International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878 (Online), Volume-8, Issue-1, May 2019

Voltage Stability Analysis using an Optimal Thevenin Equivalent Estimation Method for varying Reactive Power in a Power System

Vishal Kumar Singh, S. V. Jayaram Kumar

***Abstract:** A voltage stability method using Thevenin equivalent method has been proposed. The change in reactive power in the system introduces voltage swells or sags in the system and vice-versa giving rise to a phenomena called Voltage Stability. Our proposed method will do away with the problems associated with short circuit faults, circuit breakers action, load-switching, etc., and thus voltage instability. The idea is to obtain Thevenin equivalent parameters of the system and replacing it with the same (Eth and Xth) so that the voltage of the system remains constant during all the possible mishaps mentioned above at different places in a power system. The proof of the proposed method is shown by the simulation obtained in MATLAB/Simulink, for a two generator system and also verifying it mathematically with the proposed algorithm. The quadratic approximation/curve fitting helps us finding the optimal solution. This proposed system finds its application in various power systems containing renewable energy sources where power flow is not constant from these sources to the grid and hence causing the voltage of the main system to fluctuate. Replica of such a WINDHUB system has been examined and results show that power quality of the system can be improved by using the Thevenin's model and shunt capacitors on a medium length transmission line.*

***Index terms:** Voltage stability, Reactive power, Thevenin equivalent, Quadratic curve fitting, AQ bus, PV curve*

I. INTRODUCTION

Thevenin's theorem is a network theorem in which we calculate an equivalent voltage source of all the sources in the given circuit and an equivalent impedance of all the impedances given in the circuit across two points, particularly load. Then we replace the entire circuit with these Thevenin equivalents in series to each other across the load and simplify the circuit for further calculations. In this paper, we are dealing with transmission lines so we use only Thevenin reactance (resistance being very small comparatively is neglected).

Revised Manuscript Received on 30 May 2019.
***** Correspondence Author
Vishal Kumar Singh*, Student EEE, Gokaraju Rangaraju Institute of Engineering and Technology (JNTU-H), Nizampet, Hyderabad, India.
Dr. S V Jayaram Kumar, Professor EEE, Gokaraju Rangaraju Institute of Engineering and Technology (JNTU-H), Nizampet, Hyderabad, India.

In Fig. 1, fixed voltage source or the Thevenin's equivalent voltage Eth is shown in series with a fixed or Thevenin's reactance Xth which is further connected to a load bus [1]. As load increases, P and Q increase and hence the voltage will decrease. The phenomena is depicted in the Fig. 2, with the PV curve. The nose of the PV curve is the voltage collapse point beyond which active power and voltage both decrease resulting in voltage instability. The maximum power transfer is achieved at the tip or the nose of the PV curve.

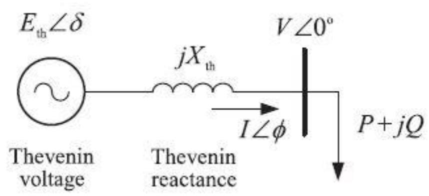

Fig. 1. Thevenin Equivalent model

For the PV curve analysis, we have assumed that Eth and Xth are constant during the analysis process [2]. It would not be true for a practical power system. The aim of our paper is to calculate such Thevenin equivalent model and analyze the effect of reactive power on the system using the values obtained in MATLAB. So, active power P, reactive power Q, and voltage V values are measured at the bus as shown which are further used to calculate the Thevenin equivalents. Earlier methods of obtaining Thevenin equivalent parameters are mainly based on curve fitting like least square approximation. The problem with these methods are that data points occupy very small part of the obtained PV graph [1]. The approach and motivation of the proposed method, the Algorithm to calculate Thevenin equivalent and the analysis part has been discussed in the following sections. Thevenin equivalent method is applied to a simple two source test system in MATLAB is also discussed. The method is later applied to a win hub replica of medium voltage transmission system in MATLAB in section IV.

