Chapter 12
Optimal Placement of Wind Power Plants for Delivery Loss Minimization

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12.1 Introduction

The dissipation of power delivery in distribution and transmission networks imposes large social and environmental costs. These costs are closely related to the average price of electricity, the characteristics of electric power systems, and the technology of the power plants. In isolated electric power systems, like those of the Azores Archipelago, these costs can be much higher than in continental power systems, such as that of the US. As an illustration, the average price of electricity on Flores is around $174 per MWh, while the average price of electricity in the USA is about $94 per MWh. Therefore, a 1 MWh loss in the distribution system of Flores costs 1.85 times more than a 1 MWh loss in the distribution system of the US. This implies that minimizing power delivery losses is an indispensable step toward economic and environmental sustainability for the Azores Archipelago.

In general, there are several conventional approaches to minimizing power delivery losses. The most well-known and commercialized method is implementing shunt and/or series capacitors in order to cancel out reactive currents through the lines. In this chapter, we show that using capacitor banks eliminates only a small portion of the power delivery losses, since reactive currents through the lines only contribute to about 20% of the losses. On the other hand, small-scale power plants, such as wind plants, can significantly reduce losses by producing both real and reactive power.

In Sect. 12.2, we investigate loss minimization on Flores. Our technical findings illustrate that by optimizing voltage settings and output powers of the available power plants, about 35% of the power delivery losses can be eliminated. Further-

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more, we investigate a scenario in which 20 % of the available diesel generation is replaced by generation from new wind power plants that are optimally located in the distribution system of the island. The results indicate that up to 57 % of the distribution losses can be eliminated by strategically locating the new wind power plants and optimally utilizing them in coordination with other generators. In the next step, the voltage profile of the distribution system of Flores is investigated using three different scenarios. The results show that when all the power plants are controlling their terminal voltage, a very flat voltage profile is obtained.

In Sect. 12.3, we close the chapter with a brief discussion of needs for developing a systematic framework that can assess the optimum locations and the methods of utilizing the new wind power plants that will achieve the results discussed throughout the chapter.

12.2   Power Delivery Losses on Flores

The electric network on Flores consists of a 15-kV radial distribution network with 45 nodes and 44 branches. Total demand on the island is around 2 MW. Four diesel power plants provide more than 50 % of the electric energy. Around 35 % of the demand is supplied by four hydro plants, and two synchronous wind plants provide the rest (approximately 15 %). Figure 12.1 illustrates the schematic of the distribution network on Flores. In this model, the diesel generator is located at the reference node. The hydro plant is located next to the diesel generator, and the wind plant is located in the middle of the island.
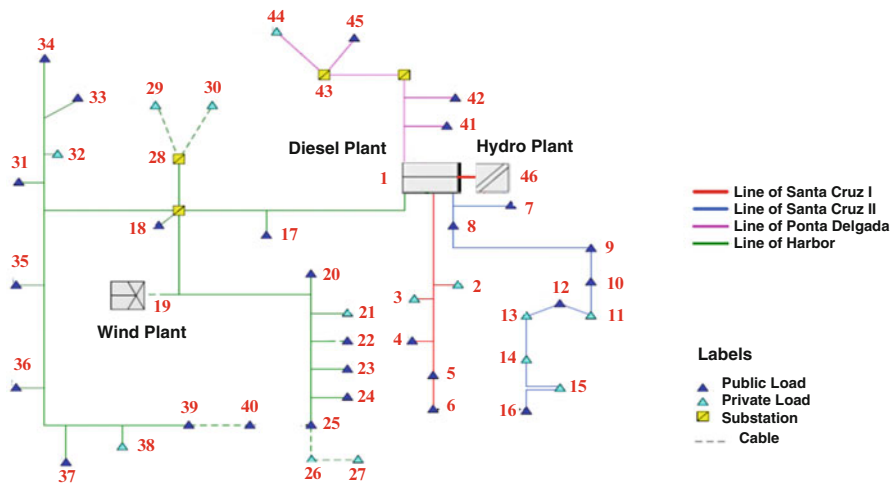

