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Power Flow Modelling of a Self-excited Induction Generator

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***Abstract*—This paper presents power flow models of a self-excited induction generator. These models are used for steady-state power flow calculation in electric power systems in which a generating plant driven by renewable energy sources, such as wind energy, is connected to partially serve loads. This research demonstrates the induction generator by two forms: i) power (PQ) model and ii) admittance (Y) model. Solution convergence and model accuracy are observed in order to predict power flow distribution through feeder lines resulting from the grid connection of a renewable power plant. From the proposed models, voltage profiles of the system can be calculated. To verify the effectiveness of the proposed models, standard IEEE 37-node, 118-node test feeders and a 22-kV power distribution systems in Nakhon Ratchasima, Thailand, were examined. In addition, satisfactory results can be employed to develop system stability analysis and operation planning in order to prevent supply service interruption and conserve the overall electrical energy.**

***Index Terms*—Power flow calculation, PQ model, admittance model, self-excited induction generator.**

I. Introduction

Renewable energy is energy derived from regenerative energy sources. It involves natural phenomena and comes from various resources, e.g. solar, wind, water, biomass, geothermal, etc [1]. The use of renewable energy increases gradually in the last decade to share approximately 30% energy use worldwide. Due to the energy crisis, the electric power industry could have a major impact on renewable energy consumption. With their limitations, a renewable-energy power plant is installed locally and equipped with a small-size generator, up to only a few MW rating [2]. Therefore, they can be located close to their local customers. Large power flowing from the power substation through distribution feeders is reduced. This concept is called distributed power generation. It permits local consumers to generate electricity for their own. A distributed generation plant normally uses a conventional synchronous generator. However, in particular, some distributed generating plant employs induction generators equipped with power electronic controllers. Induction generators are found in all fixed speed, network connected wind turbines and also in a small-scale hydro plant. The use of induction generators in the future requires distribution system engineers to take into account its impact in the system planning. To install a new induction generator at a particular location, investment and operating costs are very important. Therefore, one of the planner's goals is to minimize overall cost [3-5]. When the distribution power network structure is assumed to be invariable during the planning period, changes in load energy demand or the appearance of new loads over short period could require some action from existing reactive power equipment or investments for network upgrade might be necessary. Analysis of distribution power flow resulting from operation of an induction generator at a given location is a basic tool. It is able to further analyze some key system performances in several aspects, e.g. stability, security, economic, reliability, etc. In this paper, a self-excited induction generator running at a particular steady-state operating point is investigated to determine its significant effects on voltage profiles in power distribution systems. Its power flow models are proposed in order to obtain a single operating-point voltage solution of the entire system.

In this paper, modelling of a self-excited induction generator is proposed in Section 2. Section 3 gives solution methodology described step-by-step. Simulation results and conclusion are in Section 4 and 5, respectively.

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II. Modelling of a Self-Excited Induction Generator

A. PQ Model

The steady-state equivalent circuit of a self-excited induction generator (SEIG) is shown in Fig. 1 [6-8].

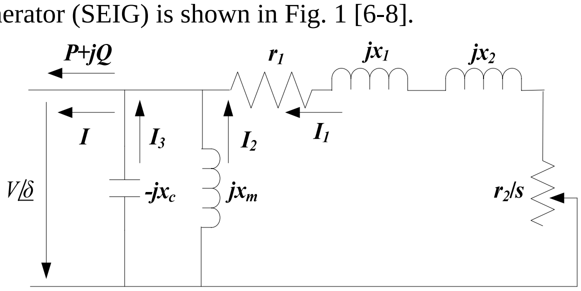

Fig. 1 Steady-state equivalent circuit of a SEIG

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Where x_1 is the stator reactance
x_2 is the rotor reactance referred to the stator side
r_1 is the stator resistance
r_2 is the rotor resistance referred to the stator side
x_m is the excitation reactance
x_c is the power-factor-correction capacitor
s is the slip of the induction generator
V is the voltage magnitude of the generator terminal
δ is the phase angle of the generator terminal voltage

Due to the relationship between real power exported and reactive power drawn, independent control of the power factor of the self-excited induction generator by itself is not available [2]. To achieve the power factor control, an appropriate capacitor is placed across its terminal. From the equivalent circuit, I_1 I_2 and I_3 can be expressed as follows.

