European Association for the Development of Renewable Energies, Environment and Power Quality (EA4EPQ)

International Conference on Renewable Energies and Power Quality (ICREPQ'11)
Las Palmas de Gran Canaria (Spain), 13th to 15th April, 2011

Online Thevenin's Equivalent Using Local PMU Measurements

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Abstract. This paper presents a method for determining Thevenin's Equivalent (TE) for a node in a power system using local PMU measurements at that node. Three consecutive voltage and current measurements are used to determine the TE. The proposed method recognizes and considers the phase angle drift caused by the slip frequency between the PMU sampling frequency and the power system frequency. The accuracy of the proposed method has been verified through application to the IEEE 30 bus test system as well as to a real system data measured at the terminals of a wind farm. The proposed method is going to be used to determine an online TE, which will be used to monitor the system capability to accommodate the wind power by updating a capability chart of the system at the node where the wind farm is connected.

Key words

Thevenin equivalent; PMU; wind power; capability chart.

1. Introduction

Having a Thevenin's equivalent (TE) for a system at one of its ports opens the door to many interesting possibilities. However, the quality and reliability of results obtained using TE is determined by the accuracy of the TE itself. For a linear system, the TE represents a perfect equivalent at the port it is determined for over the entire range of variations that may take place in voltage and/or current as long as the rest of the system is kept unchanged. In a real power system, the transmission network itself is linear, but node specifications, power injections and/or voltages, are not. Node specifications are either P, Q at load nodes or P, V at generation nodes. Hence, voltage/current relationships at the system nodes experience the nonlinearities of the specified injections. So, the problem lies mainly in the nonlinearity of the load/generation injections.

Using a TE several voltage stability indices have been developed [1-3]. In [1], loads and generators are replaced by equivalent static shunt admittance and the diagonal elements of the system bus impedance matrix, Z_{bus}, are considered the equivalent Thevenin impedances, Z_{th}, of the corresponding buses. Z_{th} is then compared with load impedance to determine the proximity of the system to voltage collapse. The same approach has been recently used in [2] but with Z_{th} calculated from local measurements. Multiple power flow solutions were used in [3] to determine a TE for the system at the weak nodes, which is then used to determine a voltage collapse proximity indicator. The TE of [3] is then used in [4] to assess the voltage stability of a system with large wind farms and in [5] to determine the system capability to accommodate wind power.

TE determined at a node will be valid as long as the rest of the system remains unchanged. This is of course not the case of monitoring a wind farm, which is the major interest of this work, as the power output from the wind farm is highly variable, power system balancing will change the output of the generators in the system to take up the power from the wind. Moreover, the power system itself is ever changing, even if no switching operations took place, loads and consequently generators are changing all the time. Therefore, the TE to be used for wind farm monitoring must be updated whenever a change takes place in the wind farm output or in the system itself.

Methods based on power flow solution [1],[3] may not suit the purpose of online TE determination as data of the whole system have to be processed each time. Moreover, the rate of updating these data is determined by the SCADA system, which is too slow to serve the purpose of wind farm monitoring. Local measurements using PMUs provide voltage and current phasors at rates as high as 1 measurement/cycle. The works of [2] tried to use one local measurement to determine a TE equivalent through making many assumptions such as neglecting the TE resistance, which cannot be justified at the voltage levels where the wind farms are usually connected.

This paper presents a new method for the determination of TE based on PMU measurements. Three consecutive voltage and current measurements are used to determine an exact TE. It is essential to have the three sets of phasor measurements be referred to the same reference. Phase drifts caused by the slip frequency between the PMU and the system are taken into consideration and can be determined accurately during the course of calculations.

The paper is organized as follows. Following this introduction, the proposed method for determining the TE is introduced followed by application to the IEEE 30 bus test system as well as to a real system data in section 3; section 4 concludes the paper.

2. The Proposed Method

A. Basics of the method

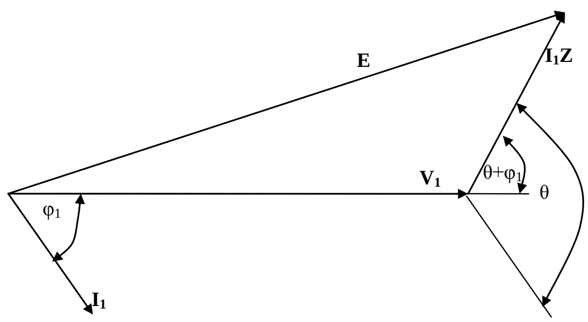
The node voltage equation using TE model is as follows.

