4140
Voltage Sag (%)	Percentage Mean Absolute Error (%MAE)								
	Phase A			Phase B			Phase C		
	noise 1%	noise 2%	noise 3%	noise 1%	noise 2%	noise 3%	noise 1%	noise 2%	noise 3%
100% (no sag)	2.8818	3.6127	4.6451	2.9058	3.6162	4.5275	2.9215	3.5931	4.6460
90%	2.8853	3.5994	4.5568	2.8291	3.5538	4.4287	2.8349	3.5443	4.4698
80%	3.8326	4.3638	5.0147	3.7038	4.1871	4.8289	3.7205	4.2118	4.8724
70%	4.2940	4.7308	5.4460	4.1210	4.5821	5.1927	4.1356	4.5588	5.2292
60%	5.1428	5.5572	6.0873	4.9922	5.3194	5.8640	4.9407	5.3198	5.8792
50%	5.8735	6.2776	6.7418	5.6993	6.0772	6.4907	5.6267	5.9967	6.4500
40%	6.7861	7.1642	7.6080	6.6507	6.9844	7.4009	6.4987	6.8380	7.3359
30%	7.7201	8.0650	8.5631	7.6002	7.8959	8.3950	7.3676	7.7034	8.1955
20%	9.1053	9.4311	9.8423	9.0591	9.3438	9.8162	8.6929	9.0134	9.4473
10%	10.4768	10.7770	11.2547	10.7123	11.0367	11.4733	10.2855	10.6142	11.0649
0% (Interruption)	12.9133	13.2380	13.7202	14.4913	14.7864	15.2032	14.3282	14.6173	15.0574

Table 3.6 Evaluation at bus no.7 for three-phase disturbance with measurement noise.

Voltage Sag	Percentage Root Mean Square Error (%RMSE)								
(%)	Phase A			Phase B			Phase C		
	noise 1%	noise 2%	noise 3%	noise 1%	noise 2%	noise 3%	noise 1%	noise 2%	noise 3%
100% (no sag)	3.3820	5.5410	7.1097	3.3686	5.4277	6.9447	3.3768	5.4720	6.9512
90%	3.9912	5.1677	6.6986	3.8612	5.0105	6.4507	3.8721	5.0344	6.5690
80%	4.1793	5.2049	6.6036	3.9152	4.9780	6.2763	3.8438	4.9497	6.1953
70%	4.5673	5.4933	6.7583	4.2792	5.2167	6.4327	4.1510	5.1852	6.4190
60%	5.5044	6.3082	7.3113	5.2263	5.8953	6.9053	5.0489	5.8428	6.9382
50%	6.4294	7.0444	7.8947	6.1667	6.7447	7.5651	5.9861	6.6042	7.4447
40%	7.7103	8.2280	8.9720	7.4867	7.9596	8.6882	7.2661	7.7511	8.5280
30%	9.0548	9.4645	10.0758	8.9319	9.3002	9.8890	8.6808	9.1028	9.6955
20%	11.1320	11.4429	11.8628	11.3029	11.6015	11.9714	11.0423	11.3245	11.7918
10%	13.2707	13.5205	13.8915	14.3390	14.5906	14.9138	14.0568	14.3513	14.6757
0% (Interruption)	19.7363	19.8980	20.1782	20.9060	21.0842	21.4015	20.9816	21.1843	21.4248

Voltage Sag	Percentage Mean Absolute Error (%MAE)								
(%)	Phase A			Phase B			Phase C		
	noise 1%	noise 2%	noise 3%	noise 1%	noise 2%	noise 3%	noise 1%	noise 2%	noise 3%
100% (no sag)	2.8818	4.4346	5.5379	2.9058	4.3246	5.3643	2.9215	4.3486	5.3867
90%	3.3234	4.1013	5.1752	3.2184	3.9841	4.9864	3.2013	3.9832	5.0629
80%	3.4098	4.0743	5.0784	3.2216	3.8969	4.8008	3.1283	3.8547	4.7480
70%	3.7635	4.3240	5.2183	3.5636	4.1307	4.9479	3.4353	4.0551	4.8983
60%	4.5265	4.9834	5.6784	4.3756	4.7257	5.3759	4.1938	4.6728	5.3441
50%	5.2231	5.6160	6.1637	5.0944	5.4236	5.9233	4.8928	5.2758	5.7980
40%	6.0760	6.4363	6.9937	6.0037	6.3334	6.8263	5.7782	6.1132	6.6626
30%	6.9188	7.2705	7.7618	6.9518	7.2732	7.7465	6.6464	7.0094	7.5219
20%	8.1497	8.4943	8.9916	8.3687	8.6749	9.1176	8.0330	8.3549	8.8710
10%	9.2815	9.6184	10.1165	10.0078	10.3147	10.7683	9.5872	9.9720	10.4404
0% (Interruption)	12.5367	12.8784	13.4153	13.8478	14.1553	14.6516	13.7872	14.1197	14.6116

Table 3.7 Evaluation at bus no.5 for single-phase disturbance with measurement noise.

Voltage Sag	Percentage Root Mean Square Error (%RMSE)								
(%)	Phase A			Phase B			Phase C		
	noise 1%	noise 2%	noise 3%	noise 1%	noise 2%	noise 3%	noise 1%	noise 2%	noise 3%
100% (no sag)	3.3820	4.4108	5.8495	3.3686	4.4071	5.6779	3.3768	4.3636	5.8149
90%	3.4549	4.4251	5.8009	3.4214	4.3521	5.7537	3.5747	4.5394	5.9704
80%	4.2469	5.0910	6.1395	3.4585	4.4398	5.5525	3.7673	4.7367	5.9568
70%	5.6059	6.2300	7.1380	3.6605	4.5173	5.7323	4.0671	4.9868	6.2868
60%	7.0184	7.4934	8.2166	3.9105	4.7772	5.8080	4.3847	5.3138	6.5075
50%	8.6304	8.9925	9.5714	4.2675	5.0394	6.0387	4.8312	5.6886	6.7210
40%	10.3780	10.6911	11.1583	4.7765	5.4757	6.4485	5.3282	6.1373	7.2754
30%	12.1970	12.4933	12.8789	5.3891	6.0449	6.8252	6.0124	6.7550	7.8170
20%	13.7387	13.9557	14.3534	6.0340	6.5892	7.3277	6.6020	7.2366	8.2211
10%	15.7450	15.9190	16.3004	7.0156	7.4620	8.1582	7.5940	8.1216	9.0688
0% (Interruption)	17.5408	17.7123	18.0402	8.2267	8.5698	9.2301	8.7821	9.3000	10.0254
Voltage Sag	Percentage Mean Absolute Error (%MAE)								
(%)	Phase A			Phase B			Phase C		
	noise 1%	noise 2%	noise 3%	noise 1%	noise 2%	noise 3%	noise 1%	noise 2%	noise 3%
100% (no sag)	2.8818	3.6127	4.6451	2.9058	3.6162	4.5275	2.9215	3.5931	4.6460
90%	2.9353	3.6203	4.6337	2.9098	3.5540	4.5578	3.0605	3.7361	4.7580
80%	3.5161	4.1130	4.8702	2.8909	3.5985	4.3968	3.1865	3.8713	4.7360
70%	4.4432	4.9212	5.6004	2.9818	3.6296	4.5208	3.3652	4.0100	4.9579
60%	5.4143	5.8138	6.3427	3.0812	3.7585	4.5477	3.5570	4.2401	5.1099
50%	6.4371	6.8073	7.2935	3.1947	3.8451	4.6562	3.7711	4.4297	5.2280
40%	7.5178	7.8853	8.3862	3.3795	4.0286	4.8691	3.9930	4.6547	5.5422
30%	8.6243	8.9801	9.4722	3.5489	4.2512	4.9629	4.2918	4.9548	5.8371
20%	9.5048	9.8697	10.3369	3.7735	4.4112	5.1679	4.5499	5.1542	6.0061
10%	10.6244	10.9603	11.4661	4.0923	4.6934	5.4553	4.9636	5.5395	6.4098
0% (Interruption)	11.6004	11.9133	12.4271	4.6887	5.2128	5.9761	5.4999	6.0982	6.8364

Table 3.8 Evaluation at bus no.7 for single-phase disturbance with measurement noise.

