A Fixed Speed Induction Generator Model for Unbalanced Power Flow Analysis

Murat Erhan Balci[1]
Mehmet Hakan Hocaoglu[2]
Ahmet Koksoy[3]
Onur Ozturk[4]
Bahtiyar Dursun[5]

Electrical and Electronics Eng. Dept.[1]
Balıkesir University
Balıkesir, Turkey
mbalci@balikesir.edu.tr[1]

Electronics Eng. Dept.[2,3,4]
Gebze Institute of Technology
Gebze, Turkey
hocaoglu[2], akoksoy[3],onurozturk[4]@gyte.edu.tr

Energy Systems Eng. Dept.[5]
Kırklareli University
Kırklareli, Turkey
bahtiyar.dursun@kirklareli.edu.tr[5]

Abstract: This paper proposes a model of the induction generator for the phase-domain power flow analysis of fixed speed wind turbine generating systems connected to balanced or unbalanced three-phase distribution systems. The proposed model is established by using a modified bi-quadratic equation, which is generally used for the calculation of node voltages in the power flow analysis of distribution systems. The main advantage of the proposed model is that it does not require slip information. Thus, it has computational efficiency when compared with the slip calculation based phase-domain induction generator model. In addition, for several unbalanced voltage cases, the numerical results of the proposed model, slip calculation based phase-domain model and time-domain d-q model are comparatively evaluated to show the validity of the proposed one.

Keywords: Induction generators, wind energy, distribution systems, unbalanced conditions, power flow.

I. INTRODUCTION

Induction generators have extensively been used in wind turbine generating systems (WTGSs) due to their advantages over synchronous generators such as smaller size and lower requirement of maintenance [1]. The WTGSs can be classified under two main categories; namely, conventional fixed speed WTGSs and variable speed WTGSs [2]. Variable speed WTGSs have high costs since they include advanced power electronic devices and control circuits. Thus, today, the majority of installed WTGSs utilize conventional fixed-speed induction generators (CFSIG). Accordingly, several models of CFSIG have been developed for the load flow of the balanced distribution systems in the literature [3], [4]. However, in the distribution systems, grid voltages and line currents are usually unbalanced due to the uneven distribution of single-phase loads over the three phases, asymmetry of the lines and power systems faults, etc. [5].

In the studies on the unbalanced load flow analysis of the distribution systems with distributed generation (DG) units [6]-[8], the injected phase active and absorbed phase reactive powers of CFSIG are generally assumed as balanced by neglecting unbalance of the grid voltages. In these studies, the CFSIGs are modelled using two different methods. According to the first method, CFSIG are treated as constant PQ load for simplicity [6], [7]. On the other hand, second method considers total reactive power absorbed by CFSIG as a function of positive- sequence grid voltage [8]. However, the numerical results presented in [9]-[11] that these approaches lead to erroneous results for the unbalanced load flow analysis.

To fulfill left out gap, ref. [10] and [11] proposed the models based on the solution of the current and voltage equations, which are provided by using Kirchhoff's circuit (current and voltage) laws, for the positive- and negative-sequence circuits of the CFSIG. Due to this, they have high computational complexity. The difference between both models is that they consist of different iterative solution methods to find slip of the CFSIG under unbalanced system conditions. In addition, the initial slip value, which is initially guessed at the first iteration, is very important for fast implementation of these models in the load flow analysis.

In this study, for the load flow analysis of unbalanced distribution systems, a phase-domain model of the WTGSs with CFSIG is developed by considering positive- and negative- sequence circuits representations of the induction machine. For the developed model, positive- sequence voltage, current and power quantities are established with the solution of the bi-quadratic equation, which is generally used for the calculation of grid voltages in the power flow analysis of distribution systems [3], [4]. In the proposed model, the mechanical input (rotor side) powers, which are inserted to the positive- and negative- sequence circuits, are found with an iterative solution algorithm.

The main advantages of the developed model are that it provides closed form power expressions. This means that its implementation does not require the solution of positive- and negative- sequence circuits. As a result, it has less computational complexity as compared with the above mentioned slip calculation based phase-domain models.

This paper is organized in the following order. Section 2 is devoted to present the proposed model. The results obtained with the proposed model, the slip calculation based phase-domain model presented in [11] and the well-known d-q model, which is already included in SIMULINK environment [12] are discussed in Section 3. The conclusion is presented in Section 4.

