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Impact of distributed generators on the power loss and voltage profile of sub-transmission network

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Abstract

This paper presents the impact of distributed generator (DG) on the power loss and voltage profile of sub-transmission network at different penetration levels (PLs). The various DG technologies are modeled based on their electrical output characteristics. Voltage profile index which allows a single value to represent how well the voltage matches the ideal value is developed. The index allows a fair comparison of the voltage profile obtained from different scenarios. The extent to which DGs affect power losses and voltage profile depend on the type of DG technology, PL and the location in which the DG is connected to the grid. The integration of DGs reduces power losses on the network, however, as the PL increases, the power losses begin to increase. A PL of 50–75% is achieved on 69 kV voltage level and 25–50% penetration on 13.8 kV voltage level without an increase in the power loss. Also more DG can be integrated into the network at point of common connection of higher voltage level compared to the low voltage level.

Keywords: Renewable distributed generation; Sub-transmission network; Power loss; Voltage profile; IEEE 14-bus system

1. Introduction

In recent years, there have been increasing interests in distributed generation. This is as a result of market deregulation, technological advancement, governmental incentives, and environment impact concerns (Freitas et al., 2006). The traditional way of generating electrical power is the vertical approach where electricity is fed to the load centers through long transmission and distribution network (Davda et al., 2011). However, the environmental and technical problems associated with the traditional method have made the horizontal approach where DGs are part of the power system a better alternative. According to Attia et al. (2010), distributed generation (DG) refers to a small-scale generation, which

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is not directly connected to the bulk transmission system and is not centrally dispatched. It can be of great advantage in isolated locations where central generation is impracticable or where grid extension is difficult (Borges and Falcao, 2003) and it can be fed back into the grid in an integrated way. The available size of DG per module can be as little as 1 kW to as high as 250 MW depending on the technology (Ackermann et al., 2001). Based on size, DGs may be classified into micro (1 W to 5 kW), small (5 kW to 5 MW), medium (5–50 MW) and large (50–300 MW)(Ackermann et al., 2001). The power ratings of medium and large DGs make it practically infeasible to utilize such generators in distribution networks.

Authors have proposed different approaches and indices in an attempt to understand the possible impact of DG on the grid: global performance index that makes use of weighting methods has been proposed by Attia et al. (2010) to study the distributed generation impacts on distribution networks. It was reported that the proposed performance index is flexible which makes it suitable as a tool for finding the most beneficial places where DGs may be located. The effect of distributed generators on line losses and network resonances on North American distribution feeder has been studied by Rangarajan et al. (2014). The network resonance study was performed using PSCAD/EMTDC simulation software while the line loss and voltage profile was determined using Distribution Engineering Simulation Software (DESS). It was concluded that DGs are beneficial to the network in term of voltage profile improvement and line loss reduction. El-Khattam and Salama (2002) focused on introducing a new approach to generate power in the distribution network and in addition enhance the distribution system's voltage profile and reduce the electric system losses by installing DG in the distribution system. It was revealed that DG has a great positive impact on improving the voltage profile and reducing the total electric power losses through the entire distribution network. Bawan (2012) investigated the usage of DGs to reduce the power losses and to improve the voltage profile based on location of DG and size of injection. The study was implemented using application program ETAP 6.0 and the Manokwari electricity distribution system as case study, the results shows that at certain location, the power injection of DG has resulted in reduction in power loss from 240.15 kW to 99.39 kW and it was found to be more economic than without DG installation.

In all the aforementioned studies, DGs are integrated into the distribution network. This makes the generators to be closer to the load centers with its attendant advantages as a result of the proximity to the load centers. However, most distribution networks are weak and radial in nature with low short-circuit capacity. Therefore, there is limit in which power can be injected into the distribution network without compromising the power quality and the system stability. To overcome this challenge, there is possibility of installing DG at the sub-transmission level. Sub transmission networks are at a higher voltage level with higher short circuit capacity compared to distribution networks and they are meshed. This allows more power injection into the power system transmission network with higher reliability. However, there is need to understand the possible impact of DG on this network. This paper seeks to investigate this by connecting DG technologies to a sub transmission network at increasing penetration level and observing the impact they have on the losses and voltage profile of the sub-transmission network.

2. Sub-transmission network

A sub-transmission network is employed in this study; it is a circuit that supplies power to distribution networks from transmission networks. It has a voltage between the transmission and distribution level. They are mesh networks which can be active. In other words, sub transmission networks might have active or reactive power generators in one or more nodes (Shahariar et al., 2014a,b). The IEEE 14 bus test network as depicted in Fig. 1 is popularly utilized for modeling sub transmission network (Shahariar et al., 2013) and it is adopted in this study. The data for the network was obtained from (Milano, 2010). It has its buses at three voltage levels – 13.8, 18 and 69 kV.

3. Modeling of distributed generators

The types of technologies employed in Distributed Generators can be classified into three based on their electrical output characteristics (Mozina, 2010). These classes are shown in Table 1 with the DG technologies categorized under them.