$$V = E_{th} + Z_{th}.I \tag{1}$$

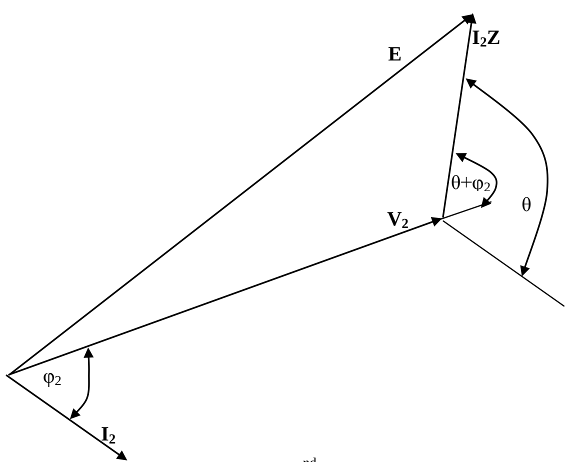
The moment accurate values for the two parameters E_{th} and Z_{th} are available, reliable estimation of all the required variables at that node, without the need of detailed system representation, is possible.

Determination of TE parameters using local measurements require at least two different (V, I) pairs measured at different time instants. V and I phasors for the different time instants must be measured to the same reference. However, due to variations in system frequency the measurement reference (MR) rotates at the slip frequency between the system and the PMU. The result is that the phase angles of V and I at subsequent time steps will be measured for different references.

Figure 1 shows the phasor diagrams for two different measurements. The effect of the PMU phase drift is to rotate all phasors by the same angle while the relative angles between individual phasors remain unchanged.



(a) Phasor diagram for the 1st measurement



(b) Phasor diagram for the 2nd measurement

Fig.1. Phasor diagrams for two different measurements

As E is the Thevenin voltage it has to be the same in the two cases. However, E in case b is shifted by an angle equal to the phase drift but its magnitude, E, is still the same. For the 1st measurement, case a, the equation for E can be written as follows

$$E^2 = V_1^2 + I_1^2 Z^2 + 2V_1 I_1 Z \cos(\theta + \varphi). \tag{2}$$

Expanding cos(θ+φ), (2) can be rewritten as

$$E^2 = V_1^2 + I_1^2 Z^2 + 2P_1 r - 2Q_1 x. \tag{3}$$

r and x are the resistance and the reactance of the Thevenin impedance Z. Similarly, for the 2nd measurement,

$$E^2 = V_2^2 + I_2^2 Z^2 + 2P_2 r - 2Q_2 x. \tag{4}$$

Subtracting (4) from (3)

$$V_1^2 - V_2^2 + (I_1^2 - I_2^2)Z^2 + 2(P_1 - P_2)r - 2(Q_1 - Q_2)x = 0 \tag{5}$$

which can be arranged and written as follows.

$$\left(r + \frac{P_1 - P_2}{I_1^2 - I_2^2}\right)^2 + \left(x - \frac{Q_1 - Q_2}{I_1^2 - I_2^2}\right)^2 = \frac{V_2^2 - V_1^2}{I_1^2 - I_2^2} + \left(\frac{P_1 - P_2}{I_1^2 - I_2^2}\right)^2 + \left(\frac{Q_1 - Q_2}{I_1^2 - I_2^2}\right)^2 \tag{6}$$

This is the equation of a circle in the impedance plane defining the locus for Thevenin impedance that satisfies the two measurements but it does not define a specific value for Z. Therefore a third measurement is required, which can be used with either the first or the second measurement in the same way as above to produce another locus for Z, another circle. The equivalent Thevenin impedance is determined by the intersection of the two circles. Having the equations of the two circles it will be straight forward to determine their intersection points. The coordinates of the intersection points in the Z-plane define the values of the resistance and reactance of the Thevenin impedance.

B. The calculation procedure

The calculation procedure consists of the following simple steps:

1. At a given instant of time, the most recent voltage and current measurements from the PMU along with the two preceding measurements are used to form two circle equations as defined by (6).
2. Intersection points of the two circles are determined defining two values for Z; namely Z_1 and Z_2.
3. Thevenin voltage, E, is determined for each value of Z using (1). Having two values of Z, two corresponding values of E will be obtained; the higher one that is near to the system voltage is taken to be E_{th} and the corresponding Z is Z_{th}.

4. The phase drift caused by the PMU can be determined by determining E_{th} using the three measurements one at a time. The angle difference between E_{th} determined using the 1st measurement and that determined by the 2nd measurement determines the drift that took place between these two measurements and so on.