$$I_1 = \frac{-(sr_2V\cos\delta \; + \; s^2xV\sin\delta)}{r_2^2 + s^2x^2} + j\frac{(s^2xV\cos\delta \; - \; sr_2V\sin\delta)}{r_2^2 + s^2x^2} \tag{1}$$

$$I_2 = \frac{-V\sin\delta \; + \; jV\cos\delta}{x_m} \tag{2}$$

$$I_3 = \frac{V\sin\delta \; - \; jV\cos\delta}{x_c} \tag{3}$$

The current injected by the induction generator is the summation of (1) – (3), thus

$$I = -\left(\frac{sr_2V\cos\delta \; + \; s^2xV\sin\delta}{r_2^2 + s^2x^2} + \frac{V\sin\delta}{x_p}\right) + j\left(\frac{s^2xV\cos\delta \; - \; sr_2V\sin\delta}{r_2^2 + s^2x^2} - \frac{V\cos\delta}{x_p}\right) \tag{4}$$

where $x = x_1 + x_2$, $x_p = \frac{x_c x_m}{x_c - x_m}$ and assume that $r_1 << r_2$

The complex power, $S = VI^* = P + jQ$, injected to the point of connection can be decomposed into real and imaginary parts as given in (5).

$$P = -\frac{sr_2V^2}{r_2^2 + s^2x^2} \tag{5}$$

$$Q = -\left(\frac{s^2xV^2}{r_2^2 + s^2x^2} + \frac{V^2}{x_p}\right) \tag{6}$$

or

$$Q = \frac{Psx}{r_2} - \frac{V^2}{x_p} \tag{7}$$

From (5) when P and V are defined, the corresponding machine slip and reactive power imported can be obtained by

$$s = \frac{-V^2r_2 \; + \; \sqrt{V^4r_2 - 4P^2x^2r_2^2}}{2Px^2} \tag{8}$$

The slip must be a negative real number. To avoid obtaining a complex slip, the condition described in (9) must be held.

$$V^4r_2 - 4P^2x^2r_2^2 \;\geq\; 0 \tag{9}$$

$$Q = \frac{-V^2 \; + \; \sqrt{V^4 - 4P^2x^2}}{2x} - \frac{V^2}{x_p} \tag{10}$$

With (5) and (10) the SEIG can be represented by the real power injection P to and the reactive power drawn Q from the connection point. This PQ model is repeatedly updated during the iterative power flow process. As can be seen, when P is specified, Q is a function of P and V. At each iteration, starting from a previously updated voltage solution, Q is then computed. It is also subjected to a negative real slip.

B. *Admittance Model*

For simplification, the equivalent circuit shown in Fig. 1 is reduced to the circuit shown Fig. 2.

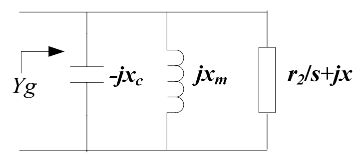

Fig. 2 Admittance model of the SEIG

The equivalent impedance Z_g of the induction generator can be simply calculated as shown in (11). Also, its equivalent admittance can be written in (12) and (13).

$$Z_g = -jx_c \,//\, jx_m \,//\, (r_2/s \; + jx) \tag{11}$$

$$Y_g = \frac{1}{-jx_c} + \frac{1}{jx_m} + \frac{1}{r_2/s \; + jx} \tag{12}$$

or

$$Y_g = \frac{sr_2}{r_2^2 + s^2x^2} - j\frac{r_2^2 + s^2x^2 + x_ps^2x}{x_p(r_2^2 + s^2x^2)} \tag{13}$$

When P and V are both assigned, the slip s can be computed. Thus, it is simple to obtain the equivalent admittance of the induction generator according to (13). The admittance model uses (13) to modify the bus admittance matrix [Y_{bus}]. Assume that the SEIG is connected to bus k. The k^{th}-row, k^{th}-column element of [Y_{bus}] requires an update as follows.

$$\left[Y_{bus}\right]_{k,k}^{(new)} = \left[Y_{bus}\right]_{k,k}^{(old)} + Y_g \tag{14}$$

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This type of modelling may cause slow convergence due to successively updating [Y_{bus}].

C. PV model

In practice, at a given real power exported, the reactive power control of the induction generator is not possible. The relationship of the injected real power and the absorbed reactive power can be characterised as a circle diagram. This means that the voltage magnitude of the generator terminal cannot be regulated. Therefore, the PV model is not appropriate in this circumstance. However, some may experience that when the voltage magnitude is fixed, the iterative power flow process tends to converge rapidly. In this paper, the solution using the PV model is not established. In the later section, the PV model is employed to recalculate the power flow solutions previously obtained by using the PQ and admittance models. In this case, the voltage magnitude across the generator terminal is already known. Therefore, the PV model is applicable.