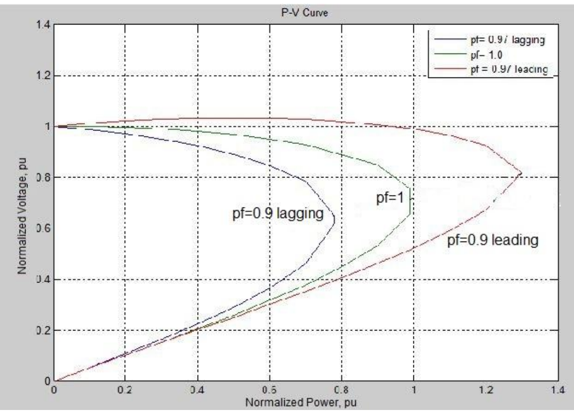

Fig. 2. PV curve of a single-source static-load system

II. PROPOSED METHOD

To represent a test system as given in Fig. 1, there should be enough variations in P and Q (specifically Q), so that the voltage computed/calculated from the Thevenin equivalent method must agree with the simulation. The sources are simple 3 phase sources and loads used are all static types which results in simple and reliable approach. To motivate the approach, we have considered a power system containing only two power sources [1]-[3], one being large PV source (system 1) and other being small swing bus source (system 2). The larger power source is connected in parallel to 80MW load and to the measurement bus through a transmission line of reactance 0.3 pu. The smaller power source is connected in the same way to the measurement bus via a transformer and a parallel load of 80 MW. We applied disturbances such as short circuit fault and load switching through circuit breakers to both the systems one by one, to obtain the P, Q, V readings. For disturbance in larger system at the left, we can calculate the Thevenin equivalent for the system at the right, and vice – versa. If a fault is applied in smaller system such that (P, Q, V) values vary, and if system at the left is represented by an equivalent Eth and an equivalent Xth, then considering only the magnitude, equation

Eth = V + j Xth * I = V + j Xth * (P + j Q) / V (1)

Eth = (V − Xth * Q / V) + j Xth * P / V (2)

Justifies and in relation for all (P, Q, V) values. If we succeed to find a correct Xth value then during all the fault periods Eth or the Thevenin voltage is a constant value with minimum error. Thus, we assume a range of values for Xth (as Xth is unknown before calculations), and use them to calculate Eth. Then the value of Xth which gives us the near constant value of Eth with minimum root mean square error qualify to be called as Thevenin equivalent values (Eth and Xth). To select an optimal value of Xth for constant Eth value given in the following proposed algorithm [1]:

Optimal Thevenin equivalent estimation Algorithm:

1) Note down the P, Q, V values from MATLAB simulation

2) Assume a range for the Xth value as 0.05, 0.1, 0.15, 0.2, etc., as Xthi , i =1, 2, ..., n

3) Calcuate Ethi(k) for each of the above Xthi from eqn. 1 where k denotes the data point time index.

4) Calculate average for each Ethi obtained above from

$$\bar{E}_{\mathrm{th}i} = \left(\sum_{k=1}^{N} E_{\mathrm{th}i}(k) \right) / N$$

where N is the number of sample points, and the root mean-square error as

$$\varepsilon_i = \sqrt{\frac{\sum_{k=1}^{N} (E_{\mathrm{th}i}(k) - \bar{E}_{\mathrm{th}i})^2}{N}}$$

5) For the lowest value of εi, the calculated Ethi and its two adjacent neighboring points Eth(i−1) and Eth(i+1) considered for obtaining an optimal Xth value from a 3-point quadratic fit algorithm in [8].