978-1-4673-6487-4/14/$31.00 ©2014 IEEE

II. PROPOSED MODEL

In this section, the wind turbine generation system, which consists of two parts such as a wind turbine and an induction generator directly inserted to the grid, will be modeled for load flow analysis of unbalanced distribution systems (see Figure 1).

It is well known from the literature that the mechanical input power of a wind turbine generator can be expressed in terms of the air density (ρ),the area swept by the rotor (A), the power coefficient (C_p) and wind speed (u) [3], [11]:

$$P_T = \frac{1}{2}\rho A u^3 C_P(\lambda) \tag{1}$$

The power coefficient depends on the tip speed ratio (λ) which can be calculated as;

$$\lambda = \frac{\omega R}{u} \tag{2}$$

where ω and R are the angular velocity and turbine rotor radius, respectively. Note that the relationship between C_P and λ can be provided from the manufacturer of wind turbines.

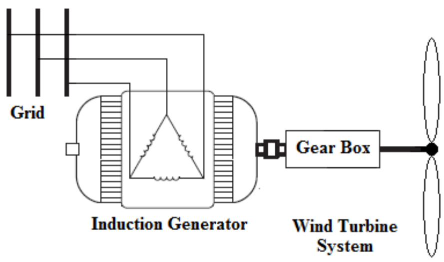


Figure 1: Induction generator with wind turbine.

First of all, let us consider an induction generator positive- and negative-sequence equivalent circuits referred to the stator side, which are given in Figure 2. In this figure, V_{sp}, V_{sn}, V_{rp} and V_{rn} are the magnitudes of the positive- and negative-sequence components of the stator sequence voltages and referred rotor sequence voltages, respectively. R_{sc} and X_{sc} indicate short-circuit equivalent resistance and reactance, respectively. R_m and X_m are the resistance and the magnetizing reactance of the induction machine's core. Here, it should be noted that both R_m and X_m can be neglected for the negative-sequence circuit due to the fact that they are considerably larger than other resistance and reactance parameters of the induction machine (R_{sc} and X_{sc}) [9]. P_{sp} and P_{sn} stand for the positive- and negative- sequence active powers absorbed by the stator from the grid, respectively. The mechanical input power of the wind turbine (P_T) is equal to the sum of the positive- and negative- sequence rotor active powers (P_{rp} and P_{rn}):

$$P_T = 3(P_{rp} + P_{rn}) \tag{3}$$

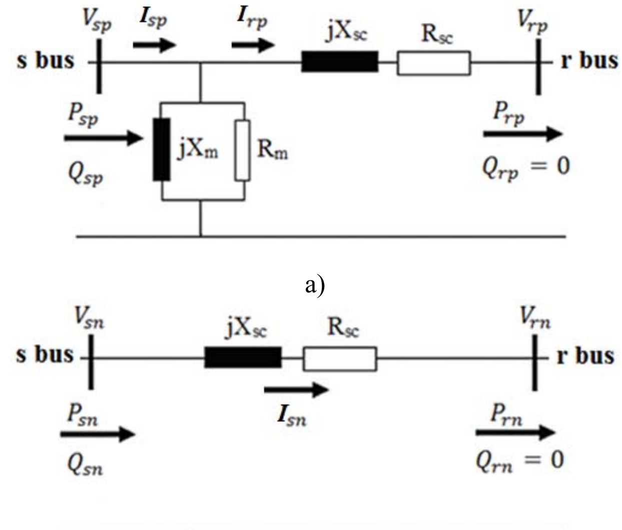
In Figure 2, Q_{sp} and Q_{sn} denote the positive- and negative-sequence reactive power demands of the induction generator. Lastly, it is clear that the positive- and negative- sequence reactive powers drawn by the rotor (r) bus should be nil (Q_{rp}=Q_{rn}=0).

By regarding positive-sequence equivalent circuit, the referred rotor positive- sequence voltage's magnitude can be expressed via well-known bi-quadratic equation, which was previously considered for modeling of the wind turbine induction generators under balanced voltage and current conditions in [3];

$$Z_{sc} = \sqrt{R_{sc}^2 + X_{sc}^2} \tag{4}$$

$$V_{rp} = \sqrt{\frac{{V_{sp}}^2 - 2R_{sc}P_{rp} + \sqrt{\left({V_{sp}}^2 - 2R_{sc}P_{rp}\right)^2 - 4Z_{sc}^2P_{rp}^2}}{2}} \tag{5}$$

where Z_{sc} is the short-circuit impedance of the induction generator.



b)

Figure 2: An induction generator (a) positive- and (b) negative-sequence circuits referred to the stator side.