III. Power Flow Calculation

Power flow calculation is to determine a set of voltage solutions that satisfy the power mismatch equation at every node [9, 10]. The main information obtained from this calculation are phasor voltages of load buses, reactive power injection by generator buses, complex power flow through transmission lines, total power losses, etc. Connected generators at generator buses can be modelled as either PV bus or PQ bus. If the voltage magnitude at the point of connection is regulated, the PV bus model can be used. Power network solutions must satisfy a set of nodal power mismatch equations. Given that there is a total of n buses in the system and one of them is assigned as the slack bus. Decomposed power flow equations of bus k (real and reactive powers) can be simply expressed [9] as follows.

$$P_{cal,k} = \sum_{i=1}^{n} |V_k V_i Y_{ki}| \cos(\theta_{ki} + \delta_i - \delta_k) \qquad (15)$$

$$Q_{cal,k} = -\sum_{i=1}^{n} |V_k V_i Y_{ki}| \sin(\theta_{ki} + \delta_i - \delta_k) \qquad (16)$$

Where

$P_{cal,k}$ and $Q_{cal,k}$ are calculated real and reactive powers of bus k

$|V_k|$ is the voltage magnitude of bus k

δ_k is the phase angle of bus k

$|Y_{ki}|$ is the magnitude of the k^{th}-row, i^{th}-column admittance matrix element

θ_{ki} is the phase angle of the k^{th}-row, i^{th}-column admittance matrix element

The solution of the power network can be obtained by employing some efficient iterative methods, e.g. Gauss-Seidel or Newton-Raphson methods, in order to solve the power mismatch equations, $\Delta P_k = P_{cal,k} - P_{sch,k} = 0$ and $\Delta Q_k = Q_{cal,k} - Q_{sch,k} = 0$ for all nodes, where $P_{sch,k}$ and $Q_{sch,k}$ are scheduled real and reactive powers of bus k.

To characterise voltage profiles of the electrical power system caused by the operation of induction generators, it assumes that the real power imported from the generator is fixed. Therefore, power flow solution can be achieved under the constant real power injection of the induction generator plant.

The iterative power flow calculation based on the *PQ* modelling of the induction generator can be summarised step-by-step as follows.

1. Assign an initial guess voltage solution at all buses
2. With given P and V of the induction generator bus, the slip and Q can be computed to formulate the *PQ* load model
3. Apply the Newton-Raphson method for obtaining voltage solutions
4. check for solution convergence

When the admittance model is applied, the step-by-step algorithm is modified slightly. During the iterative process, the bus admittance matrix is required to be updated iteratively due to the change of the machine slip at each iteration. In the same manner, the iterative power flow calculation based on the admittance model can be summarised step-by-step as follows.

1. Assign an initial guess voltage solution at all buses
2. With given P and V of the induction generator bus, the slip and therefore Y_g can be computed to formulate the admittance load model
3. Update the system bus admittance matrix
4. Apply the Newton-Raphson method for obtaining voltage solutions
5. check for solution convergence

IV. Simulation Results

To evaluate the proposed power flow modelling, the 37-node and 118-node IEEE standard test feeders [11, 12], as shown in Figs 3 and 4, and the 159-node SUT power distribution system, as shown in Fig. 5, were used for test. All test uses the maximum allowable power mismatch of 10^{-6} p.u. as the termination criterion. Parameters of the installed induction generator [13] are given in Table 1.

Table 1. Parameter of the installed induction generator

r_2 (p.u.)	x_1 (p.u.)	x_2 (p.u.)	x_m (p.u.)	x_c (p.u.)
0.00373	0.09985	0.10906	3.54708	10.6

A. The 37-node IEEE test feeder

As shown in Fig. 3, the first test feeder consists of 37 nodes with 4.8-kV and 100 kVA base. It assumes that the induction generator is installed at node 17 to serve the 30 kW load.

The obtained voltage solutions and their convergences for *PQ*, admittance (Y) and *PV* models are shown in Figs 6 – 7.