Fig. 12.1 Schematics of the distribution network on Flores Island [1]

Table 12.1 Average cost of producing electricity for different power plants on Flores [1]

	Costs (\$/MWh)
Diesel plant	261
Hydro plant	88
Wind plant	87

The difference between the system shown in Chap. 3 and the one shown in Fig. 12.1 is that here a switch with the reactance and resistance of 0.04 pu connects the hydro plant to the diesel generator. Power flow analysis for Flores demonstrates that more than 2 % of the power delivery is dissipated in the distribution network. This accounts for approximately a 1 MWh loss of energy per day and a 365 MWh waste of electric energy per year.

Given the average price of electricity on the island (\$174/MWh), 2 % power delivery losses cost the island more than \$61,000 per year. Table 12.1 demonstrates the average cost of producing electricity for the different power plants. The 2% losses also cause more than 117 tons of CO_2 emissions per year; the average CO_2 emissions on Flores are 0.32 tons/MWh. In the next section, we explore possible approaches to minimizing these power delivery losses.

12.2.1 Possible Approaches to Minimizing Losses on Flores

In this sub-section, two main approaches to minimizing the power delivery losses are studied: (1) optimizing voltage settings and output powers of the available generators and (2) optimizing the location and utilization of new small-scale power plants such as wind and/or solar plants. The second approach is motivated by the fact that the general policy of Electricidade Dos Acores (EDA) is to make the Azores Islands green. Therefore, it is expected that in the future diesel plants will be replaced by renewable sources of energy such as wind power plants. Consequently, optimal placement of the new plants will be a key factor in loss minimization.

The first step in minimizing power delivery losses is to carry out an AC optimum power flow (AC OPF) for the original system (shown in Fig. 12.1). The objective function of the optimization algorithm is to minimize total distribution losses by optimally scheduling voltage settings and output powers of the available power plants. The control variables of the optimization algorithm are the voltage and phase angles of the generators (V_G and δ_G). The mathematical representation of the optimization algorithm is presented in (12.1)–(12.7) [2, 3, 5].

$$\underset{V_G,\delta_G}{\text{Minimize}}\, P_{\text{Loss}} = \sum_{i=1}^{N_G} P_G^{(i)}\left(\delta_G,\delta_L,V_G,V_L\right) - \sum_{j=1}^{N_L} P_L^{(j)}\left(\delta_G,\delta_L,V_G,V_L\right) \qquad (12.1)$$

Subject to:

$$P_i - V_i^2 G_{ii} - \sum_{\substack{j=1 \\ j \neq i}}^{N_G+N_L} |V_i||V_j| \left(G_{ij}\cos(\delta_i - \delta_j) + B_{ij}\sin(\delta_i - \delta_j) \right) = 0 \tag{12.2}$$

$$Q_i + V_i^2 B_{ii} - \sum_{\substack{j=1 \\ j \neq i}}^{N_G+N_L} |V_i||V_j| \left(G_{ij}\sin(\delta_i - \delta_j) - B_{ij}\cos(\delta_i - \delta_j) \right) = 0 \tag{12.3}$$

$$P_{\min}^{(i)} \leq P_G^{(i)} \leq P_{\max}^{(i)} \ \forall \, i \in N_G \tag{12.4}$$

$$Q_{\min}^{(i)} \leq Q_G^{(i)} \leq Q_{\max}^{(i)} \ \forall \, i \in N_G \tag{12.5}$$

$$P_i^2 + Q_i^2 \leq S_i^2 \ \forall \, i \in N_G \tag{12.6}$$

$$V_{\min}^{(j)} \leq |V_j| \leq V_{\max}^{(j)} \ \forall \, j \in N_G + N_L \tag{12.7}$$

Here N_G is the number of generator nodes and N_L is the number of load nodes in the system. In addition, V_L and δ_L are the voltages and phase angles of the system loads.

The results of AC OPF illustrate that more than 35 % of the distribution losses could be eliminated by optimizing the voltage settings and output powers of the available power plants on the island. This would mean more than 146 MWh energy savings per year, which would save the island more than \$24,500 per year. Moreover, it would reduce CO_2 emissions by 46.8 tons per year.