Synchronous generator technologies (SGTs) has the ability to maintain their terminal voltage by varying the amount of reactive power they generate. Thus, they are able to operate at varying power factors. In the case of induction generator technologies (IGTs), reactive power is needed to magnetize their rotors and this can be supplied either by the grid or capacitor banks. The asynchronous generator based technologies (AGTs) use power electronic devices as interface to

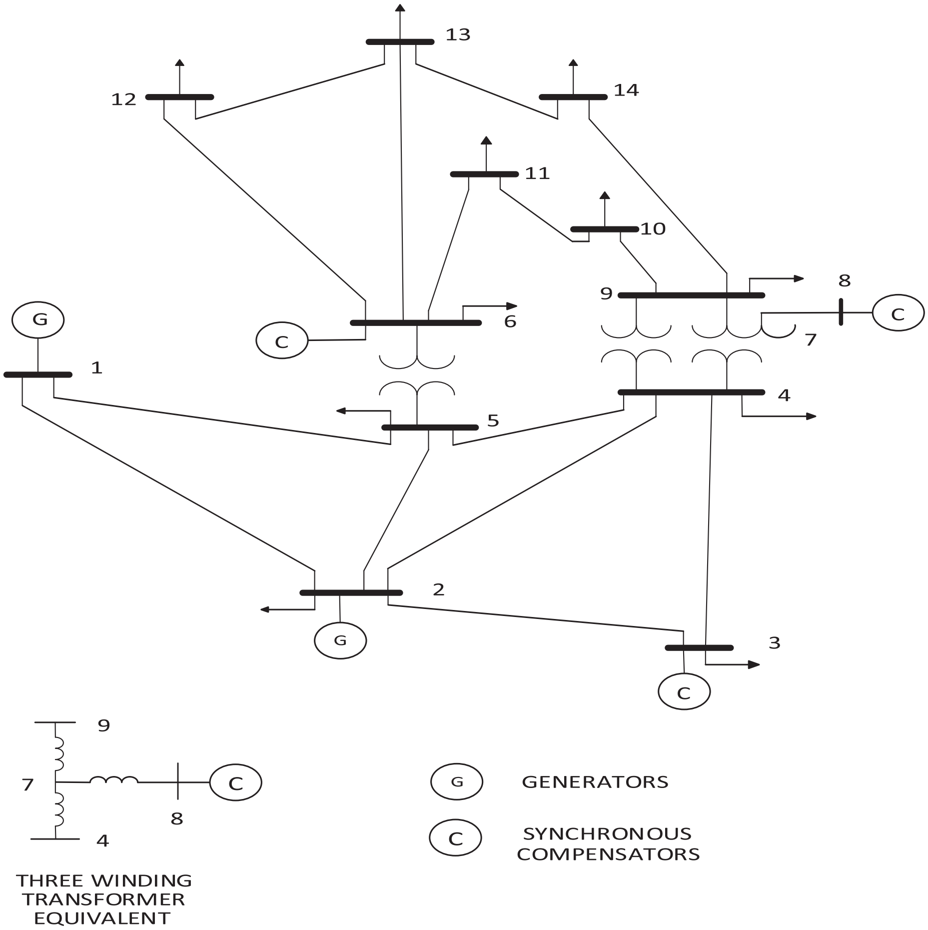

Fig. 1. IEEE 14 bus test network.

Table 1
DG technology classes (Ayodele et al., 2015).

DG technology	Type of model	Physical examples
Synchronous generator	Variable reactive power model	Reciprocating engines, combustion turbines, small hydro turbines
Induction generator	Reactive power consumption model	Squirrel cage induction generators (i.e. wind generators)
Asynchronous generator	Constant power factor model	Solar PV, fuel cells

the grid. This interface processes the power generated by the DG Technology into a form for the grid to transport with little or no technical challenges. Asynchronous generators require the power electronic devices to invert the DC power generated to AC power at the required grid frequency and voltage.

3.1. Synchronous generator technology (SGT)

SGT was modeled as generators with constant terminal voltage, known real power generation and known reactive power limits. The reactive power generated could vary within the specified limits to maintain constant terminal voltage. This model incorporates the Variable Power Factor Model of Gonzalez-Longatt (2007) and Constant Voltage Model of Teng (2007). For a given real power, P_{SGT} and terminal voltage, V_{SGT}, the reactive power, Q_{SGT} was allowed to vary as:

$$-0.75P_{SGT} \leq Q_{SGT} \leq 0.75P_{SGT} \quad (1)$$

Table 2
Machine data for the induction generator model.

Parameter	Value
Stator reactance	0.01 p.u.
Rotor reactance	0.01 p.u.
Magnetizing reactance	3.0 p.u.

3.2. Induction generator technology (IGT)

The reactive power absorbed from the grid can be derived from the equivalent circuit of an induction generators as follows (Ayodele et al., 2015; Andres and Cidras Pidre, 2000):

$$Q = V^2 \frac{X_c - X_m}{X_c X_m} + X \frac{V_2 + 2RP}{2(R^2 + X^2)} - X \frac{\sqrt{(V^2 + 2RP)^2 - 4P^2(R^2 + X^2)}}{2(R^2 + X^2)} \tag{2}$$

$$Q = -Q_0 - Q_1 P - Q_2 P^2 \tag{3}$$

where X_m, X_c and X are the magnetizing reactance, capacitor bank(s) reactance and the sum of the rotor and stator leakage reactance, respectively, R is the sum of the rotor and stator resistances and V is the voltage, P is the real power generated and it is positive when it is injected into the grid.

By considering only the first two derivatives of the McLaurin approximation of (2) and neglecting resistance R, then, the reactive power absorbed by an IGT can be approximated as:

$$Q_{IGT} \approx V^2 \frac{X_c - X_m}{X_c X_m} + \frac{X}{V^2} P^2 \tag{4}$$

Hence, for a given generated real power, P and machine parameters, X_c, X_m, and X, the reactive power consumed by the Induction based generator technologies can be obtained. The induction generator parameters used in this study is given in Table 2.