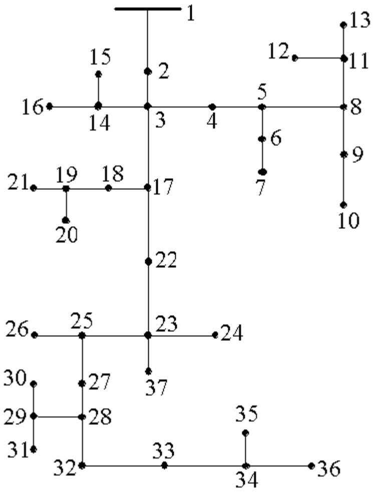

Fig. 3 37-node IEEE standard test feeder

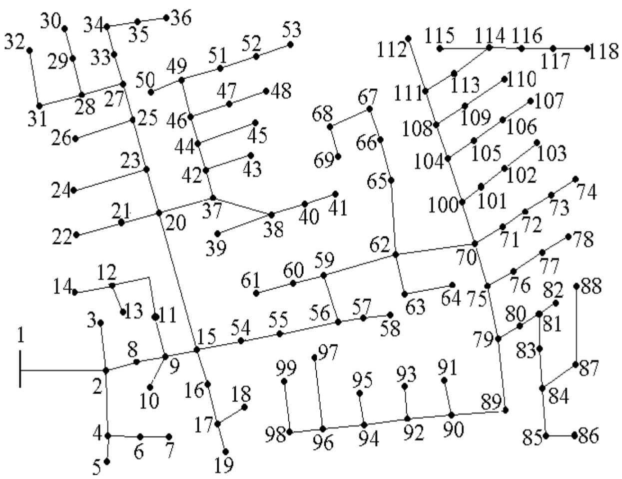

Fig. 4 118-node IEEE standard test feeder

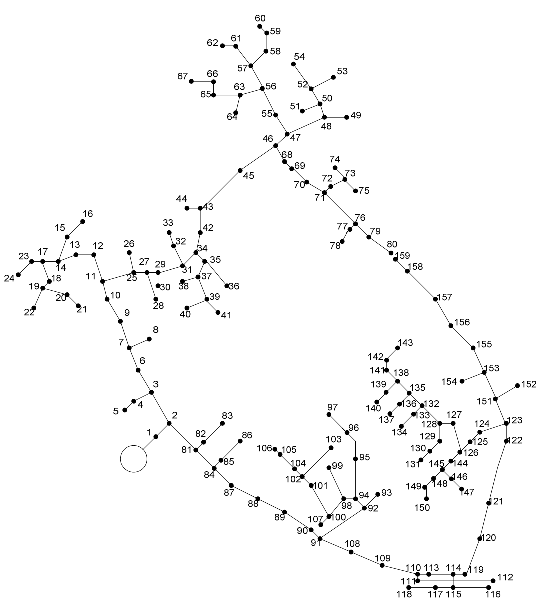

Fig. 5 159-node SUT power distribution system

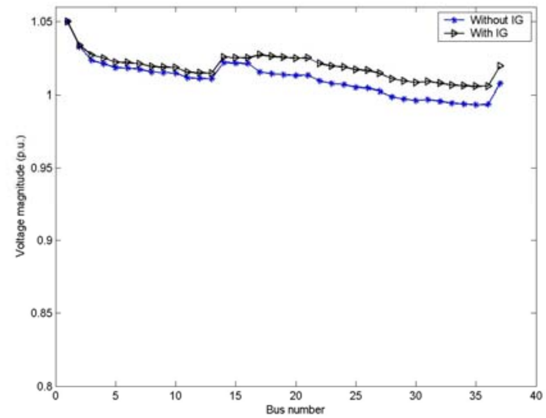

Fig. 6 Voltage solutions of the 37-node test system

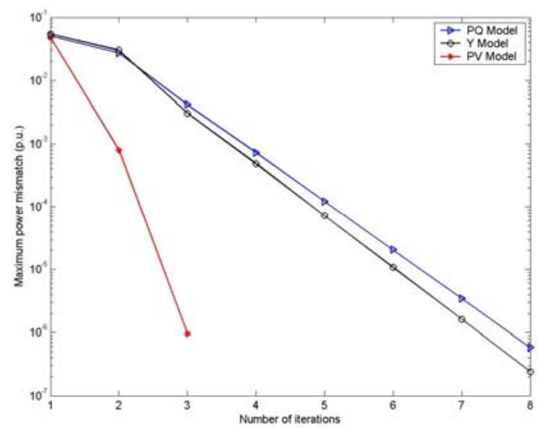

Fig. 7 Solution convergences of the 37-node test system

B. The 118-node IEEE test feeder

As shown in Fig. 4, the second test feeder consists of 118 nodes with 4.16-kV and 100 kVA base. It assumes that the induction generator is installed at node 70 to serve the 30 kW load.