6) Calculate Eth (k) using Xth, again from eqn. 1

7) Then the average Eth value is calculated for the Eth (k) values

$$\hat{E}_{\mathrm{th}} = \left(\sum_{k=1}^{N} E_{\mathrm{th}}(k) \right) / N$$

III. APPROACH AND ANALYSIS

We have worked out for three voltage step disturbances, in which (P, Q, V) values are measured from the graphs in MATALB. First we have applied short circuit fault and load switching disturbance, one after other, in system 2 and calculated Thevenin parameters for system 1. Then we did the same with system 1 by applying the circuit breaker disturbance and calculated the equivalents for system 2. We have verified our calculation with the simulation of Eth in MATLAB using the eqn. 2 mentioned in section II. We converted the equation in the Simulink model shown in Fig. 4.

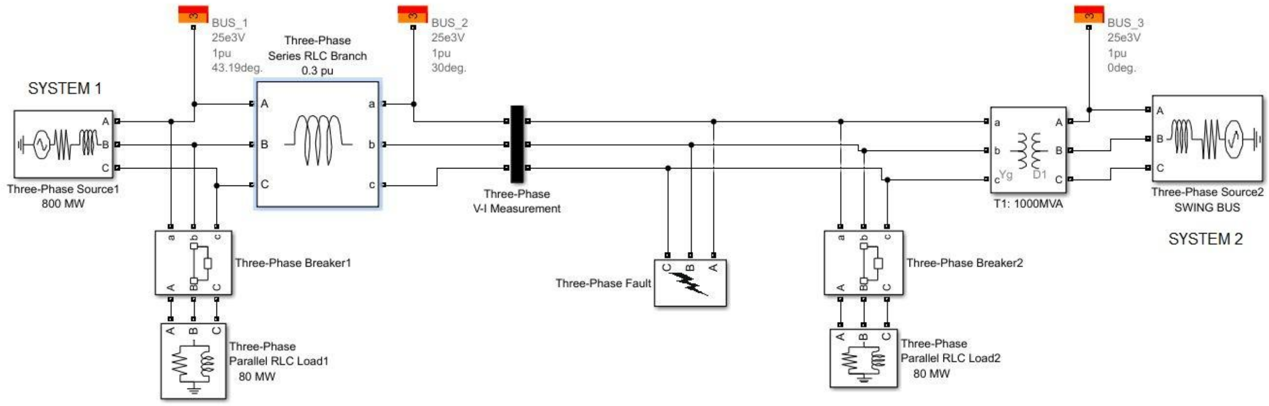

Fig. 3. A simple two source power system

Mathematically, the optimal value of Xth can be obtained using three point quadratic algorithm given in [8]. But graphically it will easier and faster to obtain exact value using MATLAB curve fitting toolbox [9]. So, in MATLAB we consider a quadratic equation as $E = aX^2 + bX + c$ and use the three points obtained to get a graph as given in Fig. 5.