For the negative- sequence circuit given in Figure 2 (b), the magnitude of the negative sequence current (I_{sn}), which flows between s and r buses, and negative- sequence active power measured at r bus can be written as:

$$I_{sn} = \frac{V_{sn}}{\sqrt{\left(R_{sc} + \frac{(R_r - R_r^2)P_{rp} - R_r V_{rp}^2}{2V_{rp}^2 + P_{rp}R_r}\right)^2 + X_{sc}^2}} \tag{6}$$

$$P_{rn} = I_{sn}^2\left(\frac{(R_r - R_r^2)P_{rp} - R_r V_{rp}^2}{2V_{rp}^2 + P_{rp}R_r}\right) \tag{7}$$

Therefore, the positive- and negative- sequence active powers, which are absorbed by the induction generator, can be expressed as in (8) and (9):

$$P_{sp} = P_{rp} + \left(\frac{P_{rp}}{V_{rp}}\right)^2 R_{sc} + \frac{{V_{sp}}^2}{R_m} \tag{8}$$

$$P_{sn} = P_{rn} + {I_{sn}}^2 R_{sc} \tag{9}$$

the total active power drawn from s bus;

$$P_s = 3(P_{sp} + P_{sn}) \tag{10}$$

In addition, the positive- and negative- sequence reactive powers taken from s bus can be written as;

$$Q_{sp} = \left(\frac{P_{rp}}{V_{rp}}\right)^2 X_{sc} + \frac{V_{sp}^2}{X_m} \tag{11}$$

$$Q_{sn} = I_{sn}^2 X_{sc} \tag{12}$$

Both reactive powers result in the total reactive power drawn by the induction generator as;

$$Q_s = 3\left(Q_{sp} + Q_{sn}\right) \tag{13}$$

On the other hand, P_{rp} and P_{rn} are unknown quantities and the model requires an iterative solution algorithm. The steps of the algorithm accompanied with the proposed model are detailed below:

Step 1: Assume that all of the mechanical power (P_T) is applied to the positive- sequence circuit and determine initial value of P_{rp} with respect to (3).

Step 2: Calculate V_{rp} with using (5).

Step 3: Find I_{sn} and P_{rn} by substituting the V_{rp} value, which is calculated in the previous step, and the P_{rp} value, which is determined regarding (3), in (6) and (7).

Step 4: Calculate P_s and Q_s via the equations between (8) and (13).

Step 5: Finalize the solution algorithm if both the relative difference between the P_s values, which are obtained for the last two iterations (i+1. and i. iterations), and the relative difference between the Q_s values, which are obtained for the last two iterations, are smaller than tolerance value (ε):

$$\varepsilon > \left|\frac{P_{Si+1} - P_{Si}}{P_{Si}}\right| \tag{14}$$

$$\varepsilon > \left|\frac{Q_{Si+1} - Q_{Si}}{Q_{Si}}\right| \tag{15}$$

Otherwise, update P_{rp} by substituting the last calculated P_{rn} value in (3) and return to Step 2.

Here it should be underlined that magnitudes (V_{sp}, V_{sn}) and angles (φ_{sp}, φ_{sn}) of the sequence voltages at the stator (s) bus are the variables which comes from the load flow analysis, and sequence active powers (P_{sp}, P_{sn}), sequence reactive powers (Q_{sp}, Q_{sn}) and magnitudes (I_{sp}, I_{sn}) of sequence currents at the stator bus are obtained after finalizing the above detailed iterative solution. In addition, angles of the positive- and negative- sequence currents at the stator bus, which are denoted as β_{sp} and β_{sn}, are found by substituting the obtained sequence active powers and magnitudes of sequence voltages and currents in (16) and (17):

$$\beta_{sp} = \varphi_{sp} - \cos^{-1}\left(\frac{P_{sp}}{V_{sp} I_{sp}}\right) \tag{16}$$

$$\beta_{sn} = \varphi_{sn} - \cos^{-1}\left(\frac{P_{sn}}{V_{sn} I_{sn}}\right) \tag{17}$$

Accordingly, positive- and negative- sequence voltages and currents of the stator side can be converted to the phase values of those quantities. As a result, for m=a, b, c phases, active and reactive powers can be calculated via (18) and (19):

$$P_m = V_m I_m \cos\theta_m \tag{18}$$

$$Q_m = V_m I_m \sin\theta_m \tag{19}$$

Note that in (18) and (19), θ_m denotes phase angle difference between voltage and current of phase m.