The second approach to minimizing losses is based on strategically locating the new wind power plants. Here, we investigate a scenario in which 20 % of the diesel generation is replaced by new wind power plant generation. The wind plants are synchronous generators with the ability to produce both real and reactive power. Given the average production of the diesel generators (1 MW), the average generation of the new wind power plants should be around 200 kW or about 10 % of the overall demand.

In order to find the optimum locations for the new wind plants, an optimization algorithm, fully elaborated in [4, 7] is carried out. Figure 12.2 shows the optimal locations for the new wind plants, highlighted by the green rectangle. Note that optimizing these locations would reduce losses by 57 %, saving the island about \$36,800 per year and reducing CO_2 emissions by 70 tons per year.

Placing the new wind plants at optimal locations would also increase reliability of the system. For example, if the line connecting the diesel plant to the center of the island is disconnected (Line 1–17 or 17–18), the wind power plants can supply loads in the center and south parts of the island.

Since the average cost of producing electricity with diesel generators is about 3 times larger than that with wind power plants, offsetting 20 % of the diesel
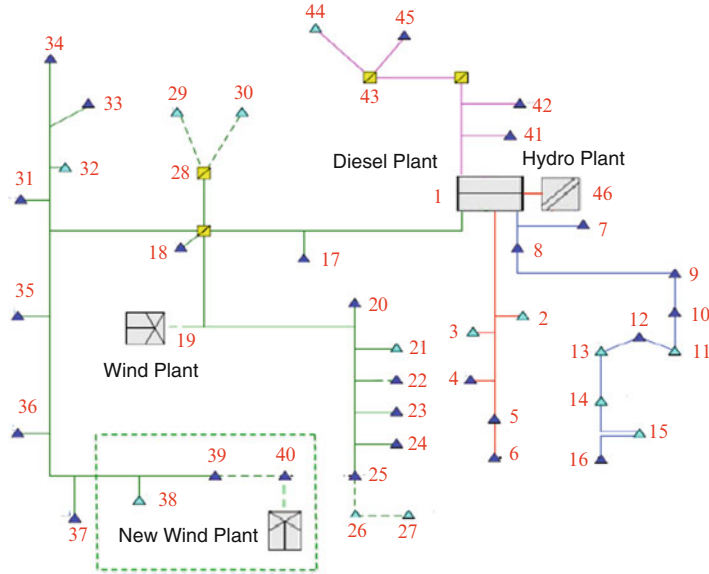
Fig. 12.2 Schematics of the optimal area of locating new wind plants

generation with wind generation, furthermore, would result in a 10 % reduction in the total cost of electricity. Therefore, the total dollar savings to the island would be more than $250,000 per year. About 15 % of the overall savings is due to reducing losses and more than 85 % is due to the offsetting of diesel generation with wind generation.

Moreover, overall CO_2 emissions would be reduced by about 1300 tons per year. Around 5 % of the reduction would be due to reducing the delivery losses and more than 95 % would be due to the offsetting of diesel generation with wind generation.