Voltage Sag	Percentage Root Mean Square Error (%RMSE)								
(%)	Phase A			Phase B			Phase C		
	noise 1%	noise 2%	noise 3%	noise 1%	noise 2%	noise 3%	noise 1%	noise 2%	noise 3%
100% (no sag)	3.3820	5.5410	7.1097	3.3686	5.4277	6.9447	3.3768	5.4720	6.9512
90%	3.9992	5.0957	6.7997	4.5054	5.5299	7.1259	4.6940	5.7066	7.3276
80%	3.9673	5.1477	6.4190	4.4909	5.4922	6.7867	4.7708	5.8645	7.2507
70%	4.6862	5.6920	7.0930	4.5630	5.4800	6.9112	4.9452	5.9920	7.4859
60%	5.8264	6.5924	7.7002	4.6248	5.5933	6.9306	5.1179	6.2084	7.6314
50%	7.1846	7.7517	8.6995	4.7597	5.6698	6.8985	5.3393	6.4046	7.8704
40%	8.7511	9.3087	10.0405	4.9807	5.8467	6.9548	5.6796	6.6535	7.9540
30%	10.4948	10.9314	11.5593	5.2843	6.1292	7.2806	6.1006	7.0307	8.2515
20%	11.9985	12.3821	12.8660	5.7018	6.4369	7.5739	6.5350	7.3961	8.7819
10%	14.0172	14.3611	14.9520	6.4285	7.1366	8.0828	7.2533	8.0861	9.1927
0% (Interruption)	16.0191	16.3038	16.7539	7.5551	8.1319	9.0062	8.3578	9.1040	10.0632
Voltage Sag	Percentage Mean Absolute Error (%MAE)								
(%)	Phase A			Phase B			Phase C		
	noise 1%	noise 2%	noise 3%	noise 1%	noise 2%	noise 3%	noise 1%	noise 2%	noise 3%
100% (no sag)	2.8818	4.4346	5.5379	2.9058	4.3246	5.3643	2.9215	4.3486	5.3867
90%	3.3107	4.0571	5.2625	3.7997	4.4332	5.4981	3.9280	4.5333	5.6664
80%	3.1905	4.0043	4.9410	3.7880	4.4094	5.2906	3.9837	4.6715	5.6020
70%	3.7810	4.4114	5.4127	3.8240	4.4130	5.3654	4.1287	4.7713	5.7844
60%	4.6774	5.1236	5.8847	3.8607	4.5028	5.4252	4.2629	4.9039	5.8841
50%	5.6282	6.0195	6.6250	3.9295	4.5078	5.3982	4.4064	5.0373	6.0743
40%	6.6519	7.0725	7.6432	4.0267	4.6078	5.4196	4.6037	5.2218	6.1446
30%	7.7408	8.1309	8.6440	4.1278	4.7538	5.6032	4.8298	5.4178	6.2926
20%	8.6360	9.0069	9.4997	4.2693	4.8619	5.7538	5.0330	5.6301	6.6180
10%	9.7930	10.1881	10.7580	4.5464	5.1561	5.9552	5.3465	5.9614	6.8158
0% (Interruption)	10.8717	11.2721	11.8279	5.0346	5.5936	6.4095	5.8945	6.4618	7.2989

3.4 Estimation with Nonlinear Equipment

The test system for evaluating the proposed algorithm when the power system contains a nonlinear characteristic equipment such as saturated transformer is shown in figure 3.20. The system in PSCAD has to be modified and figure 3.21 shows the closer look of the test system network at bus no.7 which connected the saturated transformer. However, the three-phase and single-phase fault test are assigned at bus no.8. The current measurement point is added in the primary side of the transformer between bus no.7 and no.10 for collecting data to the estimator. Therefore, the measurement matrix [H] in equation (2.25) needs to be reformed and the row corresponding to this current equation is added to [H] as shown in figure 3.22.

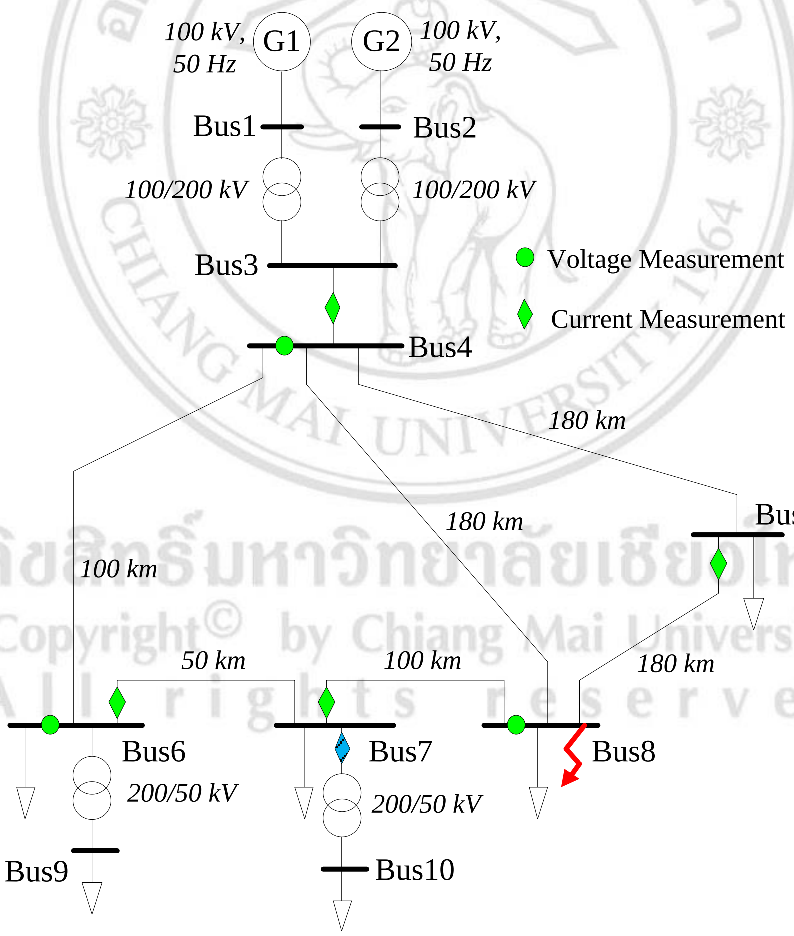

Figure 3.20 Test system for estimation with a saturated transformer.

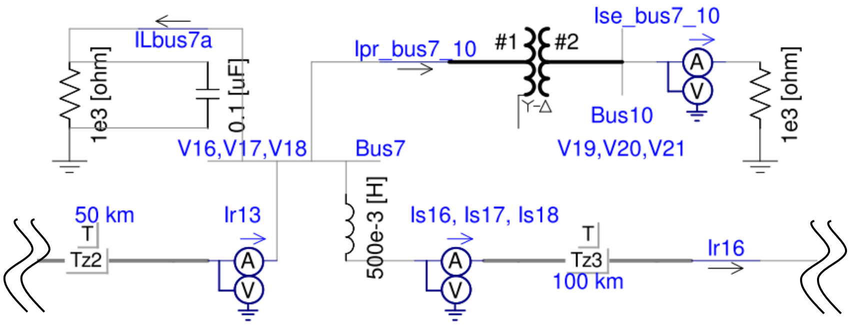

Figure 3.21 Closer look at bus no.7 in PSCAD.

The adjustment of the magnetic core saturation characteristics are assigned according to section 2.7. These parameters of the saturated transformer considered in this test system are set as follows: the air core reactance is 0.2 pu, the knee voltage is 1.25 pu and the magnetizing current is 1%.

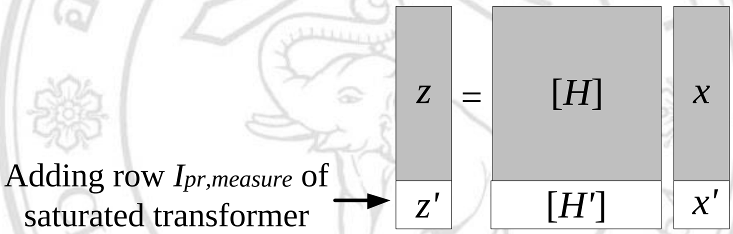

Figure 3.22 Rebuild $[H]$ with adding $I_{pr,measure}$ of saturated transformer.

The state space matrix needs to rebuild by add new measurement data, x' stands for the additional of system state vector, z' stands for the additional set of measurement vector and $[H']$ stands for the additional of measurement matrix. At bus no.7, the current flowing through the load is

$$I_{load} = \hat{I}_{recv,est} - I_{send,measure} - I_{pr,measure} \tag{3.1}$$

which I_{load} is current flowing through the load, $\hat{I}_{recv,est}$ is the estimated current flowing from bus no.6 to no.7, $I_{send,measure}$ is the measured current flow from bus no.7 to no.8, and $I_{pr,measure}$ is measured current at the primary side of transformer between bus no.7 and no.10. This load current is used to calculate the voltage at bus no.7.

The results of the proposed algorithm evaluated with the saturated transformer are as follows: figure 3.23-3.24 show the comparisons of voltage waveforms and difference values between the actual value and estimated value (solid and dashed lines) for three-phase fault that affected 80% sag case. The testing results for single-phase fault (disturbance at phase A) are shown in figure 3.25-3.26 (Only 80% sag cases are shown). In this case, the magnitude of voltage at bus no.5 and bus no.7 are decreasing because of characteristics of saturation of the transformer.