The obtained voltage solutions and their convergences for *PQ*, admittance (*Y*) and *PV* models are shown in Figs 8 – 9.

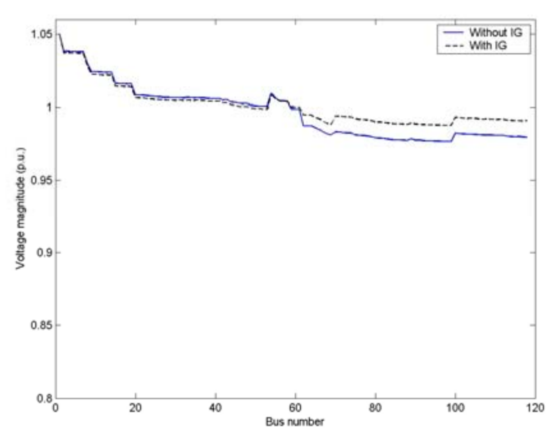

Fig. 8 Voltage solutions of the 118-node test system

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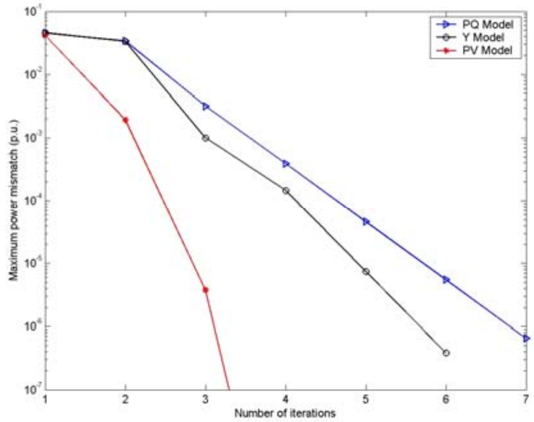

Fig. 9 Solution convergences of the 118-node test system

C. *The 159-node SUT power distribution feeder*

As shown in Fig. 5, the last test feeder consists of 159 nodes with 22-kV rating. It describes the power distribution network of Suranaree University of Technology (SUT), Nakhon Ratchasima, THAILAND. The university farm, located at node 22, has installed a small-rating generator of a biomass power generating plant up to 100 kVA capacity. Also, there exists the university energy park equipped with wind-turbine-driven induction generator of a solar tower generating plant located at bus 150. It assumes that each induction generator is operated to serve a 30 kW load equally. However, to experience significant effects of induction generator operation on a practical power distribution system, three sub-cases are situated as follows.

First, the induction generator is installed at bus 22 only. The obtained voltage solutions and their convergences for *PQ*, admittance (*Y*) and *PV* models are shown in Figs 10 – 11.

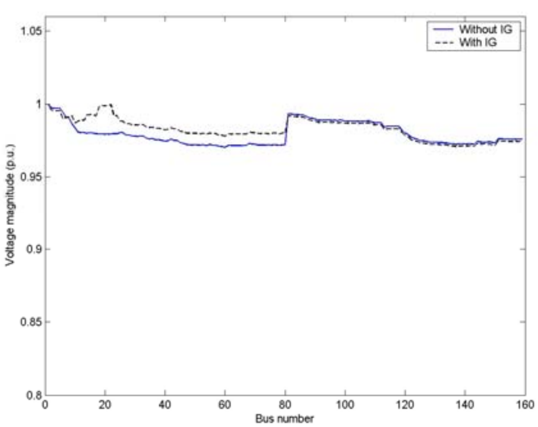

Fig. 10 Voltage solutions of the SUT system for the first case

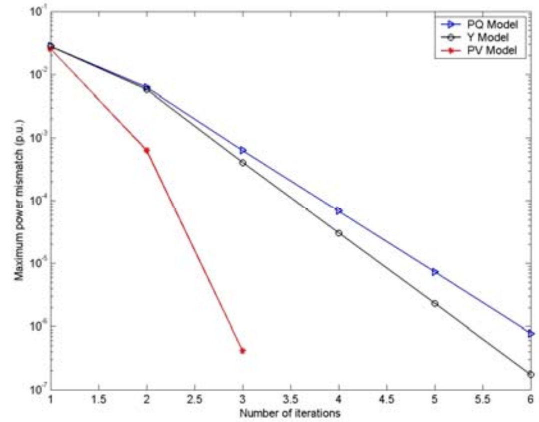

Fig. 11 Solution convergences of the SUT system for the first case

Second, the induction generator is installed at bus 150 only. The obtained voltage solutions and their convergences for *PQ*, admittance (*Y*) and *PV* models are shown in Figs 12 – 13.