3.3. Asynchronous generator technology (AGT)

By varying the triggering angles for the power electronic interfaces of AGT, they can be made to operate at varying power factors. For a given generated real power, P_{AGT} and power factor, $\cos\phi$, the reactive power generated is given as:

$$Q_{AGT} = \pm \sqrt{P_{AGT}^2 \left(\frac{1}{\cos^2 \phi} - 1 \right)} \tag{5}$$

If $\cos\phi \geq 0$, $Q_{AGT} \geq 0$. Otherwise, $Q_{AGT} < 0$.

4. System under study

The power system network used in the study is the IEEE 14 bus test network. The system consists of 20 lines, 14 buses, 2 generators, 3 synchronous compensators, 10 load points, a two-winding transformer and a three-winding transformer. The 20 lines and transformers were modeled using their pi-equivalent circuits while the generators and synchronous compensators were modeled using their steady state real and reactive powers as well as their reactive power generation limits. The loads were modeled using steady state values of the real and reactive power they consume.

Furthermore, buses with either generators or synchronous compensators were modeled as buses with known voltages and real power generation (PV Buses) while load buses have only real and reactive power generation or consumption known (PQ Buses). The DG Technologies were connected to PQ Buses of the test network, i.e. Bus 4, 5, 9, 10, 11, 12, 13 and 14. The power flow and the steady state analysis was carried out using the load-flow function of Matlab based Power System Toolbox (PST) (Chow and Rogers, 2008). This allows flexibility in testing various scenarios.

4.1. Connection of AGT to the network

Asynchronous generator technology was connected to the load (PQ) buses by modeling it as negative loads. If P_{li} is the real power consumed by the load at bus i and Q_{li} is the reactive power consumed by the load at the same bus, on connecting the asynchronous generator technology, the new real and reactive power consumed at bus i can be written as (6) and (7) respectively.

$$P_{nli} = P_{li} - P_{AGT} \quad (6)$$

$$Q_{nli} = Q_{li} - Q_{AGT} \quad (7)$$

where P_{nli} is the new real power consumed at bus i and Q_{nli} is the new reactive power consumed at the same bus.

4.2. Connection of SGT to the network

The PQ bus where the SGT is to be connected was changed to a PV bus and P_{nli} and Q_{nli} were determined as:

$$P_{nli} = P_{li} - P_{SGT} \quad (8)$$

$$Q_{nli} = Q_{li} - Q_{SGT} \quad (9)$$

4.3. Connection IGT to the network

Since the voltage at PQ buses are unknown until convergence of a load flow algorithm, Eq. (4) cannot be used in a straight forward manner to determine the reactive power consumed at the PQ Bus. The reactive power consumed by the induction generator can be determined as follows:

i. The load flow of the test network with no IGT connected was determined.
ii. The voltage obtained at the bus where the generator is to be connected is used in solving Eq. (4).
iii. P_{nli} and Q_{nli} are determined from the pre-determined P and calculated Q_{IGT} in (4) as follows:

$$P_{nli} = P_{li} - P_{IGT} \quad (10)$$

$$Q_{nli} = Q_{li} - Q_{IGT} \quad (11)$$

5. Determining the impact of DGs on the network

The impacts of the different DGs on the network are determined using the active and the reactive power losses resulting from their connection to the network, and the effect of their connection on the voltage profile. These two indices are based on steady state characteristics of the network. A program was developed in Matlab™ based on Power System Toolbox (PST) to obtaining the power flow solution of the network before and after integrating the DG Technologies. The real and reactive power losses as well as the voltage at all the buses were also determined using the developed program.

5.1. Determination of losses in sub-transmission network

If the current flowing through a transmission line i is I_i, and the line is between bus i and bus j, the real and the reactive power loss can be calculated as follows:

$$P_{loss} = I_i^2 R \quad (12)$$

$$Q_{loss} = I_i^2 X \quad (13)$$

where R is the resistance of the line and X is the reactance of the line. The line current I_i can be obtained as:

$$I_i = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij} V_j \tag{14}$$

where V_i and V_j are the voltages at bus i and j respectively, y_{ij} is the admittance of the transmission line. The total real and reactive power losses in the network can be calculated as follows:

$$\sum_{k=1}^{N} P_{loss_k} \tag{15}$$

$$\sum_{k=1}^{N} Q_{loss_k} \tag{16}$$

where N is the total number of lines in the network.

5.2. Determination of Voltage Profile Index (VPI)

To be able to compare the voltage profile obtained from different scenarios, an index was developed to assign a single value to represent how well the voltage matches the ideal. VPI is defined as follows:

$$VPI = \log_{10}\left(k \times \left|\frac{1}{V_\mu - 1}\right|\right) \tag{17}$$

V_μ and k can be determined as follows:

$$V_\mu = \frac{1}{N}\sum_{i=1}^{N} V_i \tag{18}$$

$$k = 1 - V_\sigma \tag{19}$$

$$V_\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(V_i - V_\mu\right)^2} \tag{20}$$

where N is the number of buses in the network, V_i is the magnitude of the voltage at bus i, V_μ is the mean bus voltage of the network, V_σ is the standard deviation of the bus voltages.

For two scenarios, X and Y, if $VPI_X > VPI_Y$, scenario X provides a better voltage profile.

5.3. Penetration level (PL)

Penetration level (PL) refers to how much of the real power demand of the network is met by the DG technologies. It can be mathematically represented as:

$$PL = \frac{P_{DG}}{P_{load}} \times 100\% \tag{21}$$

A PL of 0% represents when the load demand is totally met by the grid and a 100% PL represents when the load demand is supplied entirely by the DG Technologies. P_{DG} can be any of P_{SGT}, P_{IGT} or P_{AGT}

6. Simulation results and discussion

Simulation was carried out to determine the effect of DGs on voltage profile and power loss of sub-transmission power system as shown in the flow chart of Figs. 2 and 3.