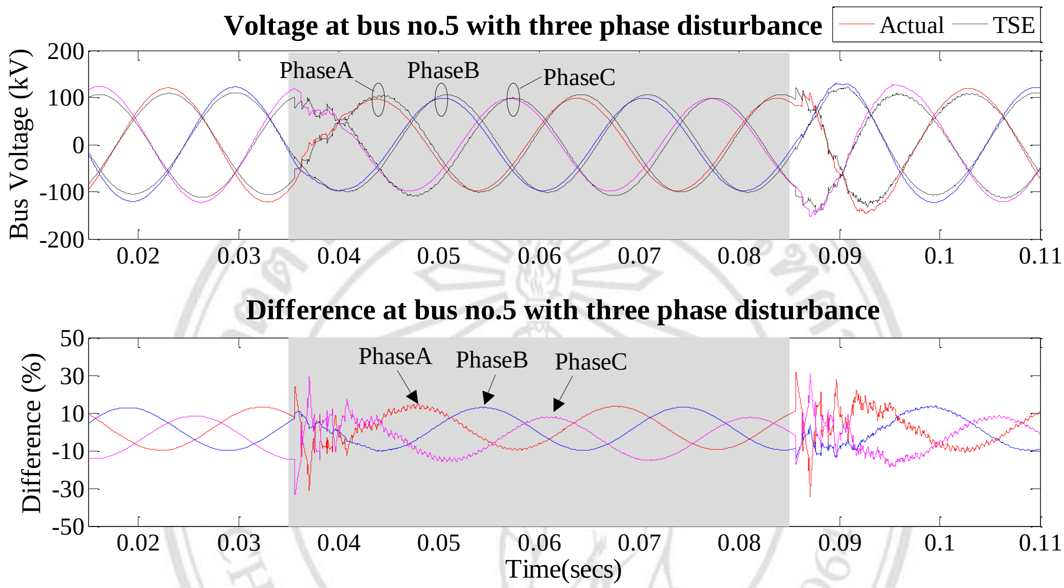

Figure 3.23 Voltage at bus no.5 (three-phase disturbance: 80% sag with considering the saturation of transformer).

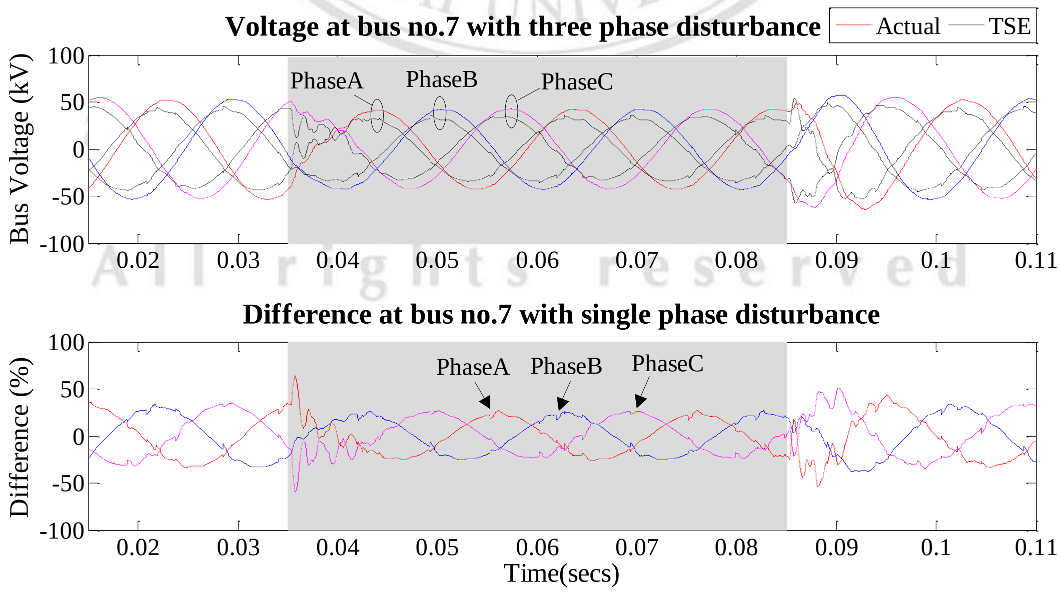

Figure 3.24 Voltage at bus no.7 (three-phase disturbance: 80% sag with considering the saturation of transformer).

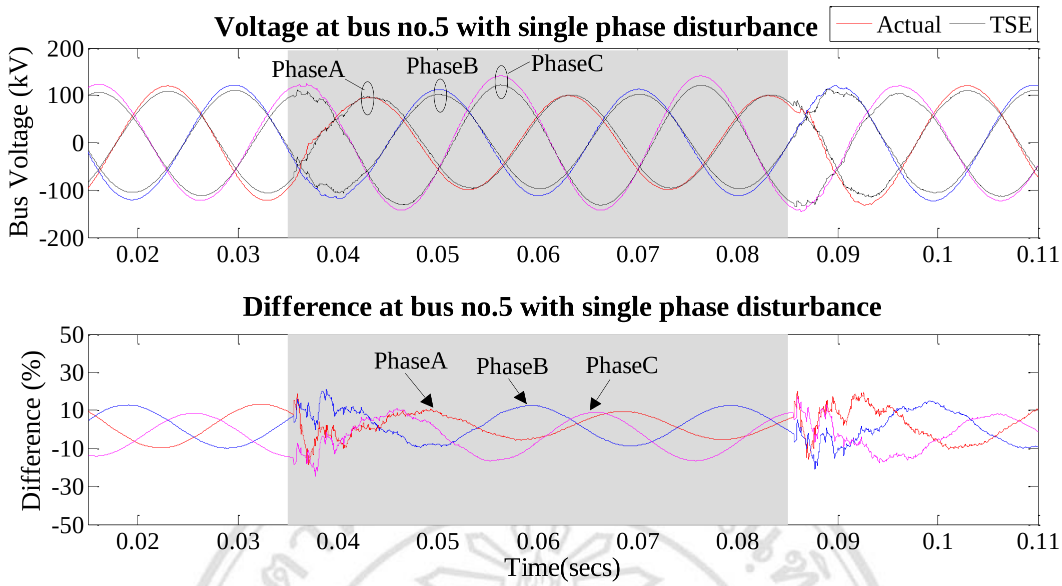

Figure 3.25 Voltage at bus no.5 (single-phase disturbance at phase A: 80% sag with considering the saturation of transformer).

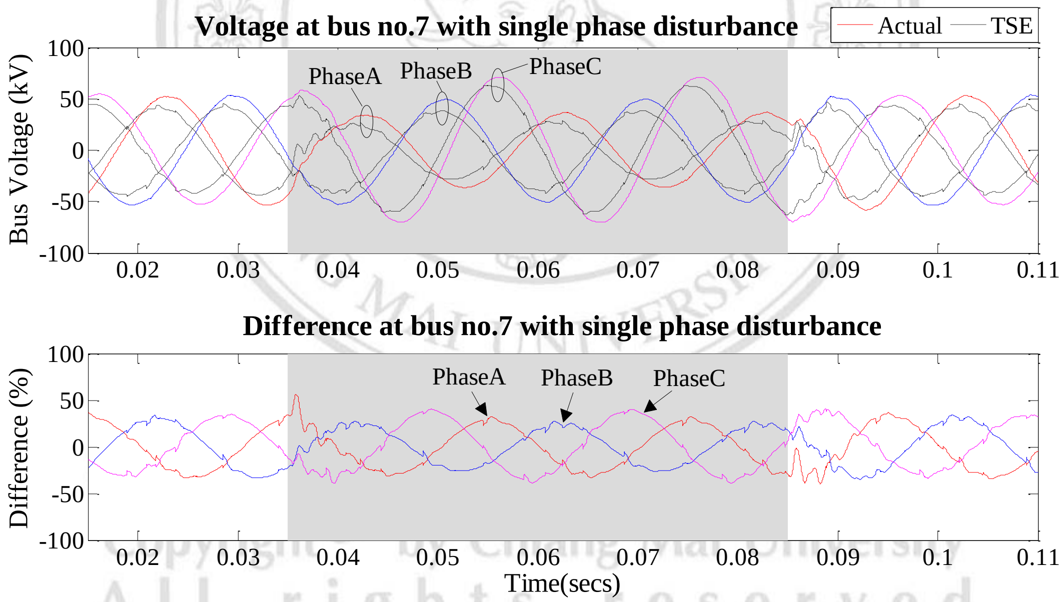

Figure 3.26 Voltage at bus no.7 (single-phase disturbance at phase A: 80% sag with considering the saturation of transformer).

Figure 3.27-3.30 show the %RMSE at bus no.5 and 7 for both three-phase and single-phase fault testing. The results indicate that the saturated transformer reduced the performance of the proposed algorithm especially at bus no.7 which connected with saturated transformer, the percentage of error has a behavior that like a nonlinear response.