3. Test Cases and Application

A. IEEE 30 Bus Test System

The IEEE 30 bus system with its standard data is used as a test system. Different loading cases at bus 30 were simulated; voltage and current at that bus were recorded as the measurements. Phase drift was simulated by shifting the phase of voltage and current in a way imitating the phase drift introduced by the PMU.
The first set of test cases were generated by varying the load at bus 30 while representing all the generators as voltage sources with their voltage and phase angles are set equal to its values at the base case. This is a reasonable assumption for online application where measurements are taken at small intervals, usually one measurement per cycle. All other loads are kept unchanged. Load at bus 30 is changed until no convergence obtained. Fig. 2 shows the Z circles in the impedance plane for some of the cases. The legend shows the active and reactive power at bus 30 corresponding to the two measurements used to draw each circle. It is clear that all the circles intersect at the same two points. On the figure also shown the Thevenin impedance calculated using multiple power flows [3], which exactly coincides with one of the intersection points.

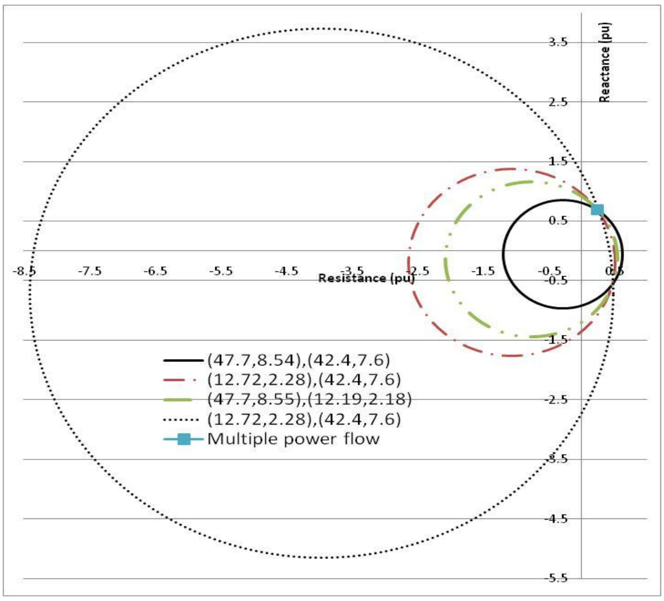


Fig.2 Impedance plane for bus 30 of the IEEE 30 bus system with generators replaced by voltage sources.

The second set of test cases were generated while the generators are treated as PV buses. The active power generated at each generation bus is kept at its base case value. The load at bus 30 is again varied, but this time small variations are made to test the sensitivity of the proposed method. Fig 3 shows the impedance plane plots for some of the cases. In this case, all the circles have a common point, which is the equivalent Thevenin impedance and is the same as that obtained by multiple power flow solutions and the one obtained considering generators as voltage sources. The only difference is that the second solution for Z depends on the loading condition, but this solution is not a usable one anyway.

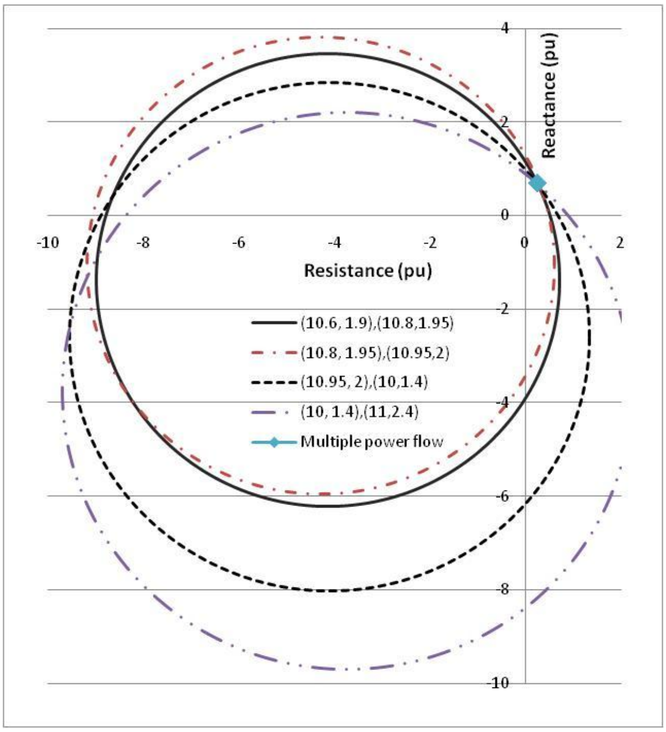


Fig.3 Impedance plane for bus 30 of the IEEE 30 bus system with generators as PV buses

B. Application to real system data

The proposed method has been applied to voltage and current phasors obtained from PMU records at a wind farm in Northern Ireland. Each data record includes a time stamp, three phase voltage and current phasors as well as the system frequency at a rate of one measurement per cycle. Table I lists a part of the data used.
TE parameters are plotted in Fig. 4. It can be noticed that E varies around 1 pu (66 kV); resistance varies between 0.6 and 0.8 pu; most interesting that reactance is less than r and varies between -0.3 and 0.22 pu. Despite the fact that at that voltage level, 66 kV, equivalent reactance should be at least two times the resistance. However, the low and negative reactance values obtained at the measurement point can be explained by the effect of power factor correction capacitors connected at the wind farm.