Different scenarios were created to foster understanding of the possible impact of DGs on the network. The base case represents a scenario in which no DG was connected to the network. Other scenarios were obtained by connecting

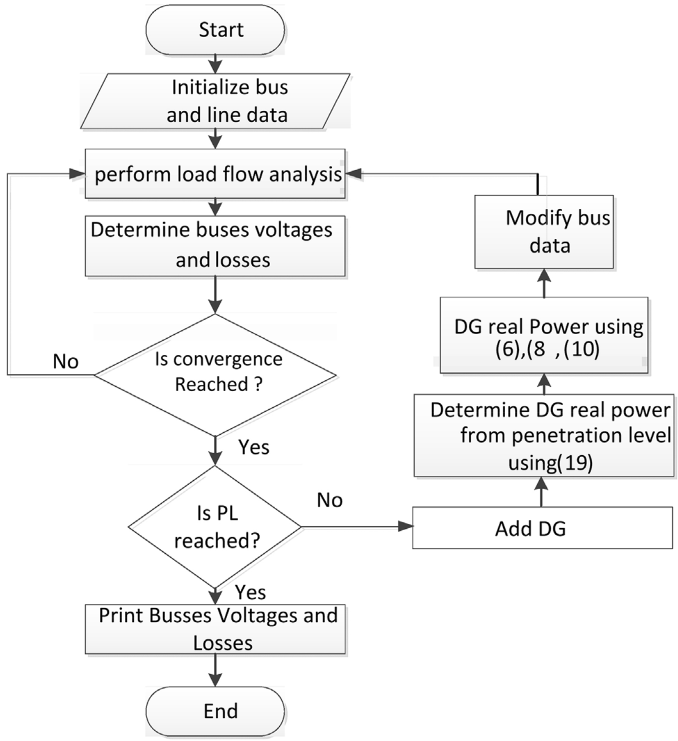

Fig. 2. Flow chart to obtain losses and bus voltages on connecting synchronous and asynchronous based DG.

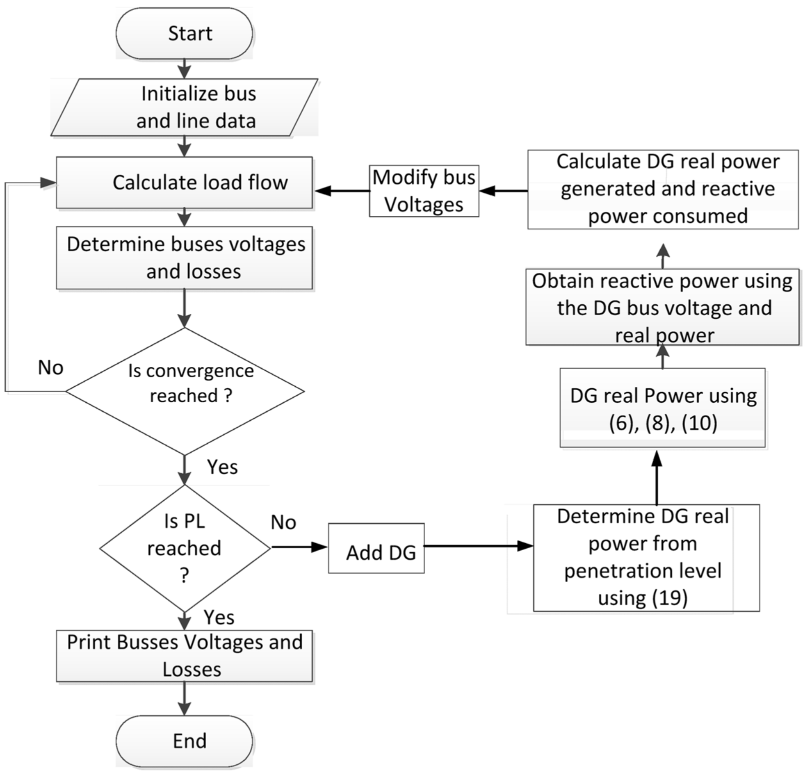

Fig. 3. Flow chart to obtain losses and bus voltages with induction generator based DG.

Table 3
Result for base case scenario.

Parameter	Value
Total load real power demand	2.5900 p.u.
Total load reactive power demand	0.8140 p.u.
Total real power loss	0.1361 p.u.
Total reactive power loss	0.2744 p.u.
Voltage profile index (VPI)	1.3763

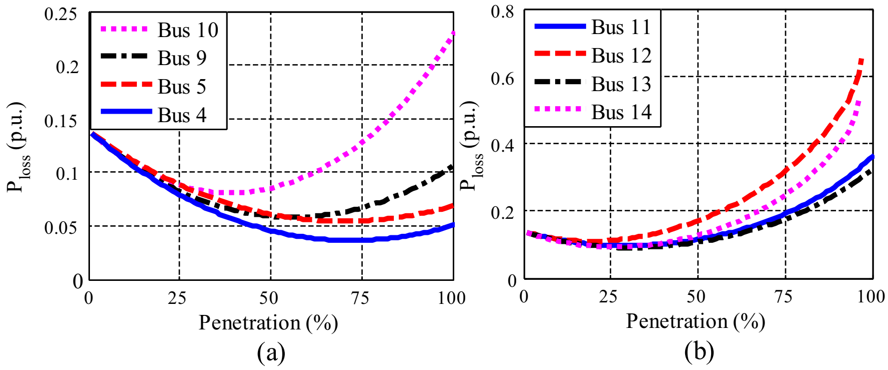

Fig. 4. Real power loss when AGT based DG was connected to (a) buses at 69 kV voltage level; (b) buses at 13.8 kV voltage level.

different DG technologies to the network at different buses in turn and then increasing the penetration level. The Losses and VPI for each penetration level were obtained for different DG technology.