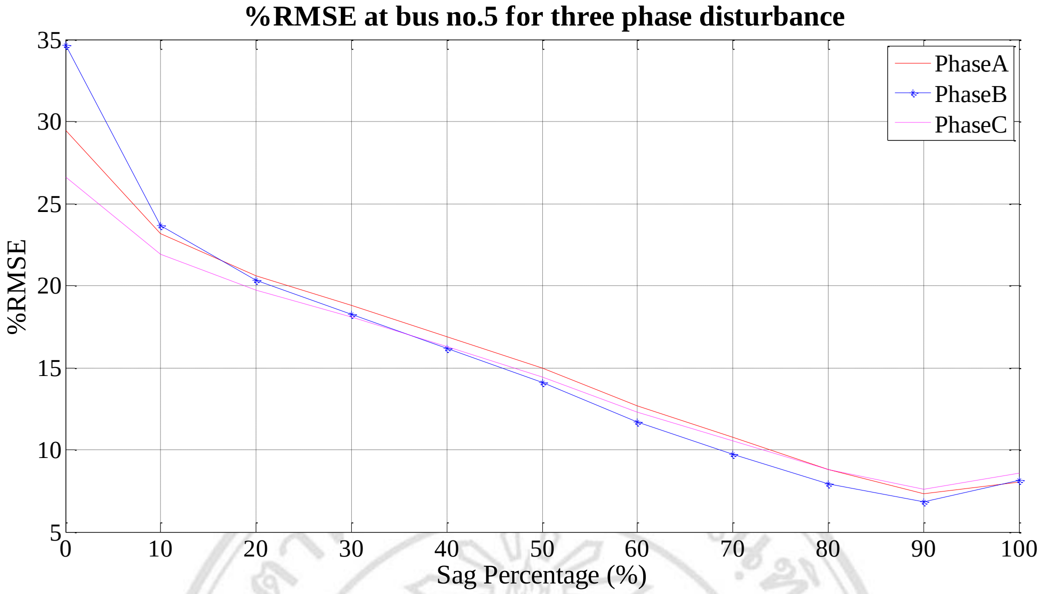

Figure 3.27 %RMSE at bus no.5 for three-phase disturbance with considering the saturation of transformer.

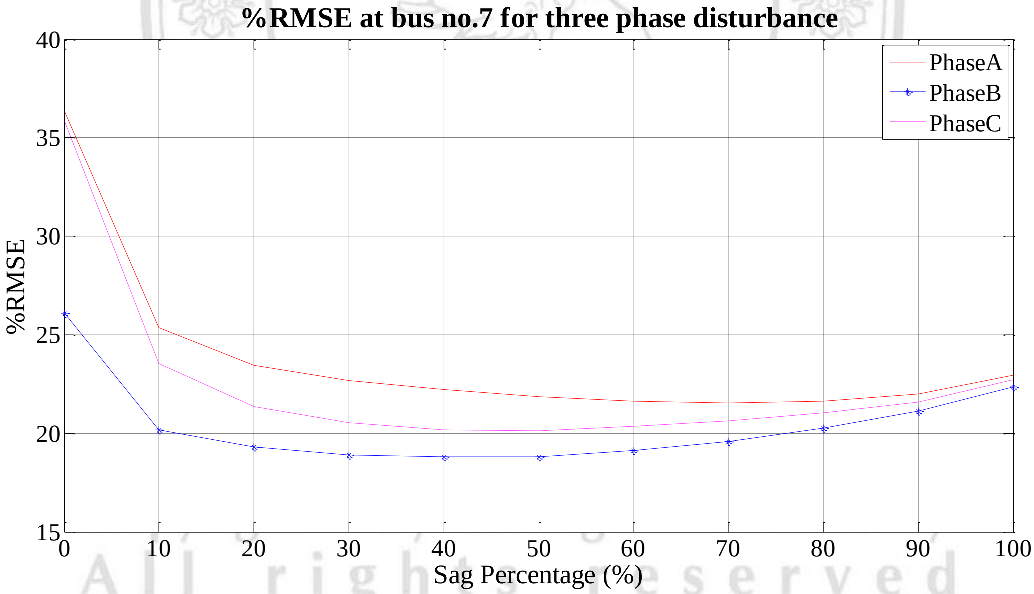

Figure 3.28 %RMSE at bus no.7 for three-phase disturbance with considering the saturation of transformer.

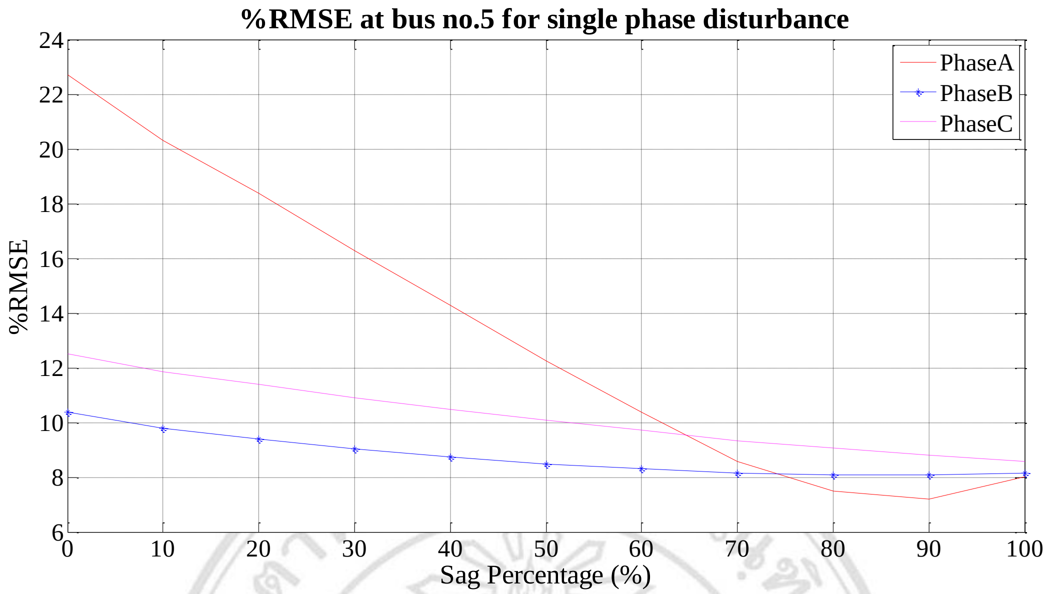

Figure 3.29 %RMSE at bus no.5 for single-phase disturbance
with considering the saturation of transformer.

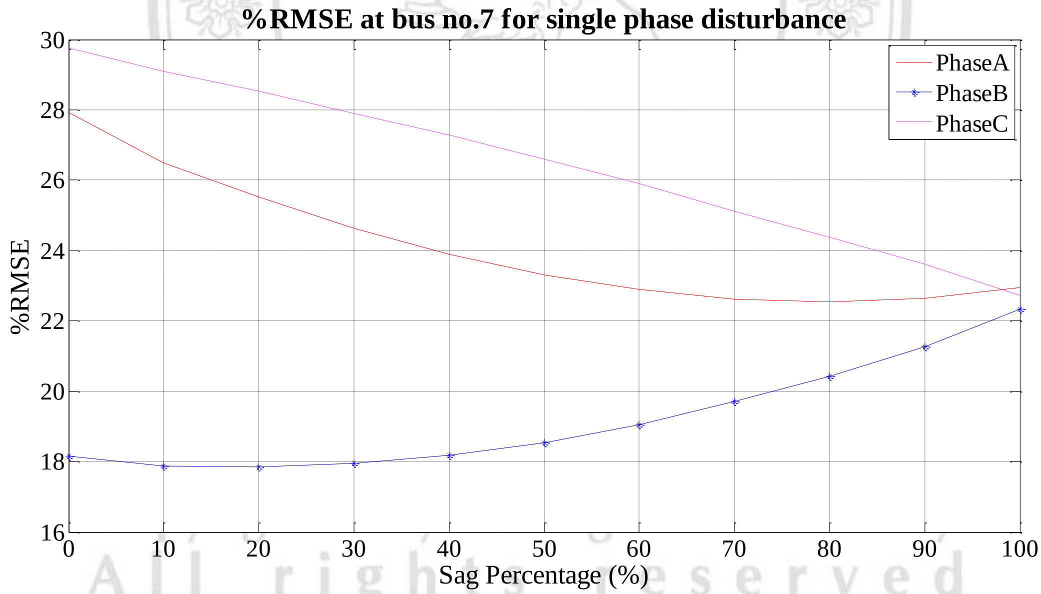

Figure 3.30 %RMSE at bus no.7 for single-phase disturbance
with considering the saturation of transformer.

For single-phase fault testing (with considering the saturation of transformer) can found that at bus no.5 %RMSE occurred more at phase-A than the others. But at bus no.7, the voltage sag occurred at phase-A and affected to over voltage at phase-C, together with effect of the connecting of saturated transformer lead to %RMSE of phase-C is more than other phase.

Both table 3.9 and 3.10 are summarize the results of %RMSE and %MAE at bus no.5 and 7 with considering the saturation of transformer for three-phase fault. Similarly, the evaluation for single-phase fault case is shown in table 3.11 and 3.12.

Table 3.9 Evaluation at bus no.5 for three-phase disturbance with considering the saturation of transformer.