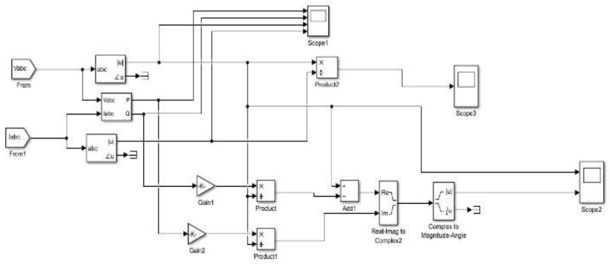

Fig. 4. Equivalent Simulink model for Eth simulation

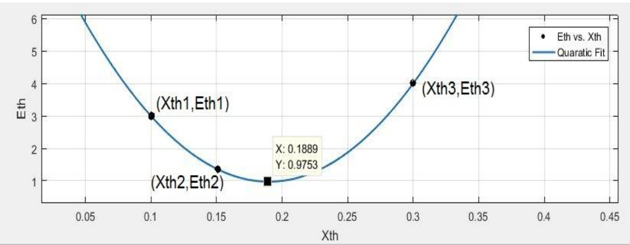

Fig. 5. Quadratic Curve Fitting using MATLAB toolbox

A. *Three phase Short Circuit Fault Disturbance*

Firstly, applying 3ph short circuit fault to ground in system2 as shown in Fig. 3 and adjusting its fault and ground resistances (5 and 10 ohms respectively), we obtained the P, Q, and V values as shown in Fig. 6 below. We also simulated the eqn. (2) in MATLAB to obtain Eth values for a range of Xth values from 0.05 to 0.25. Fig. 7 shows Xth = 0.184 pu approx. and Eth = 0.9363 pu. The simulated Eth and Xth values are in approximate agreement with the calculated values with the root mean square error in the Thevenin voltage approximation as 0.000416 pu. The fault is applied at 2 and 4 seconds, and has been removed at 3 and 5 seconds. We can see from Fig. 7 that Eth value is constant (green) for Xth = 0.184.

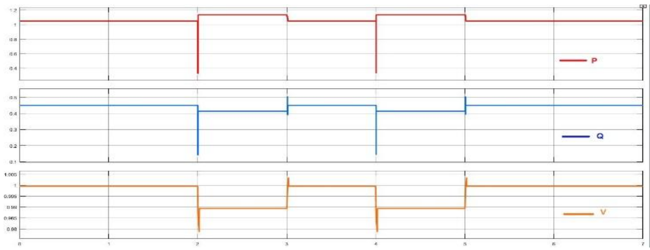

Fig. 6. (P, Q, V) graphs for 3ph short circuit fault

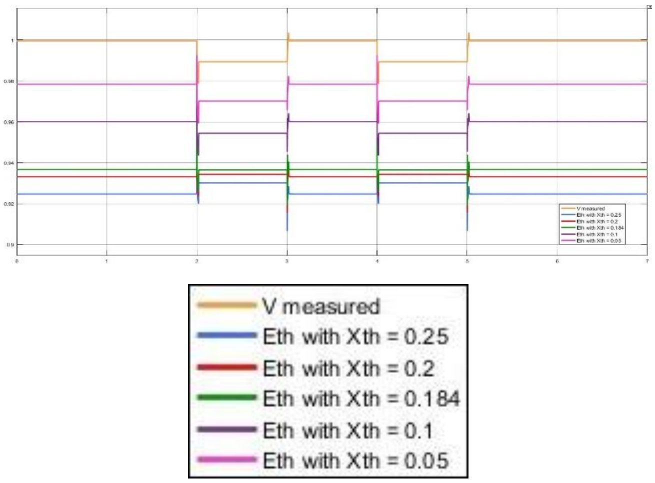

Fig. 7. Graph of *E*th for various values of *X*th.

B. *Load Switching Disturbance in System 2*

Next, disturbance caused by circuit breaker action or what we call as a load switching disturbance is applied in system 2 and P, Q, and V values are obtained as in Fig. 8 and Thevenin equivalents are calculated as Eth = 0.9246 and Xth = 0.25 pu. The results are verified with the simulation in Fig. 9. We need to adjust the three phase circuit breaker resistance as it plays a crucial role in obtaining desired results with individual operating parameters. In our case, we kept it 40 ohms. All other operating conditions are same as short circuit disturbances. The RMS error in this case was 0.000408. Thevenin equivalents obtained are nearly in agreement with that of former.