III. NUMERICAL RESULTS

In this section, the proposed model, the slip calculation based phase-domain model [11] and the well-known d-q model are comparatively evaluated to show the validity of the proposed one. For this aim, the results are obtained by these models under several unbalanced grid voltages. In these analysis, the equivalent rms voltage definition (V_e), which is placed in IEEE standard 1459-2010 [13], and voltage unbalance factor (*VUF*), which is widely used voltage unbalance index in the literature [14]-[16] are considered to identify the test voltages with different voltage rms and unbalance levels. The expressions of V_e and *VUF* can be written as:

$$V_e = \sqrt{\frac{V_{ab}^2 + V_{bc}^2 + V_{ca}^2}{9}} = \sqrt{V_{sp}^2 + V_{sn}^2} \tag{20}$$

$$VUF(\%) = \frac{V_{sn}}{V_{sp}} \cdot 100 \tag{21}$$

where V_{ab}, V_{bc} and V_{ca} are rms phase-to-phase voltages.

Thus, by regarding the (20) and (21), two parametrical analyses cases (Case 1 and Case 2) are provided below. Note that a 160 kW induction machine is handled in the analysis cases, and its circuit properties are detailed in the appendix.

A. Case 1: Comparative evaluation for the test voltages with VUF values from 1% to 5% andVe=1.0 pu

In this case, for the constant grid voltage level as *Ve*= 1.0 pu, *VUF* value of the test voltages is increased from 1% to 5%. Under these voltage conditions, P_T is kept as the rated power of the induction generator (160 kW). Therefore, each phase active and reactive powers, which are calculated via the proposed, the slip calculation based phase-domain (SCP) and d-q models, are given in Figure 3. It can be seen from this figure that under the unbalanced voltage with the *VUF* value as 1%, the induction generator (IG) injects active powers calculated as 0.357pu, 0.318pu and 0.303pu to phase a, b and c of the grid, respectively. For the same *VUF* value, it draws reactive powers calculated as 0.185pu, 0.133pu and 0.190pu from phase a, b and c of the grid.

On the other hand, under the unbalanced voltages with the *VUF* value as 5%, the phase active powers injected by IG are 0.480pu, 0.284pu and 0.211pu for phase a, b and c, respectively. In the case of the same *VUF* value, the phase reactive powers drawn by IG are 0.254pu, -0.005pu and 0.282pu for phase a, b and c.

In addition, one can see that *VUF* value highly affects the phase active and phase reactive powers of the induction generator.

B. Case 2: Comparative evaluation for the test voltages with Ve values from 0.6 pu to 1.2 pu and VUF=5%

In the second case, for the constant *VUF* level as 5%, the grid voltage level (V_e) is increased from 0.6 pu to 1.2 pu. Similar to the first case, under these voltage conditions, P_T is kept as 160 kW.