Voltage Sag	Phase A		Phase B		Phase C	
(%)	%RMSE	%MAE	%RMSE	%MAE	%RMSE	%MAE
100% (no sag)	8.0309	7.0441	8.1607	7.2139	8.5732	7.3815
90%	7.3477	6.2175	6.8368	5.9180	7.6026	6.2751
80%	8.7939	7.5224	7.9058	6.9534	8.8111	7.4560
70%	10.7449	9.0738	9.7198	8.4113	10.5325	8.8861
60%	12.6946	10.5030	11.6764	9.8373	12.3024	10.1919
50%	14.9941	12.1143	14.0923	11.5072	14.4462	11.6482
40%	16.9036	13.3961	16.1600	12.8909	16.2629	12.8064
30%	18.8063	14.6187	18.2666	14.2398	18.0775	13.9191
20%	20.6028	15.7124	20.3252	15.4762	19.7399	14.8622
10%	23.1835	17.1122	23.6434	17.2496	21.8988	15.9709
0% (Interruption)	29.4500	20.3391	34.6557	23.2372	26.6368	18.5502

Table 3.10 Evaluation at bus no.7 for three-phase disturbance with considering the saturation of transformer.

Voltage Sag	Phase A		Phase B		Phase C	
(%)	%RMSE	%MAE	%RMSE	%MAE	%RMSE	%MAE
100% (no sag)	22.9415	20.4594	22.3331	19.7902	22.7296	20.0563
90%	21.9950	19.4187	21.1450	18.6419	21.5963	18.7877
80%	21.6271	18.7227	20.2490	17.6915	21.0431	17.9802
70%	21.5181	18.2004	19.5773	16.8971	20.6096	17.2548
60%	21.6200	17.8331	19.1017	16.2531	20.3285	16.6148
50%	21.8585	17.4287	18.8115	15.6194	20.1169	15.9531
40%	22.2271	17.2158	18.8088	15.2362	20.1598	15.5779
30%	22.6835	17.0994	18.8952	14.9419	20.5492	15.4458
20%	23.4627	17.3746	19.2942	14.9298	21.3394	15.6025
10%	25.3438	18.5537	20.1637	15.2735	23.5360	16.7437
0% (Interruption)	36.3527	27.5062	26.0810	17.8717	35.8406	26.4079

Table 3.11 Evaluation at bus no.5 for single-phase disturbance (phase A disturbance) with considering the saturation of transformer.

Voltage Sag	Phase A		Phase B		Phase C	
(%)	%RMSE	%MAE	%RMSE	%MAE	%RMSE	%MAE
100% (no sag)	8.0309	7.0441	8.1607	7.2139	8.5732	7.3815
90%	7.1817	6.1111	8.0929	7.0948	8.8001	7.5891
80%	7.4972	6.3048	8.0975	7.0050	9.0533	7.7930
70%	8.5784	7.3090	8.1603	6.9598	9.3387	8.0003
60%	10.3671	8.7480	8.3007	6.9788	9.7082	8.2554
50%	12.2560	10.1384	8.4911	7.0297	10.0807	8.4998
40%	14.2799	11.5518	8.7405	7.1066	10.4886	8.7607
30%	16.2898	12.9068	9.0363	7.1974	10.9116	9.0165
20%	18.3706	14.2904	9.3982	7.3011	11.3786	9.2858
10%	20.3135	15.5680	9.7887	7.4084	11.8461	9.5411
0% (Interruption)	22.6916	17.1210	10.3844	7.6283	12.4970	9.8857

Table 3.12 Evaluation at bus no.7 for single-phase disturbance (phase A disturbance) with considering the saturation of transformer.

Voltage Sag	Phase A		Phase B		Phase C	
(%)	%RMSE	%MAE	%RMSE	%MAE	%RMSE	%MAE
100% (no sag)	22.9415	20.4594	22.3331	19.7902	22.7296	20.0563
90%	22.6344	20.1465	21.2677	18.7906	23.6185	20.8183
80%	22.5446	19.9283	20.4302	17.9410	24.3881	21.4360
70%	22.6198	19.8925	19.7206	17.1775	25.1092	21.9988
60%	22.8937	20.0065	19.0365	16.3663	25.9056	22.6177
50%	23.3156	20.2108	18.5423	15.6842	26.6021	23.1610
40%	23.9033	20.5004	18.1685	15.0540	27.2798	23.6925
30%	24.6219	20.8452	17.9388	14.4967	27.9083	24.1923
20%	25.5192	21.2763	17.8438	14.0590	28.5302	24.6713
10%	26.4998	21.7854	17.8833	13.8217	29.0887	25.0887
0% (Interruption)	27.9279	22.5296	18.1527	13.9656	29.7654	25.5733

Generally, Transmission line distance effects to travelling time and also the calculation of past history of current in equation (2.35) and (2.36). Therefore, bus no.7 should has %RMSE and %MAE less than bus no.5 since the distance of transmission line between bus address and fault location is shorter. But the effect of nonlinear characteristic of saturated transformer affects the %RMSE and %MAE at bus no.7 more than bus no.5. However, this error can reduce by decreasing step size of calculation.

3.5 Consideration of estimated result in modal domain

During modal transformation process corresponding with equation (2.27) and (2.30), the data in modal domain can indicate the performance of proposed algorithm. There were three cases used in consideration; TSE algorithm, TSE algorithm with noise, and TSE algorithm with nonlinear equipment. Each case was investigated with three-phase and single-phase disturbance.

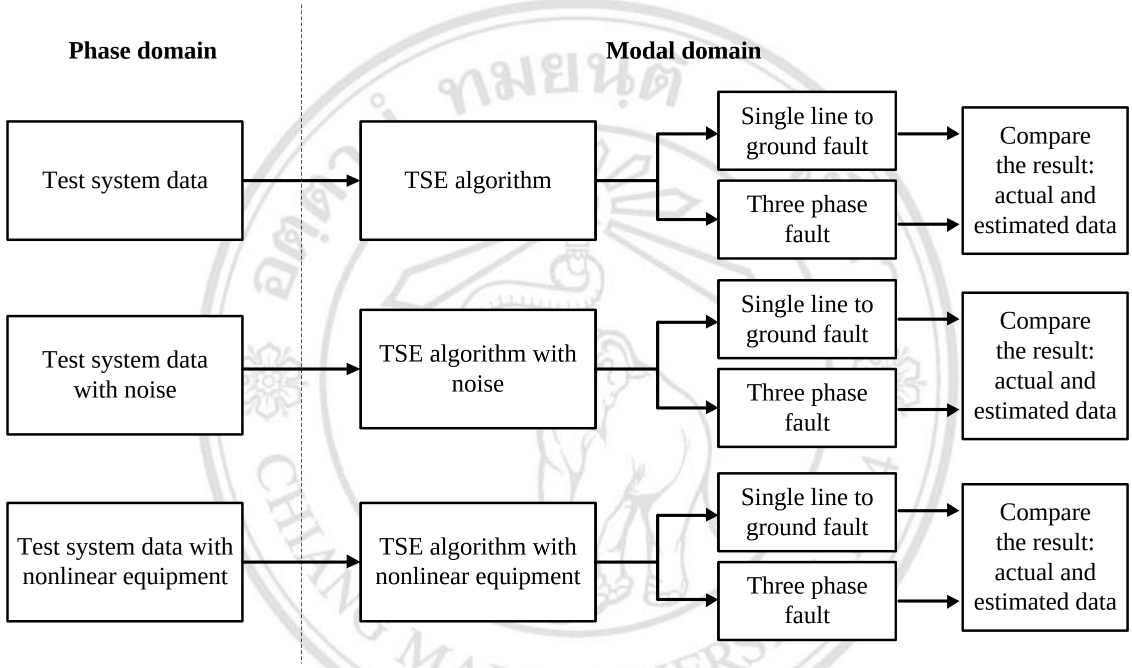

Figure 3.31 Work flow for consideration of estimated result in modal domain.

3.5.1 Case of TSE algorithm

Due to a symmetrical source fed to the power system, the balance of three-phase in power system occurs. The zero sequence voltage in modal domain corresponding with equation (2.27) and (2.30) is zero value. For three-phase fault duration, the system is still balance which leads to zero value of zero sequence voltage as show in figure 3.32 for bus no.5 and figure 3.33 for bus no. 7.