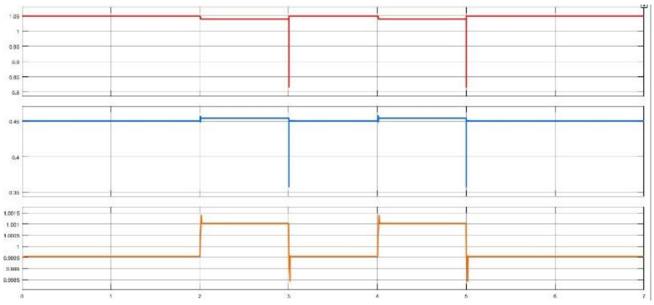

Fig. 8. (P, Q, V) graphs for load switching in system2

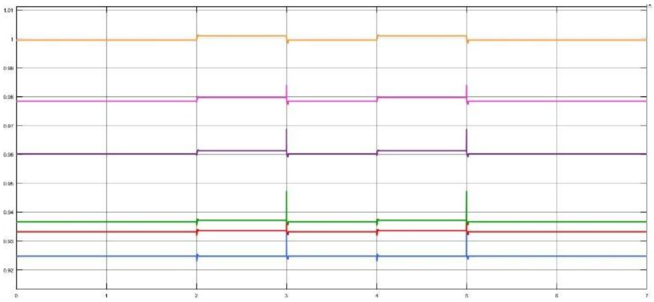

Fig. 9. Graph of *E*th for various values of *X*th.

C. *Load Switching Disturbance in System 1*

For the third case, we applied a similar load switching disturbance in system 1 rather to obtain Thevenin equivalent for system 2. Fig. 10 shows the graphs of P, Q, V and variations when circuit breaker was switched ON. The circuit breaker resistance is kept as 8 ohms in this case so as to obtain desired results. Here we see that the simulated Eth and Xth values are far from what we obtained for system 1. Fig. 11 shows that Eth = 0.9602 and Xth = 0.1 pu. The RMS error in this case is calculated as 0.000432 pu. Looking at the P, Q, and V values, this analysis shows that voltage disturbance hence stability largely depends on change in reactive power in the power system. More is the reactive power change more the voltage change and vice – versa.

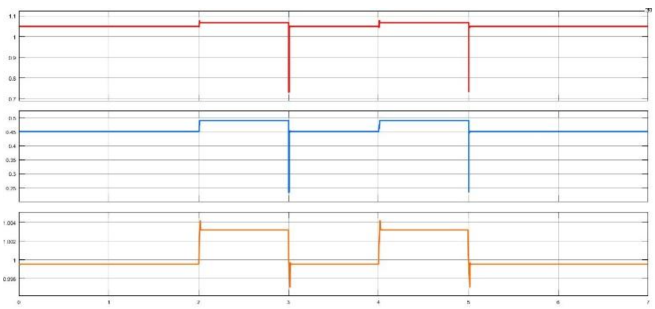

Fig. 10. (P, Q, V) graphs for load switching in system1

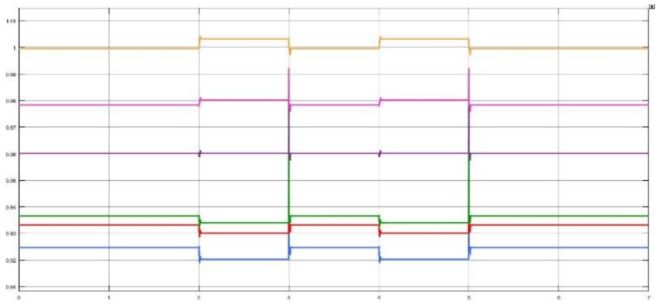

Fig. 11. Graph of *E*th for various values of *X*th.