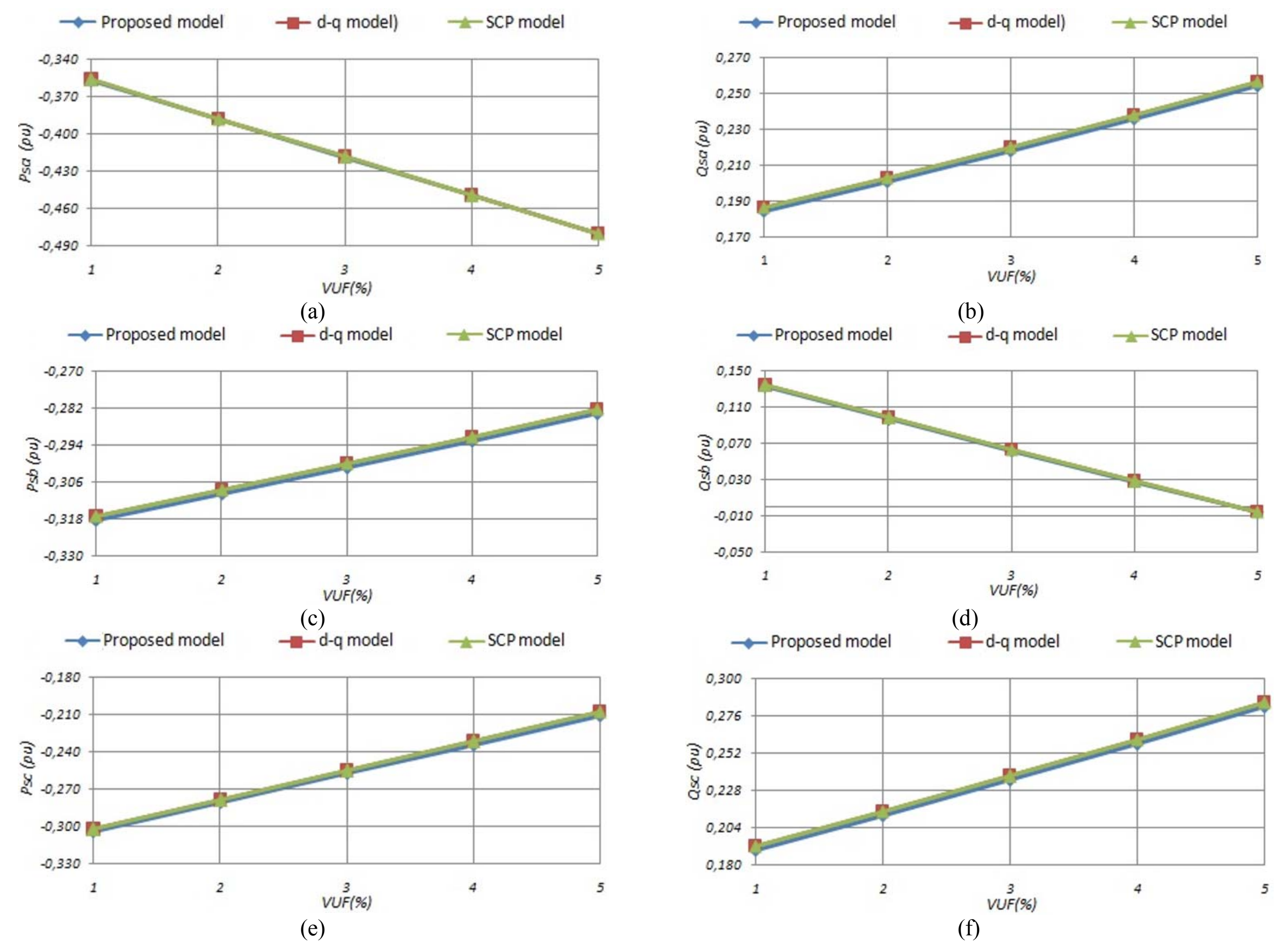


Figure 3: (a) P_{sa}, (b) Q_{sa}, (c) P_{sb}, (d) Q_{sb}, (e) P_{sc} and (f) Q_{sc} values obtained via proposed, SCP and d-q models for Case 1.

The results provided with the proposed, SCP, d-q models are given in Figure 4. This figure shows that for V_e value as 0.6 pu, active powers injected by phase a, b and c of the IG are 0.367pu, 0.291pu and 0.282pu, and reactive power drawn by the respective phases of the IG are 0.175pu, 0.064pu and 0.171pu. Under the voltage level with V_e value as 1.2 pu, for phase a, b and c, the IG injects active powers as 0.548pu, 0.273pu and 0.155pu, and it draws reactive powers as 0.336pu, -0.027pu and 0.386pu. According to the above mentioned numerical results, it is obvious that voltage level (V_e) highly contributes the unbalance among the phase active or phase reactive powers.

IV. CONCLUSION

In this paper, a phase-domain model of the WTGSs with CFSIG is developed for the load flow analysis of unbalanced distribution systems. The main advantages of the developed model are that it provides closed form power expressions. This means that its implementation does not require the solution of positive- and negative- sequence circuits. As a result, it has less computational complexity as compared with the slip calculation based phase-domain models.

It can be concluded from the numerical results observed under several unbalanced grid voltages that proposed model is consistent with the SCP based phase-domain model and d-q model. In other words, the developed model can safely be employed for the analysis of the WTGS with fixed speed induction generators under the wide ranges of *VUF* and V_e parameters.

In the future works, authors aim to incorporate the developed model to an unbalanced power flow algorithm.