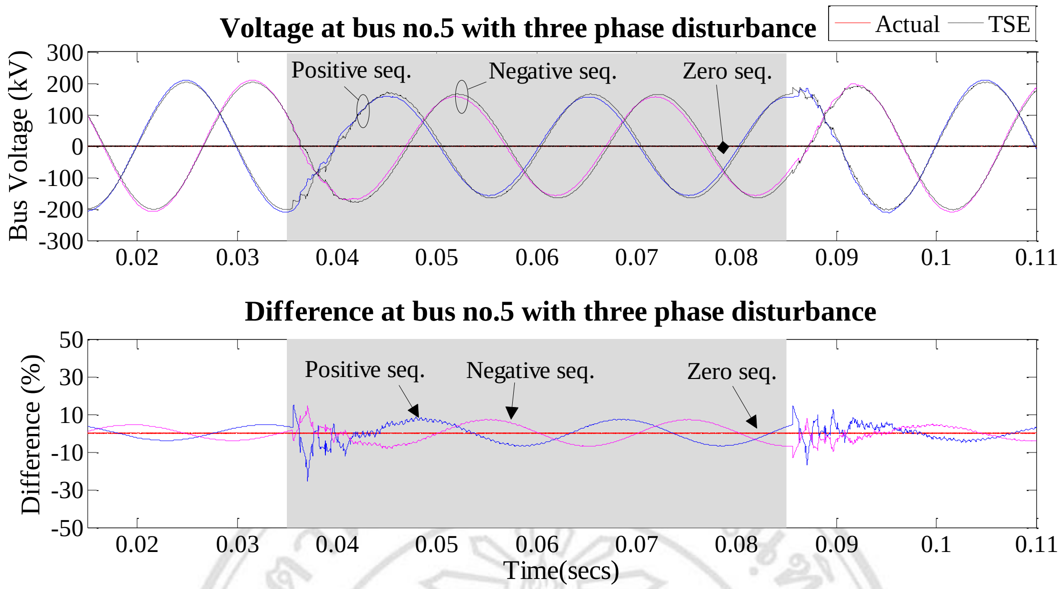

Figure 3.32 Voltage at bus no.5 in modal domain (three-phase disturbance: 80% sag).

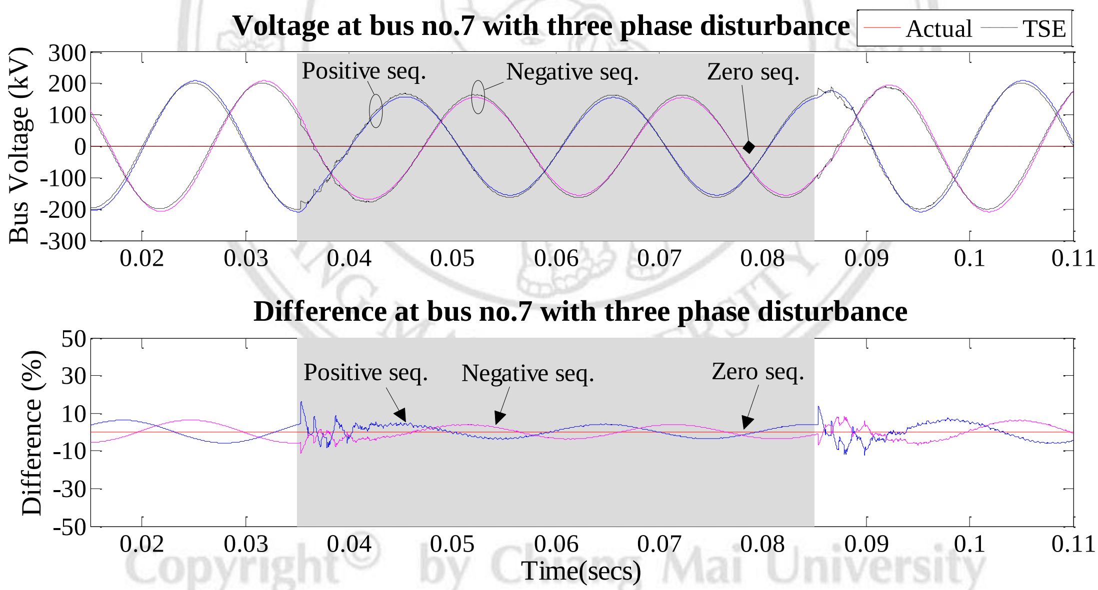

Figure 3.33 Voltage at bus no.7 in modal domain (three-phase disturbance: 80% sag).

For steady state, zero sequence component in balance three-phase is zero value. But for the single line to ground fault, it occurs in power system that leads to unbalance three-phase power system. Therefore, the zero sequence component is not zero value in fault duration as shown in figure 3.34-3.35.

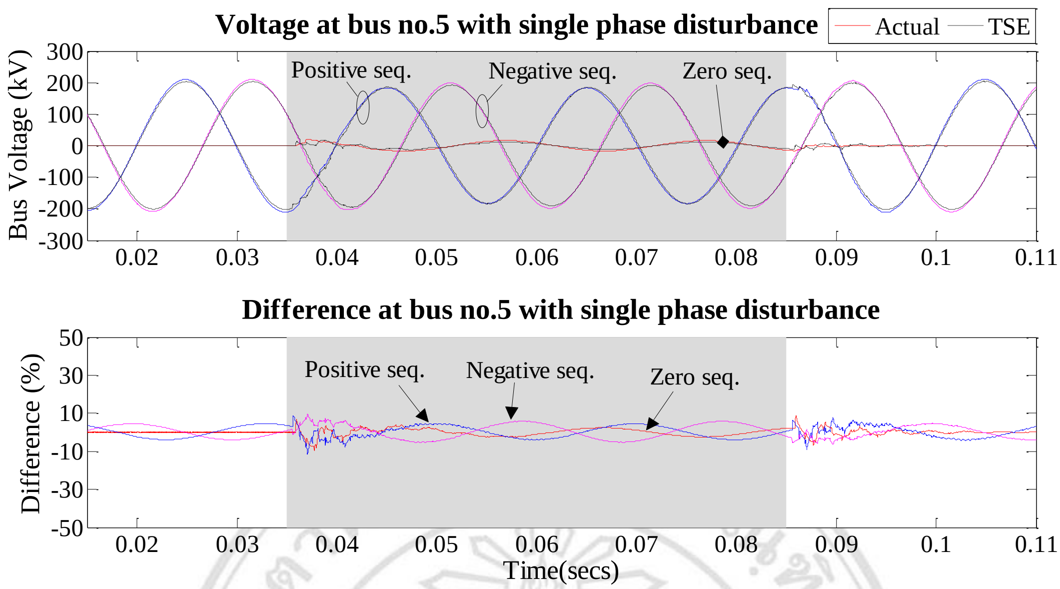

Figure 3.34 Voltage at bus no.5 in modal domain (single-phase disturbance at phase A: 80% sag).

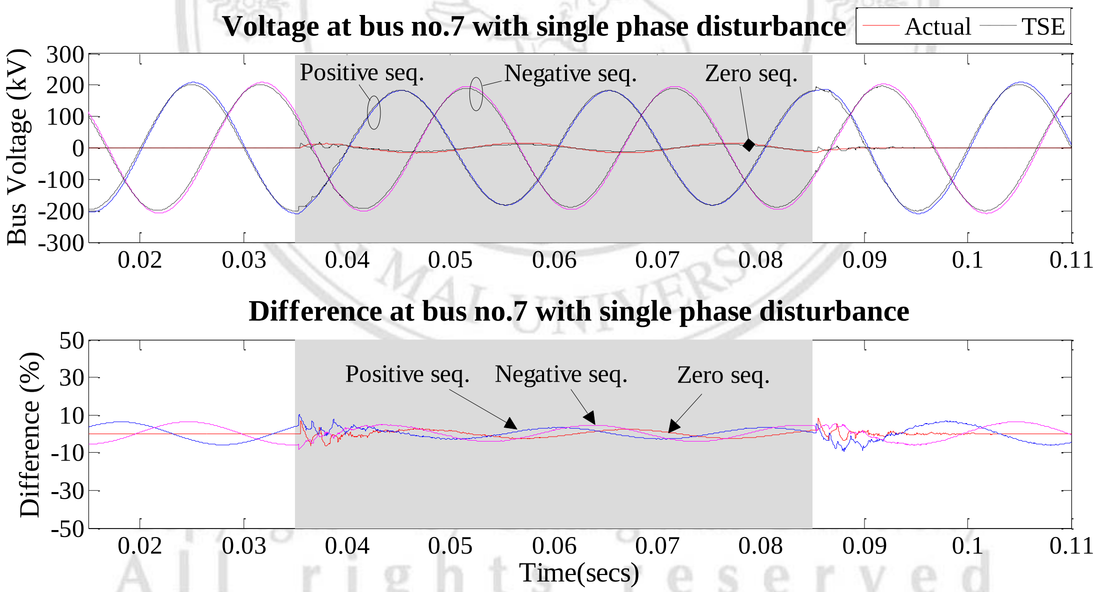

Figure 3.35 Voltage at bus no.7 in modal domain (single-phase disturbance at phase A: 80% sag).

3.5.2 Case of TSE algorithm with noise

The results trend of TSE algorithm with noise case is similar to noiseless case. But the addition of noise reduced performance of the proposed algorithm. For three-phase fault, the power system is in balance situation which leads to zero value of zero sequence voltage as shown in figure 3.36 for bus no.5 and figure 3.37 for bus no.7.