12.2.2 Comparison Between Small-Scale Power Plants and Capacitor Banks

In this sub-section, we show that shunt and/or series capacitors cannot notably reduce power delivery losses, whereas small-scale power plants, such as synchronous wind plants, can significantly eliminate losses by offsetting real and reactive currents. To this end, we explore first the effects of active and reactive currents on power delivery losses. We see in Fig. 12.3 that active currents through the lines are about two times larger than reactive currents. Since power delivery losses are related to the square of the current, the losses due to active currents (**Pr**) are four times larger than the losses due to reactive currents (**Px**).
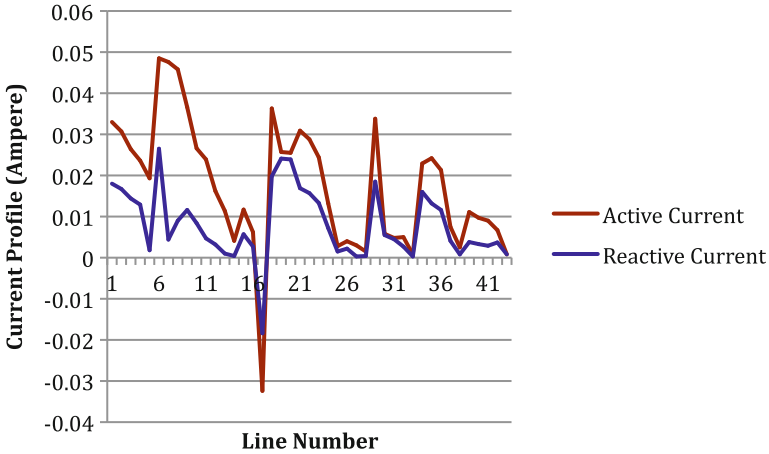
Fig. 12.3 Active and reactive current profile through the lines
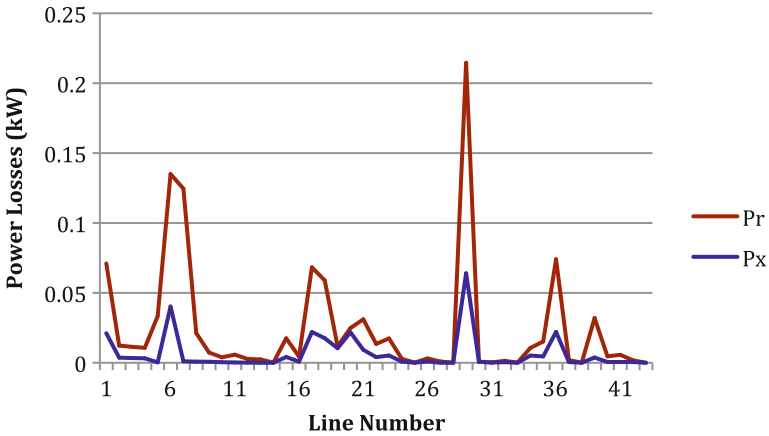

Fig. 12.4 Distribution losses due to active and reactive currents

In other words, reactive currents contribute to only 20 % of the losses; active currents cause the rest (80 %). This implies that installing shunt and/or series capacitors, which compensate for reactive currents only, can eliminate only a small portion of power delivery losses.

On the other hand, small-scale power plants can offset both real and reactive currents through the lines and therefore reduce a large portion of the power delivery losses. We have shown in the previous section that by producing 10 % of the demand with strategically placed and utilized wind power plants about 57 % of the power delivery losses can be eliminated.

In general, minimizing power delivery losses has profound social and environmental advantages. Therefore, using AC OPF-based dispatch to gain such

advantages, which would otherwise not be possible, is an indispensable step toward sustainability of Flores. To this end, EDA needs to implement both SCADA and computer tools such as AC OPF for computing the on-line voltage adjustments and the output power of the generators. Given that today the distribution power system on Flores does not rely on on-line monitoring and dispatch, it is essential to understand the necessity of doing this in order to allow the transformation of Flores into a green and sustainable island.

12.2.3   Improvement of the Voltage Profile on Flores

In this sub-section, we investigate the effect of automatic voltage control of the wind power plants on the improvement of the overall voltage profile of the island. To this end, three main scenarios are assessed: (1) operating the available wind plants without voltage control, (2) operating the available wind generators with voltage control, and (3) strategically locating and utilizing the new wind power plants. In the third scenario, all the wind plants have automatic voltage control.

In general, there exists an acceptable voltage range for electric distribution systems. Violating this limit can damage electrical equipment or diminish its life expectancy. In the worst case, this can lead to overall voltage collapse. Hence, from the perspective of consumers, an ideal voltage profile is a flat voltage profile with a voltage level of 1 pu throughout the distribution system [6]. In this condition, all the electrical equipment operates at the nominal voltage (1 pu), and therefore, the risk of damage is minimized.

Investigating the voltage profile of the island in the three scenarios shows that in Case 1 the wind power plant absorbs the reactive power. Therefore, voltage drops in the vicinity of the plant. In Case 2 the wind plant controls its terminal voltage at 1 pu. As shown in Fig. 12.5, in this scenario the overall voltage profile of the system is much closer to the idea scenario.