6.1. Base case (BC)

The BC which represents the scenario in which no DG was connected to the network is to allow us make a good comparison with when DGs are connected. Simulation was performed for the BC and the total real and reactive power demand, real and reactive power losses and the voltage profile were determined as depicted in Table 3.

The table revealed that the real and reactive power losses are 0.1361 and 0.2744 p.u., respectively while the voltage profile index is 1.3763. The total real power demand by the loads is 2.59 p.u. while the total reactive power demand by the loads in the network stands at 0.814 p.u.

6.2. Impact of asynchronous generator technology on sub-transmission network

AGT based DG was connected to different bus in the network in turn at the power factor of 1. Buses 4, 5, 9 and 10 are at 69 kV voltage level while buses 11, 12, 13 and 14 are at 13.8 kV voltage level in the sub-transmission network. The results for real power losses, reactive power losses and the voltage profile index when AGT is connected to these buses at increasing penetration level are depicted in Figs. 4–6, respectively.

From the figure it is observed that both the real and reactive power loss exhibits a bath-tub characteristic with the increase in the penetration of the DG. This indicates that at the initial penetration (when DG injection was low), the DG contributed positively to the network by reducing the overall power loss in the network. However, as the penetration increases both the active and the reactive power loss began to increase, meaning that, at higher penetration of DG, the real and reactive power loss increase. The figures also show that there is a penetration level (PL_{min}) at which the real and reactive power loss is minimum. This point however, varies from bus to bus. It is generally observed that the loss (real and reactive power) is least at buses 4 and 13. Generally at the 69 kV buses, PL_{min} occurs between 50% and 75% as shown in Fig. 4(a) while the DG connected to 13.8 kV have PL_{min} between 25% and 50% as seen from Fig. 4(b). This implies that more power can be injected into the network at 69 kV buses compared to 13.8 kV buses. Similarly, Fig. 5(a) show that the minimum reactive power loss was obtained between 60 and 80% penetration level for the 69 kV

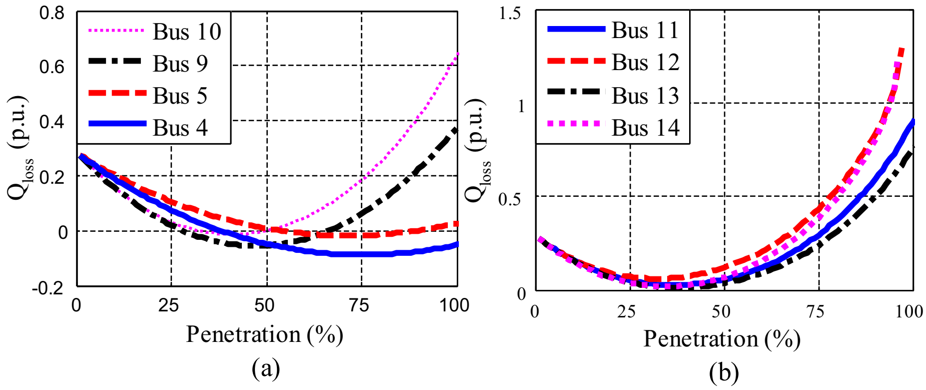

Fig. 5. Reactive power loss when AGT based DG was connected to (a) buses at 69 kV voltage level; (b) buses at 13.8 kV voltage level.

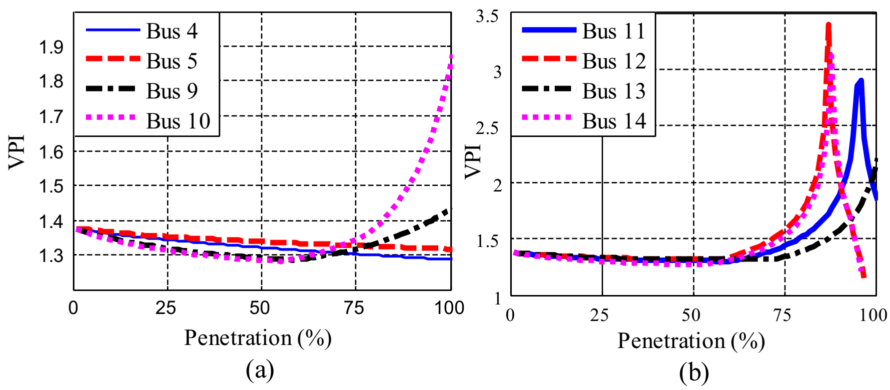

Fig. 6. Voltage profile index when AGT based DG was connected to (a) buses at 69 kV voltage level; (b) buses at 13.8 kV voltage level.

buses, indicating that the total reactive power in the network was continually improved until about 60–80% penetration level while the 13.8 kV buses has minimum reactive *power* between 30 and 50% penetration. The voltage profile index as depicted in Figs. 5 and 6 show that the DG has little impact on the voltage profile at lower penetration, however as the penetration level increases, the voltage profile was improved by about 30%.

6.3. Impact of synchronous generator technology based DG on sub-transmission network

The AGT based DG was removed and replaced with the synchronous generator technology (SGT) and the impact on real and reactive power loss of the network as well as the voltage profile was again simulated. The results are presented in Figs. 7–9.