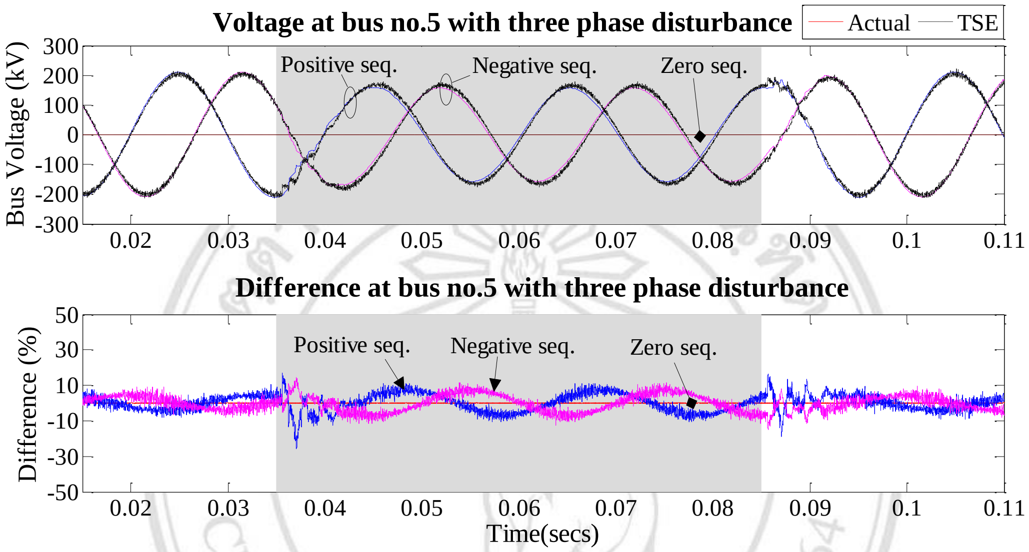

Figure 3.36 Voltage at bus no.5 in modal domain (three-phase disturbance: 80% sag with a 1% measurement noise).

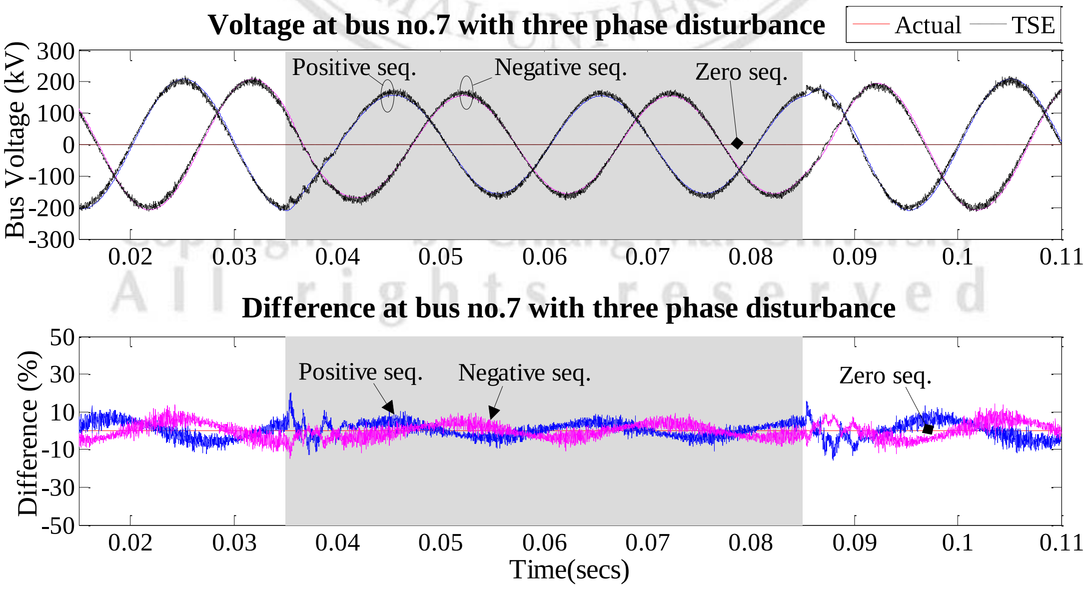

Figure 3.37 Voltage at bus no.7 in modal domain (three-phase disturbance: 80% sag with a 1% measurement noise).

In case of single line to ground fault occurs in power system, it leads to unbalance phase power system. Therefore, the zero sequence component in modal domain will not be zero value between fault duration as shown in figure 3.38-3.39.

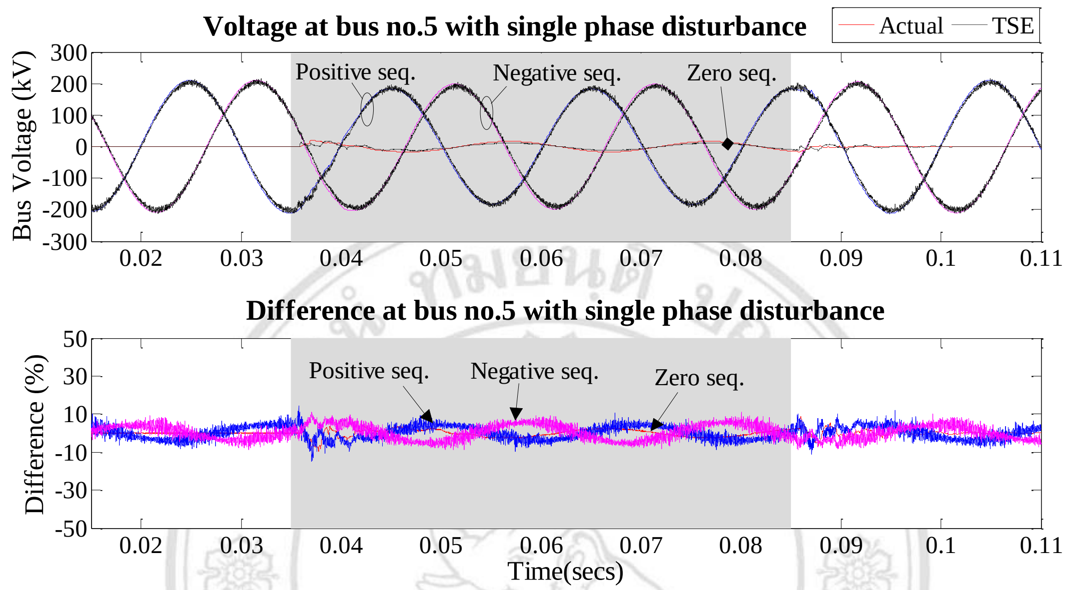

Figure 3.38 Voltage at bus no.5 in modal domain (single-phase disturbance at phase A: 80% sag with a 1% measurement noise).

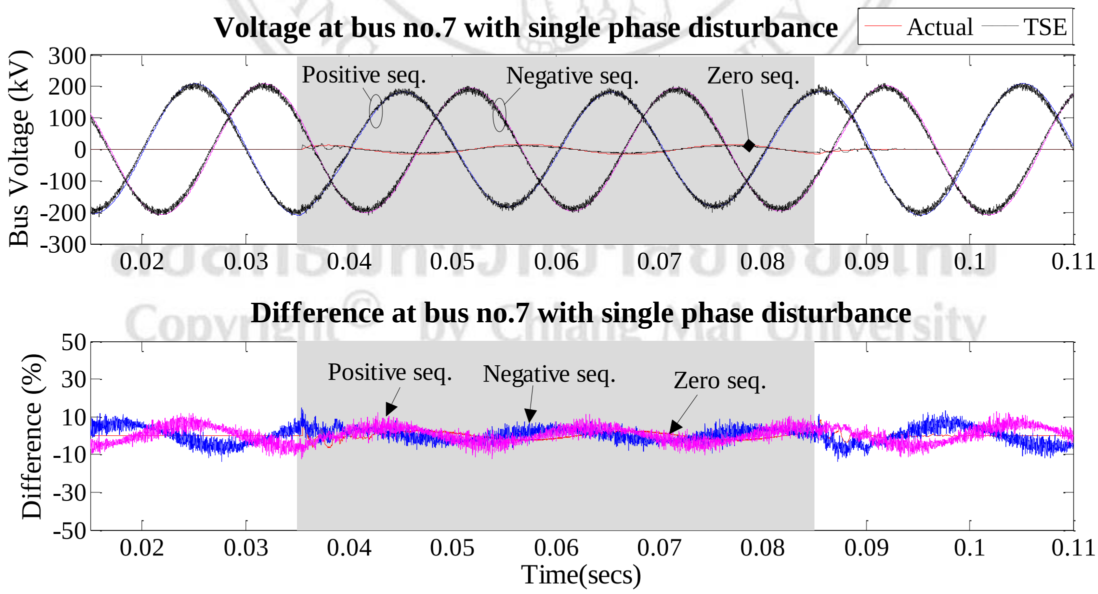

Figure 3.39 Voltage at bus no.7 in modal domain (single-phase disturbance at phase A: 80% sag with a 1% measurement noise).