IV. ANALYSIS OF WINDHUB REPLICA SYSTEM AND VOLTAGE STABILITY

Here, we have derived two Thevenin equivalents for a wind hub shown in Fig. 12 using MATLAB simulation. The WINDHUB is a 230 kV bus which connects six wind farms [4]. It consists of 4 type-2 and 2 type-3 wind turbines, with a combined maximum output of 600 MW. We have used PQ and PV power sources to replicate wind turbines. We also used two 30 MVAR shunt capacitors to support the voltage at the wind hub bus. The wind farm is also supported many shunt capacitors and reactors [6]. The wind hub bus is connected to the west via a transmission line of reactance 0.15 pu and to the east via 0.05 pu. The 500 kV system is a large system comprising of large generators and lies near to the east system. Thus east system is regarded as stronger than the west system. Before we start voltage stability analysis, the flow of reactive power supply at the wind hub bus is studied. Our objective is the safe transfer of maximum power to the west and to the east by representing east and west system with their respective Thevenin equivalents. The approach remains same as we have done with the two source system above. In addition to that we are keen in observing and analyzing the voltage change of the systems with respect to reactive power demand or supply. The advantage of analyzing a wind hub is that power generation from the wind turbines is not constant and Thevenin equivalent models works best with variations in P and Q values. The AQ bus method in [5] is used for our analysis purpose in which bus angle and reactive power are fixed. This method does away with the Jacobian singularity at the maximum power transfer point, specify the voltage angle for the load bus. The reduced Jacobian matrix is nonsingular at the maximum power transfer/loading point. Even though the bus is supplying power, the wind hub is chosen as the AQ bus [7]. We conducted the voltage stability analysis by increasing the angle difference / separation between the wind hub (*AQ* bus) and the swing bus. Here we need to know the amount of power flowing to the west and the east system from the wind farm to solve the power flow for the system.

A. *Thevenin Equivalent of the West system*

We obtained the Thevenin equivalent voltage as shown in Fig. 13 for various values of Xth ranging from 0.05 to 0.3 pu. The simulated voltage is constant for a value of Xth = 0.15 pu and which coincides with our mathematical calculation. Hence, we successfully obtained Eth as 1.073 pu and Xth as 0.15 pu and verified the algorithm. The Eth calculated by us has an RMS error of 0.0031 pu. We also noticed that Power transfer increases when we switch on the capacitors attached to the wind hub 230kV bus. Without capacitor the power transfer is 1.423 pu and 2.673 pu for west and east systems respectively. With both capacitors switched ON, it is 1.429 pu and 2.693 pu respectively without any outages.

Thus we see that the power profile can be improved or can be kept constant during the faults with the help of shunt capacitors. Also, the Reactive power varied for the system by switching PQ generators and shunt capacitors at the wind farm and result is analyzed.

B. *Thevenin Equivalent of the East system*

The optimal Thevenin equivalent estimation method is repeated for the east system and similar results have been obtained for the RMS error value of 0.0018.