From the figures, it is observed that both the real and reactive power loss when SGT is connected to the network has similar characteristics as when AGT based DG is connected to the network. The characteristics have a bath-tub shape, implying that there is a maximum penetration level beyond which the real and the reactive power loss is compromised. In the same manner, the 69 kV buses allow higher penetration than 13.8 kV buses and more loss reduction is obtainable at the 69 kV buses than at the 13.8 kV buses. The minimum loss for the 13.8 kV buses occurred between 20% and 40% penetration level as depicted in Fig. 7(a). The 69 kV buses had minimum real power loss within a penetration level range of 50% and 75% as shown in Fig. 7(b). It is again observed that buses 4 and 13 presents the minimum loss when SGT is connected to each of the bus in turn. The voltage profile index as depicted in Fig. 9 is also observed to be higher than that of the BC, indicating a better improved voltage profile. The improvement is due to the fact that SGT has the ability to inject reactive power to the network to improve the voltage profile.

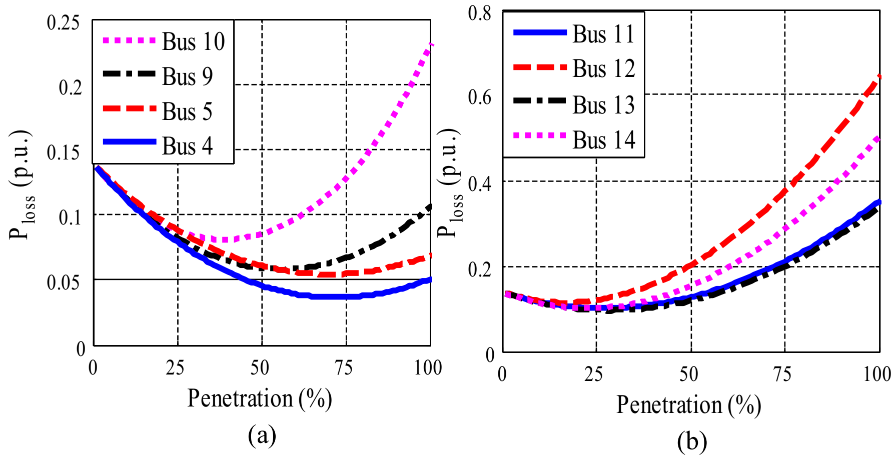

Fig. 7. Real power loss when SGT based DG was connected to (a) buses at 69 kV voltage level; (b) buses at 13.8 kV voltage level.

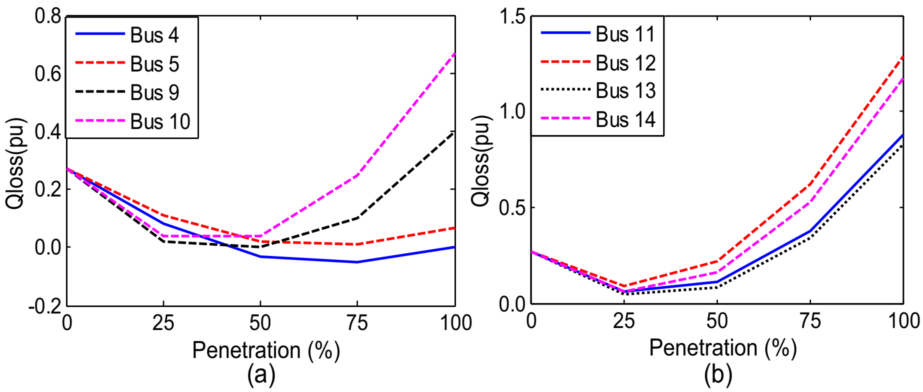

Fig. 8. Reactive power loss when SGT based DG was connected to (a) buses at 69 kV voltage level; (b) buses at 13.8 kV voltage level.

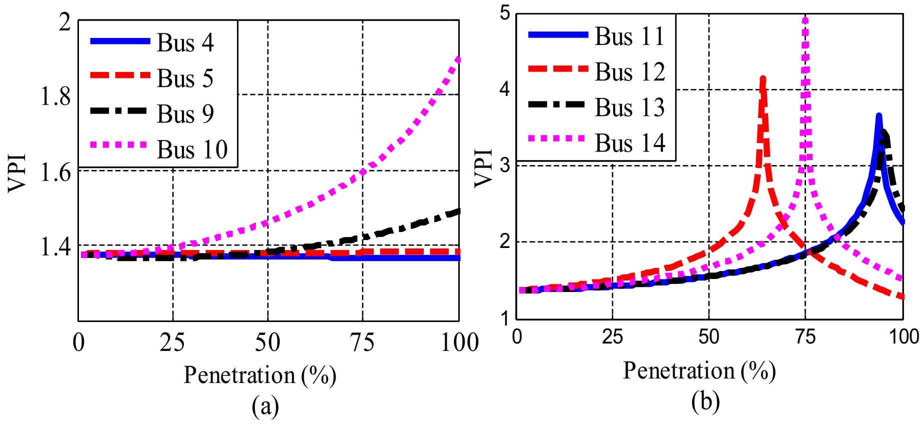

Fig. 9. Voltage profile index when AGT based DG was connected to (a) buses at 69 kV voltage level; (b) buses at 13.8 kV voltage level.