V. APPENDIX

Properties of ind. machine considered in the simulations:

Rated voltage:400 V (rms), Rated power: 160 kW

Short-circuit resistance and inductive reactance values:

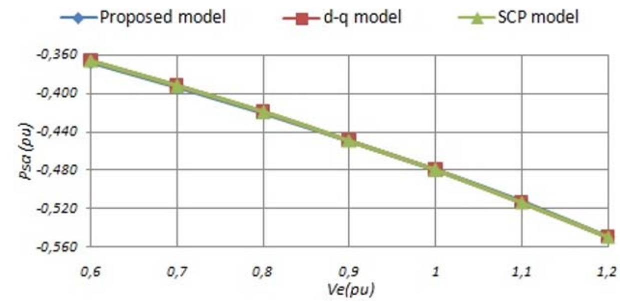
R_{sc}= 0.021518 Ohm, X_{sc}=0.095504 Ohm

Core resistance and magnetization reactance values:

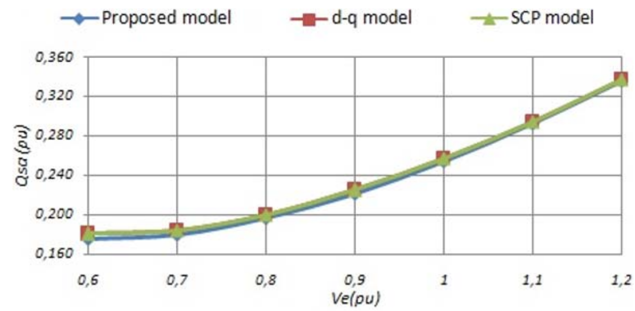
R_m= Neglected, X_m=2,415885 Ohm

VI. ACKNOWLEDGMENT

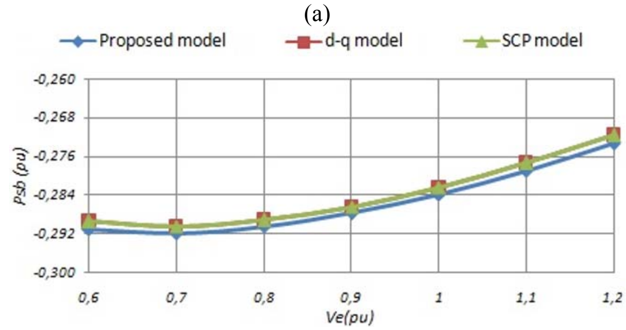
This work was supported by the Scientific and Technological Research Council of Turkey (TUBITAK) under project number 112E222.



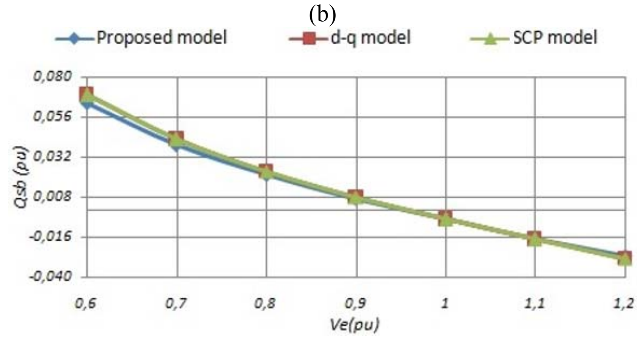
(a)



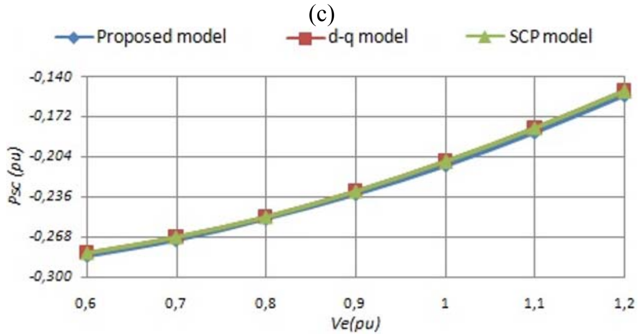
(b)



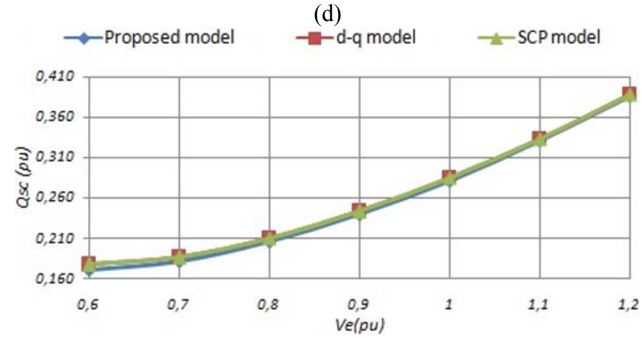
(c)



(d)



(e)



(f)

Figure 4: (a) P_{sa}, (b) Q_{sa}, (c) P_{sb}, (d) Q_{sb}, (e) P_{sc} and (f) Q_{sc} values obtained via proposed, SCP and d-q models for Case 2.