3.5.3 Case of TSE algorithm with nonlinear equipment

The saturated transformer is connected to test system at bus no.7 to consider the performance of proposed algorithm with nonlinear equipment. The detail of calculation and the characteristics of saturated transformer are assigned in section 3.4. The results indicate that the saturated transformer reduced the performance of the proposed algorithm. However, the three-phase fault produces the balance three-phase of power system. The zero sequence voltage in modal domain is zero value. The voltage waveform with fault phenomena in modal domain and percentage of difference are shown in figure 3.40 for bus no.5 and figure 3.41 for bus no.7.

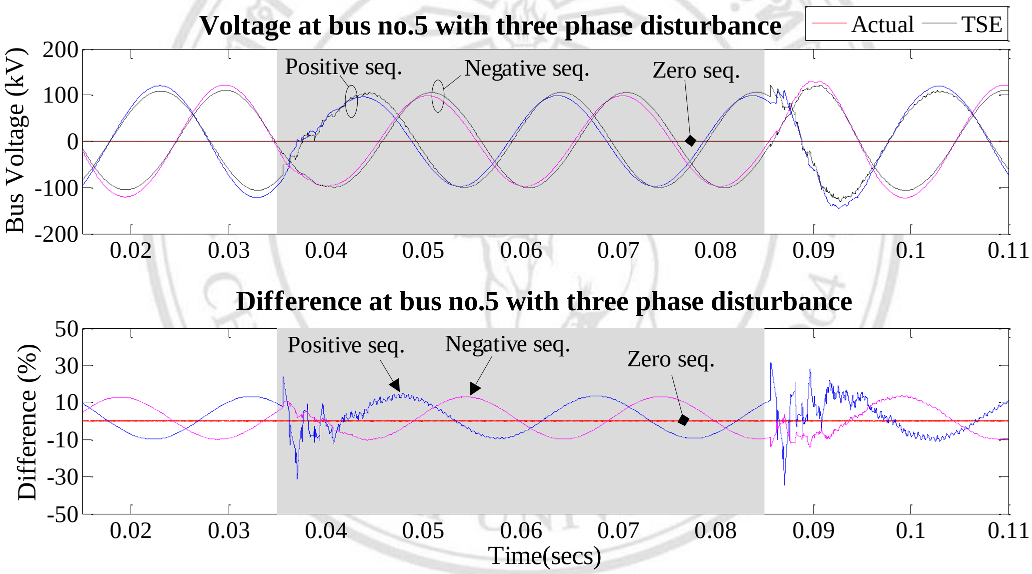

Figure 3.40 Voltage at bus no.5 in modal domain (three-phase disturbance: 80% sag with considering the saturation of transformer).

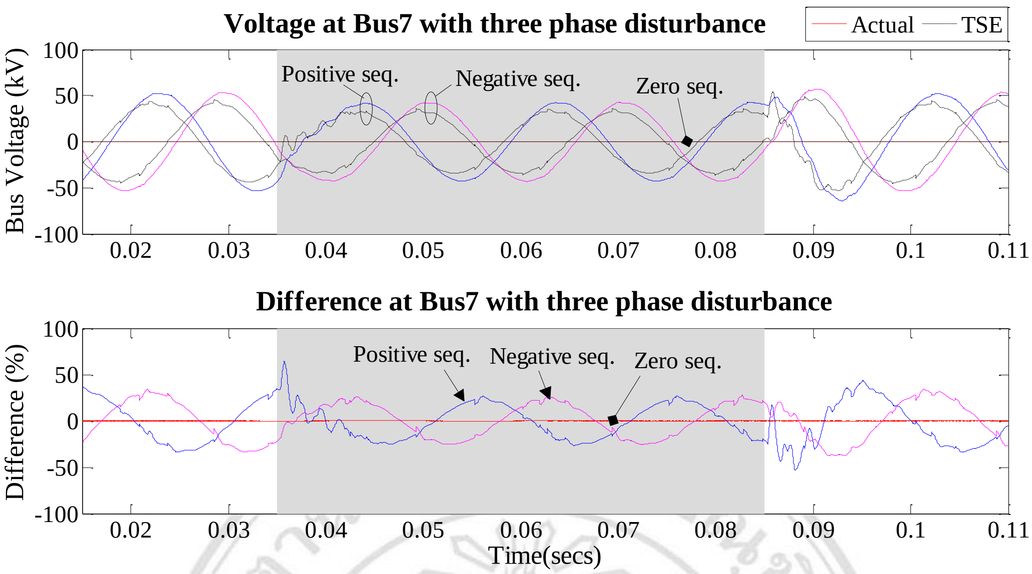

Figure 3.41 Voltage at bus no.7 in modal domain (three-phase disturbance: 80% sag with considering the saturation of transformer).

For single line to ground fault with saturated transformer, the fault occurs in phase A and lead to unbalance phase of power system. Therefore, the zero sequence component in modal domain is not zero value between fault duration as shown in figure 3.42 for bus no.5 and figure 3.43 for bus no.7.

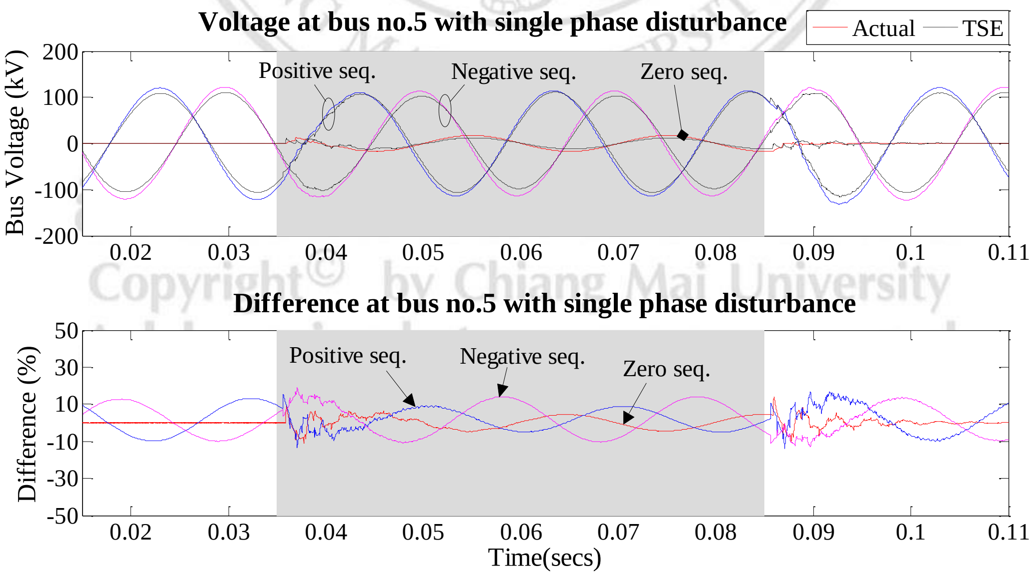

Figure 3.42 Voltage at bus no.5 in modal domain (single-phase disturbance at phase A: 80% sag with considering the saturation of transformer).

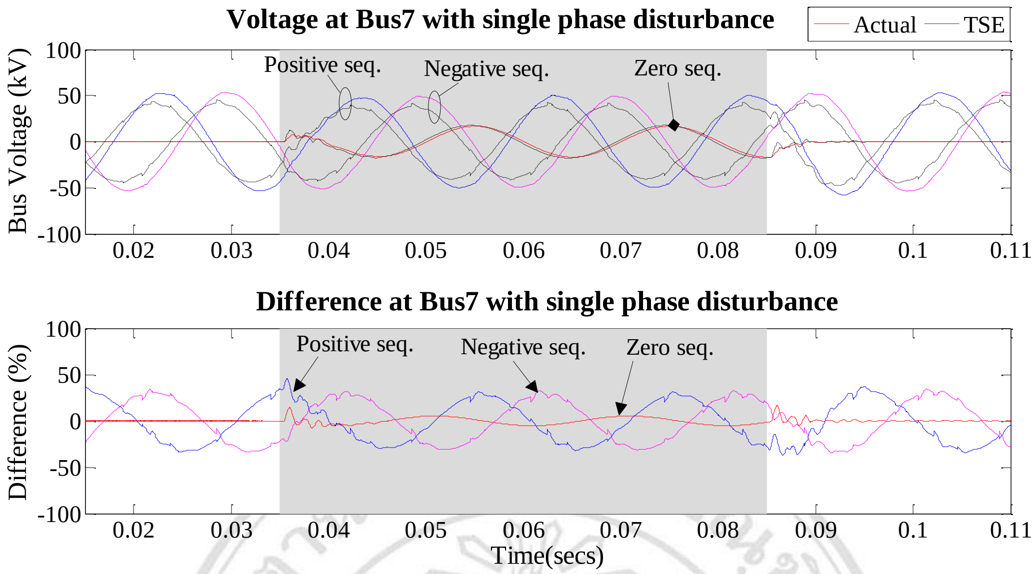

Figure 3.43 Voltage at bus no.7 in modal domain (single-phase disturbance at phase A: 80% sag with considering the saturation of transformer).