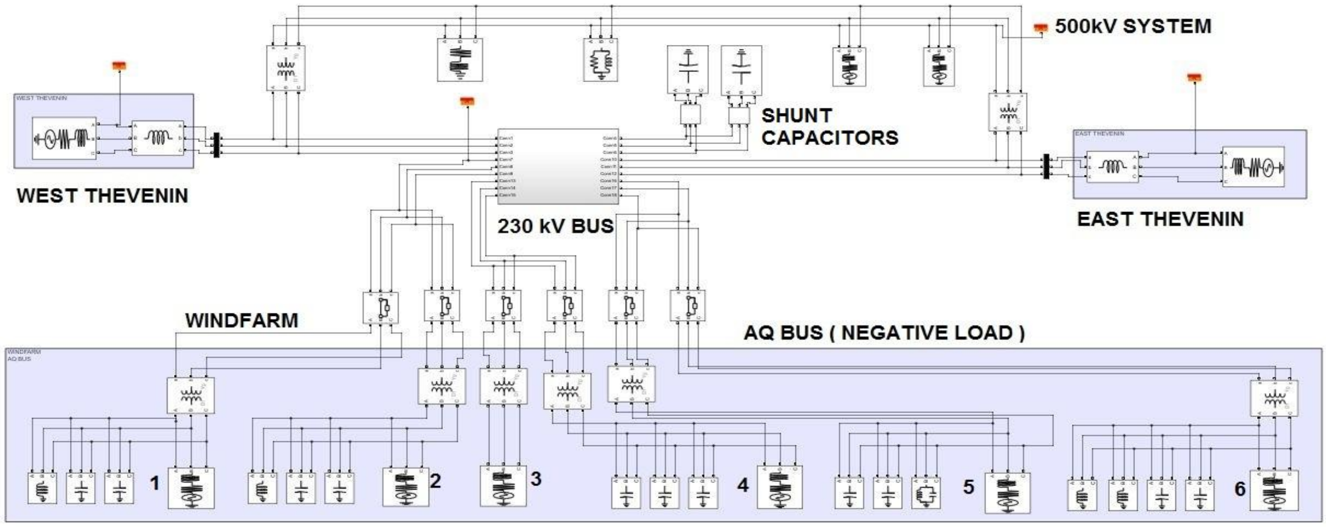

Fig. 12. Wind Hub Substation Layout

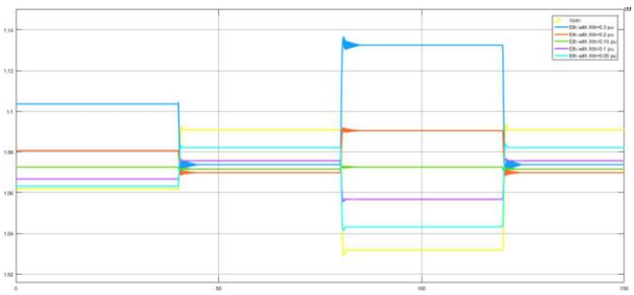

Fig. 13. Graph of *E*th for various values of *X*th for West system

OUTAGES OF THE WIND MILLS	WITHOUT SHUNT CAPACITORS							
	WEST SYSTEM (pu values)				EAST SYSTEM (pu values)			
	P	Q	V	Xth	P	Q	V	Xth
1(PQ)	1.432	0.1372	1.133	0.0564	2.228	-31.47	0.6941	0.0214
1,2(PQ)	1.440	0.2180	1.126	0.0561	1.815	-31.19	0.6878	0.0212
1,2,4(PQ)	1.445	0.2834	1.120	0.0559	1.483	-30.94	0.6827	0.0211
1,2,4,5(PQ)	1.455	0.3591	1.113	0.0556	1.070	-30.69	0.6776	0.0210
3(PV)	-0.472	2.752	0.300	0.0111	-3.36	25.65	0.6647	0.0269
3,6(PV)	-0.266	3.117	0.452	0.0248	-3.14	15.99	0.3895	0.0148
NONE	1.423	0.0525	1.141	0.0566	2.673	-31.73	0.7005	0.0215

(a)

OUTAGES OF THE WINDMILLS	WITH SHUNT CAPACITORS							
	WEST SYSTEM (pu values)				EAST SYSTEM (pu values)			
	P	Q	V	Xth	P	Q	V	Xth
1(PQ)	1.439	0.1207	1.135	0.0562	2.247	-31.62	0.6969	0.0214
1,2(PQ)	1.447	0.2013	1.128	0.0560	1.834	-31.34	0.6907	0.0213
1,2,4(PQ)	1.453	0.2664	1.122	0.0558	1.501	-31.10	0.6857	0.0212
1,2,4,5(PQ)	1.462	0.3419	1.115	0.0554	1.088	-30.85	0.6806	0.0211
3(PV)	-0.473	2.750	0.2998	0.0111	-3.359	25.68	0.6657	0.0270
3,6(PV)	-0.266	3.117	0.4526	0.0248	-3.141	15.99	0.3897	0.0148
NONE	1.429	0.0361	1.143	0.0564	2.693	-31.88	0.7033	0.0216

(b)

Table 1: Comparison of system values (a) without shunt capacitors, (b) with shunt capacitors.

V. CONCLUSION

An optimal Thevenin model equivalent estimation method has been proposed. It has been observed that the voltage profile and Eth graphs show much variations when reactive power change is large. Active power change has very small role in obtaining Eth and Xth.