VII. REFERENCES

[1] T. F. Chan, “Capacitance requirements of self-excited induction generators,” IEEE Trans. on Energy Conversion, vol. 8, no. 2, pp. 304-311, Jun. 1993.

[2] Y. Amirat, M.E.H. Benbouzid, B.Bensaker, R.Wamkeue, “Generators for wind energy conversion systems: state of the art and coming attractions”, J. of Electrical Syst.,vol. 3, no. 1, pp 26-38, Mar. 2007.

[3] U. Eminoglu, B. Dursun, M. H. Hocaoglu, “Incorporation of a new wind turbine generating system model into distribution systems load f ow analysis,” Wind Energy J., vol. 12, no. 4, pp. 375–390, May 2009.

[4] U. Eminoglu, “Modeling and application of Wind Turbine Generating System (WTGS) to distribution systems”, Renew. Energy J., vol. 34, no. 11, pp.2474 -2483, Nov. 2009.

[5] E.F. Fuchs, M.A.S. Masoum, “Power quality in power systems and electrical machines”, 1st Edition, Elsevier Academic Press, Burlington, MA, 2008.

[6] S. M. Moghaddas-Tafreshi and E. Mashhour, “Distributed generation modelingfor power flow studies and a three-phase unbalanced power flow solution forradial distribution systems considering distributed generation”, Elect. Power Syst. Res., vol. 79, no. 4, pp.680 -686, Apr. 2009.

[7] X. Yang, Z. Wei, G. Sun, Y. Sun, Y. Yuan, Z. Lu, X. Xu, L. Huang, “Power flow calculation for unbalanced three-phase distribution network with DGs based on phase-sequence hybrid modeling,”, IEEE SEGE 2013, pp.1-6, 28-30 Aug. 2013.

[8] J. Fengli, P. Zailin; W. Shihong, H. Rui, Z. Yunan, “Power flow calculation for radial distribution systems with distributed generation,” IEEE ICMA 2012, pp.1287,1291, 5-8 Aug. 2012.

[9] A. H. Ghorashi, S. S. Murthy, B. P. Singh, B. Singh,“Analysis of wind driven grid connected induction generators under unbalanced grid conditions”, IEEE Trans. on Energy Conv.,vol. 9, no. 2, pp. 217–223, Jun. 1994.

[10] D. R. R. Penido, L. R. de Araujo, S. Jr. Carneiro, J. L. R. Pereira, P. A. N. Garcia, “Three-phase power flow based on four-conductor current injection method for unbalanced distribution networks”, IEEE Trans. on Power Syst., vol. 23, no. 2, pp.494 -503, May 2008.

[11] M. Abdel-Akher, K. Mahmoud, “Unbalanced distribution power-flow model and analysis of wind turbine generating systems”, Euro. Trans. Electr. Power, vol. 23, no. 5, pp. 689-700, Jul. 2013.

[12] Matlab/SIMULINK SimPowerSystems Documents, accessed online from http://www.mathworks.com/help/physmod/powersys/getting-started-with-simpowersystems.html, July 2013.

[13] IEEE Standard Definitions for the Measurement of Electric Power Quantities under Nonsinusoidal, Balanced, or Unbalanced Conditions, IEEE Std. 1459 – 2010.

[14] IEC Standard 60034-26, Rotating Electrical Machines, Part 26: Effects of Unbalanced Voltages on the Performance of Three-Phase Induction Motors, 2002.

[15] A. Jouanne, B. Banerjee, “Assessment of voltage unbalance”, IEEE Trans. on Power Deliv., vol. 16, no. 4, pp. 782 – 790, Oct. 2001.

[16] S. B. Singh, A. K. Singh, P. Thakur, “Assessment of induction motor performance under voltage unbalance condition”, IEEE ICHQP 2012, pp. 256 - 261, 17-20 Jun. 2012.