In Case 3 all the power plants adjust their terminal voltage to 1 pu. Figure 12.6 illustrates the voltage profile of the system for all the scenarios. The technical results show that a voltage profile closest to the ideal is obtained when all the plants adjust their terminal voltage.

12.3   Conclusions and Future Outlook

In this chapter, we highlight that by strategically placing new wind power plants and optimally operating them in coordination with other generators about 57 % of the power delivery losses can be eliminated from the distribution system of Flores. This would result in energy saving per year of more than 220MWh. In addition, it would save the island more than \$250,000 per year and reduce CO_2 emissions by 1,300 tons per year.
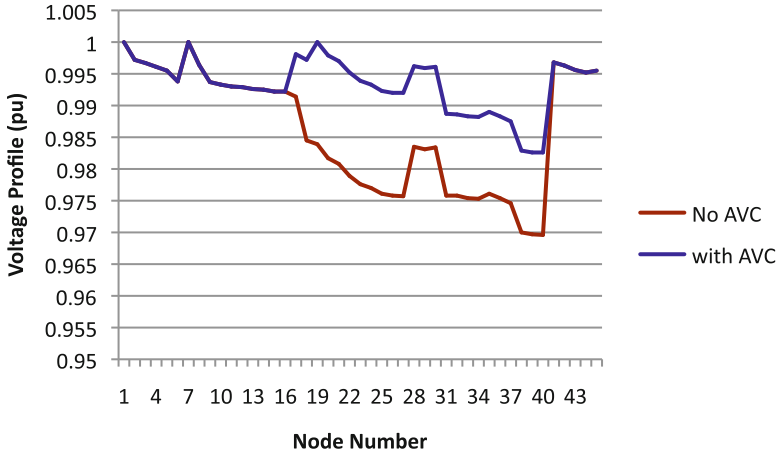
Fig. 12.5 Voltage profile of the island with and without voltage control for the wind power plant
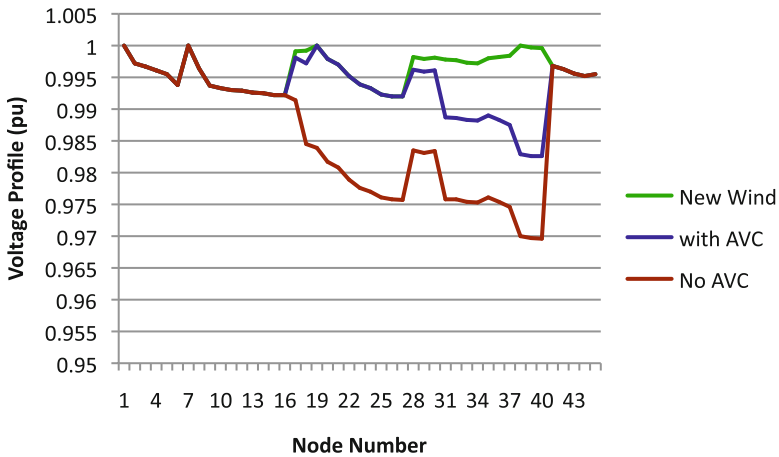
Fig. 12.6 Voltage profile of the island in three different scenarios

Our technical findings furthermore illustrate that loss reduction highly depends on the location and voltage settings of the power plants. We show that capacitor banks can eliminate only a small portion of the power delivery losses, while wind power plants with automatic voltage regulators can significantly reduce power delivery losses by offsetting both real and reactive currents through the lines.

In order to improve voltage profile and minimize the risk of voltage collapse, all wind plants need to be equipped with automatic voltage regulators whose set points should be optimized as conditions vary. This helps the system to maintain a flat voltage profile throughout the distribution system.

While the utility studies are being carried, and new candidate power plants are being considered, it is essential to develop a systematic framework that assess the optimal locations and utilization methods for the new power plants in order to minimize power delivery losses and maximize environmental sustainability.

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