6.4. Impact of induction generator technology based DG on sub-transmission network

The SGT based DG is replaced with inducting generator technology (IGT) and simulation was performed. The results showing the impact of the DG on real power loss, reactive power loss and the voltage profile are shown in Figs. 10–12

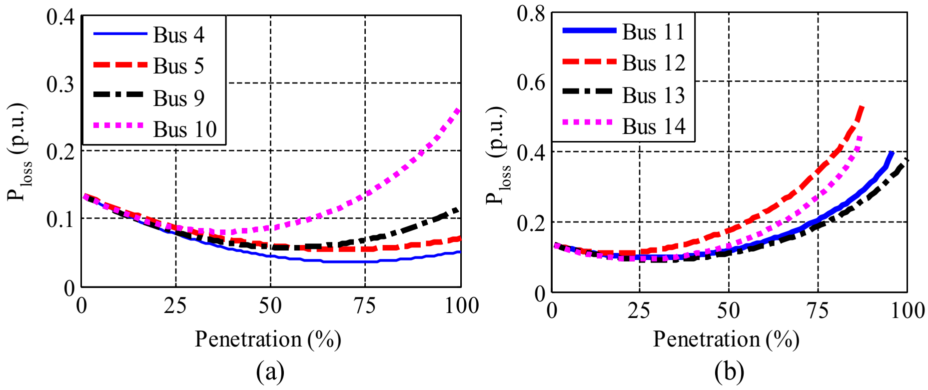

Fig. 10. Real power loss when IGT based DG was connected to (a) buses at 69 kV voltage level; (b) buses at 13.8 kV voltage level.

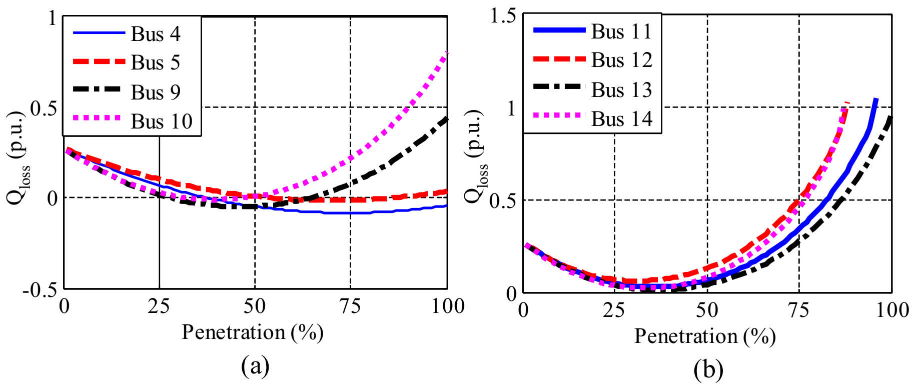

Fig. 11. Reactive power loss when IGT based DG was connected to (a) buses at 69 kV voltage level; (b) buses at 13.8 kV voltage level.

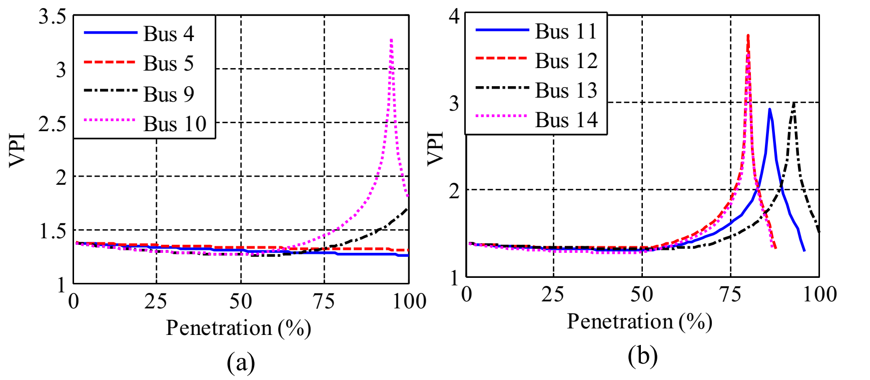

Fig. 12. Voltage profile index when IGT based DG was connected to (a) buses at 69 kV voltage level; (b) buses at 13.8 kV voltage level.

From the figures, it is revealed that the connection of IG based DG technologies to the network resulted in a reduction in both the real and the reactive power loss at lower penetration level. As the penetration increases, the losses increase. With IGT based DG, it was observed that 100% penetration could not be achieved at Bus 11, 12 and 13 within voltage constraints. Thus, the maximum achievable penetration levels at these buses were 96%, 88% and 87% respectively. Fig. 10 demonstrated that minimum real power loss on 69 kV buses was achieved with penetration level between 50% and 75% while the minimum real power loss occurs at the penetration level between 25% and 50% on 13.8 kV. Figs. 10 and 11 both indicate that bus 4 has minimum real and reactive power loss on the 69 kV voltage level while

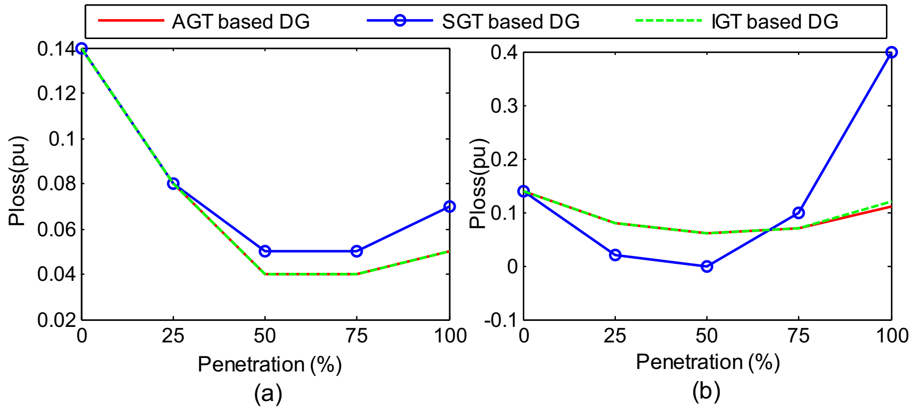

Fig. 13. Comparison of real power loss (P_{loss}) by different generator technology connected to (a) bus 4 (69 kV voltage level); (b) bus 9 (13.8 kV voltage level).