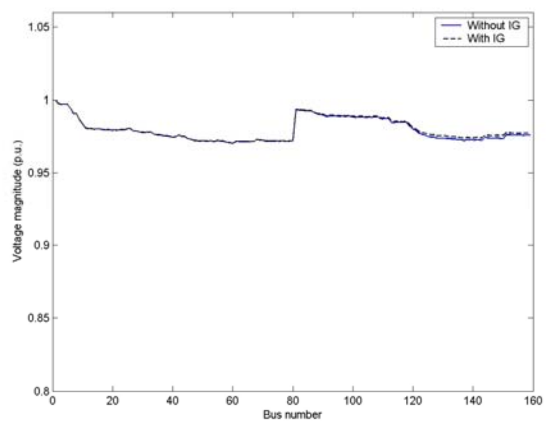

Fig. 12 Voltage solutions of the SUT system for the second case

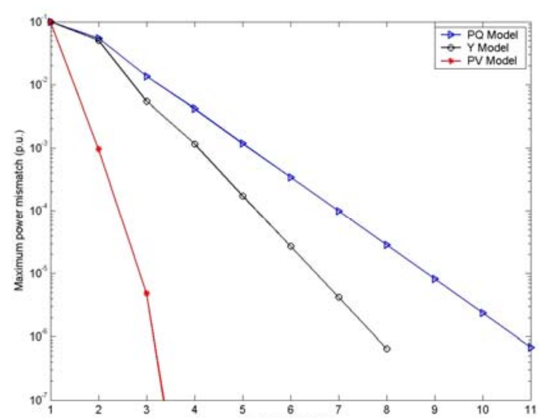

Fig. 13 Solution convergences of the SUT system for the second case

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Last, two induction generators are installed at bus 22 and 150 to serve a 30 kW load equally. The obtained voltage solutions and their convergences for *PQ*, admittance (*Y*) and *PV* models are shown in Figs 14 – 15.

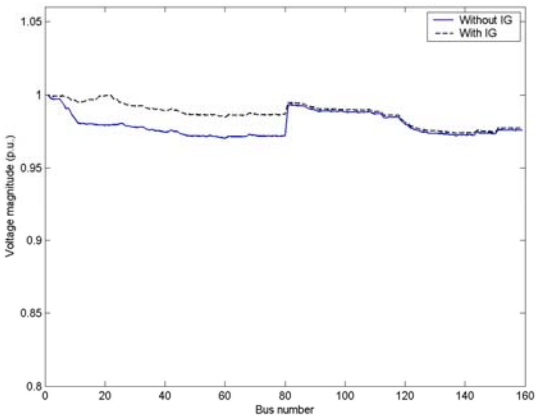

Fig. 14 Voltage solutions of the SUT system for the third case

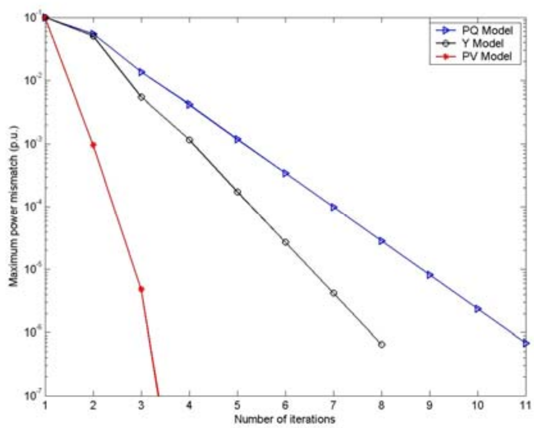

Fig. 15 Solution convergences of the SUT system for the third case

As a result, the solution obtained by using the admittance model converged faster than that of the PQ model for all test cases. In addition, from the SUT test cases, installing the induction generator can improve voltage profiles along the distribution feeder. However, its effect may be less significant if the induction generator is installed close to the farthest node.

V. Conclusion

The models proposed in this paper work well with the test case scenarios. The iterative updating process is the most advantage of the proposed models. It is simple to calculate and easy to understand.

To extend the work proposed here voltage instability problems of electric power distribution systems with operation of induction generators can be analysed. Moreover, in this paper, only self-excited induction generators are employed. The similar concept can contribute a simple technique to characterise doubly-fed induction generators.

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