If the TE resistance and reactance for a system at a node are r and x respectively, and a capacitor with reactance x_c is connected at that node, the new TE resistance and reactance at the node will be changed to

TABLE I. SAMPLE PMU MEASUREMENTS AT A WIND FARM

Sample No.	Voltages						Currents						Freq. (Hz)
	Phase A		Phase B		Phase C		Phase A		Phase B		Phase C		
	V (kV)	Angle	V (kV)	Angle	V (kV)	Angle	I (kA)	Angle	I (kA)	Angle	I (kA)	Angle	
1	65.804	160.976	66.087	41.338	66.160	-79.118	1.129	157.068	1.137	39.289	1.164	-81.104	49.930
2	65.835	158.302	66.102	38.656	66.139	-81.785	1.136	155.014	1.136	36.769	1.167	-83.606	49.930
3	65.808	155.663	66.063	36.010	66.120	-84.445	1.136	152.758	1.143	34.663	1.163	-86.055	49.932
4	65.787	153.007	66.041	33.375	66.124	-87.105	1.134	149.816	1.132	32.005	1.160	-88.519	49.930
5	65.767	150.305	66.054	30.677	66.101	-89.775	1.129	147.295	1.124	29.302	1.150	-90.498	49.929
6	65.784	147.578	66.055	27.950	66.133	-92.496	1.104	144.583	1.105	26.333	1.132	-93.039	49.929
7	65.756	144.857	66.081	25.223	66.114	-95.216	1.089	141.340	1.089	23.268	1.116	-96.170	49.929

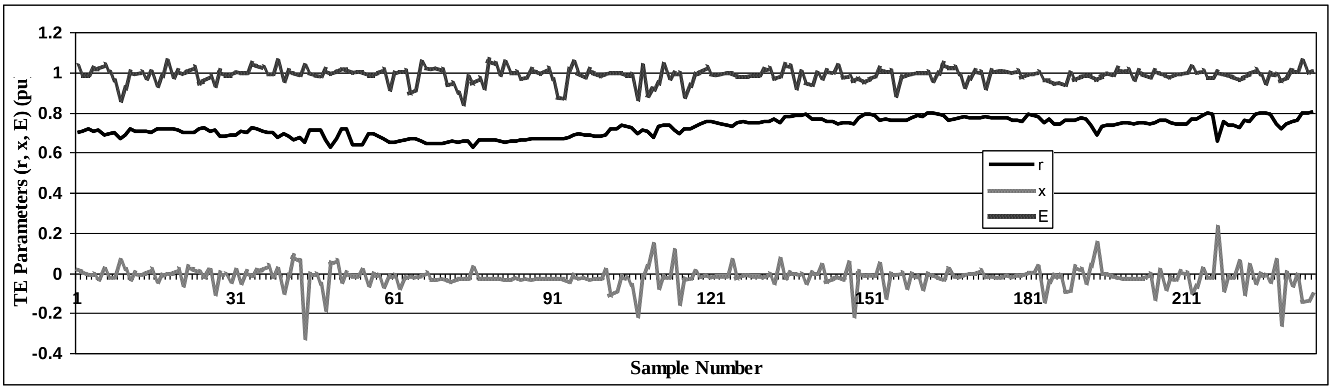


Fig.4. Thevenin equivalent parameters at the terminals of a wind farm determined using PMU measurements

$$r_{eq} = \frac{r.x_c^2}{r^2 + (x - x_c)^2}, \text{ and}$$
$$x_{eq} = \frac{x.x_c(x_c - x) - r^2.x_c}{r^2 + (x - x_c)^2}. \qquad (7)$$

From (7) it is clear that r_{eq} gets larger as a result of connecting the capacitor as x_c is usually much larger than x, while x_{eq} will be smaller and may be negative depending on x_c. However, it is preferable to connect the PMU in a way that keeps capacitors in the wind farm side to get the real TE of the system without the effect of capacitors.

4. Conclusion

A method for determining the TE of the system at a node using PMU is presented. Local measurements are used and hence no need for system wide measurements or power flow data. Phase drift due to slip frequency between the system and PMU is accounted for by using three consecutive samples instead of two. Calculation of TE is fast enough to be used for online assessment of system capability to accommodate wind power, voltage stability of the wind farm, and the monitoring functions required for the wind farm operation.

Acknowledgement

This work was supported in part by The Charles Parsons Energy Research Awards, which were created in September 2006 by the Minister for Communications, Marine & National Resources of Ireland to stimulate and develop Irish energy research capacity.

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