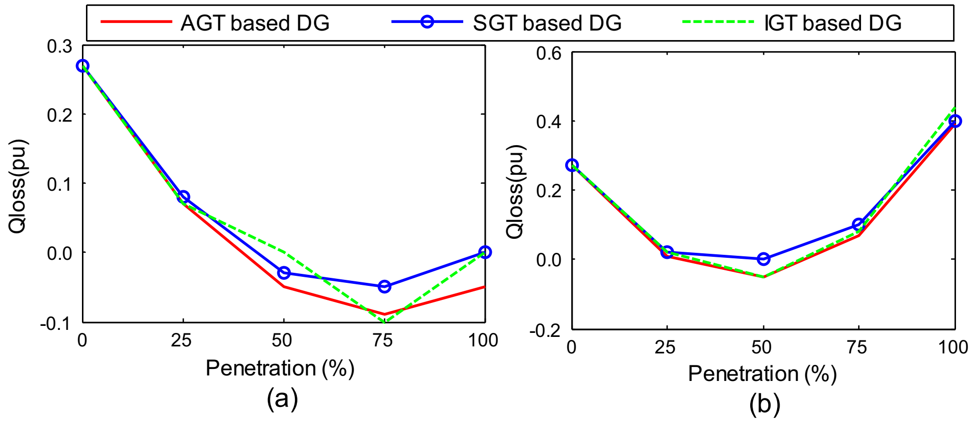

Fig. 14. Comparison of reactive power loss (Q_{loss}) by different generator technology connected to (a) bus 4 (69 kV voltage level); (b) bus 9 (13.8 kV voltage level).

bus 13 presents the minimum loss for the 13.8 kV buses. Fig. 12 reveals that the VPI of the network is lower than the BC, indicating that IGT does not improve the voltage profile of the network except at 75% penetration level.

7. Comparison of generator technology

In order to have insight into the comparative assessment of the different DG technologies on possible impact on sub-transmission network, simulation was performed with each of the DG technology connected to bus 4 for 69 kV voltage level and bus 9 for 13.8 kV voltage level in turn. The results are presented in Figs. 13–15 for real power loss, reactive power loss and voltage profile index, respectively.

Figs. 13 and 14 generally revealed that real and reactive power can generally be improved by DGs integrating DG into sub-transmission network. Fig. 13(a) shows that the impact of AGT and IGT based DGs on real power loss are similar with better performance on 69 kV buses (bus 4). However, SGT has a better performance on 13.8 kV buses, indicating that P_{loss} is lesser with SGT compared to the other two technologies. Fig. 14(a) and (b) shows that irrespective of the voltage level of the point of common connection, the DGs have similar contribution to the network in term of reactive power loss. Fig. 15 reveals that SGT has higher voltage profile index, indicating that it performs better compared to the other technologies on voltage profile of the network.

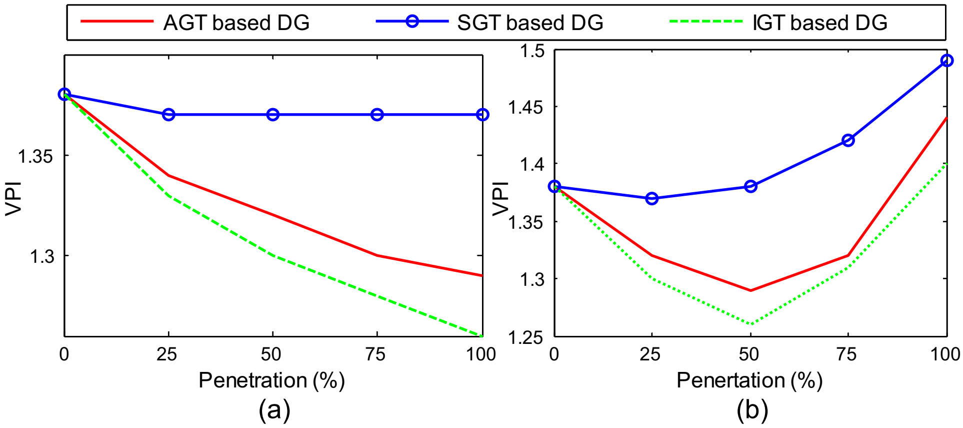

Fig. 15. Comparison of voltage profile index (VPI) by different generator technology connected to (a) bus 4 (69 kV voltage level); (b) bus 9 (13.8 kV voltage level).

8. Conclusion

The effect of three different models of DG technologies on real power loss, reactive power loss and the voltage profile of a sub-transmission network have been investigated. From the results, the followings are concluded:

i. The DG technologies generally reduce the amount of power loss occurring in a network. However, loss obtained varies among the different types of DG technology and buses.
ii. The impacts of the DGs on the power losses form a bath-tub shape with penetration level. This indicates that at lower penetration of DG, the losses are reduced, however, as the penetration increases, a time will come that the power losses begin to increase. This means that there is a maximum penetration level beyond which the DG will increase losses in the network.
iii. The penetration level at which minimum loss is obtained varies with the voltage level at the point of common connection, DG technology employed and from bus to bus,
iv. The effect of DG Technologies on the voltage profile of the network depends on the voltage level. The VPI characteristics obtained were similar among buses of the same voltage levels. Generally, SGT based DG has better performance on the voltage profile of sub-transmission network with higher VPI. This is expected as the technology has the capability to regulate reactive power within the network. The IGT has the least performance, as a result of its inability to contribute to the network reactive power.

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