The changes in the power system voltage with respect to reactive power change such as shunt reactor/capacitor bank switching in the system is deeply studied and analyzed. From observation Table 1, it is clear that the trend in the change of power and voltage profiles are different for the east and west systems. We observe that Thevenin equivalent decreases gradually with the outage of PQ generators but shows a drastic change with PV generators outage. Further, Xth values has negligible effect of the shunt compensation in both the cases. But, we noticed that the system values improved with shunt compensation. The above method can be effectively used to improve the power quality of the power system and to deal with the voltage instability issues.

VI. FUTURE WORK

Future works include further studying the wind hub system under the influence of SVC and STATCOM, when these are attached to the wind farm. The same work is to be done for PMU measurements. Then we are about to extend the study to a nine bus system where power fluctuations are more and voltage is less stable.

REFERENCES

1. Stephen M. Burchett, Daniel Douglas, Scott G. Ghiocel, Maximilian W. A. Liehr, Joe H. Chow, "An Optimal Thevenin Equivalent Estimation Method and its Application to the Voltage Stability Analysis of a Wind Hub," IEEE transactions on power systems, vol. 33, no. 4, pp. 3644-3652, July 2018
2. C. W. Taylor, Power System Voltage Stability. New York, NY, USA: McGraw-Hill, 1994.
3. Prabha Kundur, Power System Stability and Control. New York, McGraw-Hill, Inc.
4. M. Parniani, J. H. Chow, L. Vanfretti, B. Bhargava, and A. Salazar, "Voltage stability analysis of a multiple-infeed load center using phasor measurement data," in Proc. IEEE Power Syst. Conf. Expo., Oct. 2006, pp. 1299–1305.
5. S. G. Ghiocel, J. H. Chow, R. Quint, D. Kosterev, and D. J. Sobajic, "Computing measurement-based voltage stability margins for a wind power hub using the AQ-bus method," in Proc. Power Energy Conf. Illinois, 2014, pp. 1–6.
6. E. Heredia, D. Kosterev, and M. Donnelly, "Wind hub reactive resource coordination and voltage control study by sequence power flow," in Proc. IEEE Power Energy Soc. General Meeting, 2013, pp. 1–5.
7. S. M. Burchett, M. Liehr, S. G. Ghiocel, J. H. Chow, A. Faris, and
8. D. Kosterev, "Voltage stability analysis of a wind hub using Th`evenin
9. Equivalent models estimated from measured data," in Proc. Power Tech.
10. Conf., Manchester, U.K., 2017, pp. 1–6.
11. Website:https://www.futurelearn.com/courses/maths-linear-quadratic-relations/0/steps/12130
12. Website: https://in.mathworks.com/help/curvefit/curve-fitting.html

AUTHORS PROFILE

Vishal Kumar Singh, Student, M.Tech in power systems (EEE) from GRIET Hyderabad, B.Tech in EEE from BVRIT Narsapur Hyderabad, GATE 2017 qualified singhvishalkumar@rocketmail.com, 9441778759

Dr. S. V. Jayaram Kumar, Professor EEE department in GRIET from 2104 to 2019, Professor EEE department in JNTU Hyderabad till 2014, Ph.D from IIT Kanpur, ME and BE from Andhra university Vishakhapatnam, Publications: Model based control design of a TCSC compensated power system Electrical power & Energy systems (ELSIEVER) 1999, Subsynchronous resonance analysis using discrete time model of thyristor controlled series compensator. Electrical power and Energy systems (ELSIEVER) 1999, Damping of subsynchronous resonance oscillations with TCSC and PSS and their control interaction. Electrical power system research (ELSIEVER) 2000, Load flow solution for ill conditioned power system with FACTS devices Journal of theoritical and applied information technology 2009, A smart discrete fourier transform algorithm based digital multi-function relay for power system protection. International journal of computer and electrical engineering. 2011, Selection of capacitors for the Self excited induction generator 2012, svjkumar101@rediffmail.com