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

International Conference on Renewable Energies and Power Quality
(ICREPQ'10)
Granada (Spain), 23rd to 25th March, 2010

Network losses with photovoltaic and storage

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Abstract. Recent development of dispersed generation technologies employing sustainable energy resources has encouraged the entry of power generation at distribution level. The close distance between load and generation reduces the network losses. However, DG system with electronic devices gives harmonic distortion. Harmonics introduce additional losses and could cause premature ageing as well as earlier re-investment of network components. This paper examines the network losses of a grid-connected photovoltaic (PV). The fundamental and harmonic losses of main network components, including transformer and cables, are calculated and compared among three cases: 1) without PV, 2) with PV, and, 3) with PV and storage.

Key words

Photovoltaic power systems, Losses, Harmonic distortion, Power transformer losses, Dispersed storage and generation.

1. Introduction

Concerning to the CO2 emission reduction and less dependence on conventional fuels, renewable energy resources are increasingly employed in power sector. With high penetration of distributed energy resources (DERs), microgrid has been introduced as a possible solution to increase the reliability in low voltage distribution systems. By integrating DERs together with storage devices and controllable loads, a microgrid can possibly operate autonomously.

The first microgrid in the Netherlands is built on the Bronsbergen holiday park. This park consists of 210 holiday houses, of which 108 have been installed with over 3,000 m2 with 315kWp solar panels on the roof. A MV/LV 10kV/400V, 400 kVA transformer connects the Bronsbergen network to the public grid. Four outgoing feeders are used for connecting all the cottages to the transformer, mainly using 150Al low-voltage cables. Furthermore, two battery banks have been installed as electrical storage. A program started in June 2005 to monitor all power quality aspects in the low voltage network. Fig. 1 illustrates an image of the Bronsbergen microgrid and Fig. 2 shows its simplified single-line diagram.

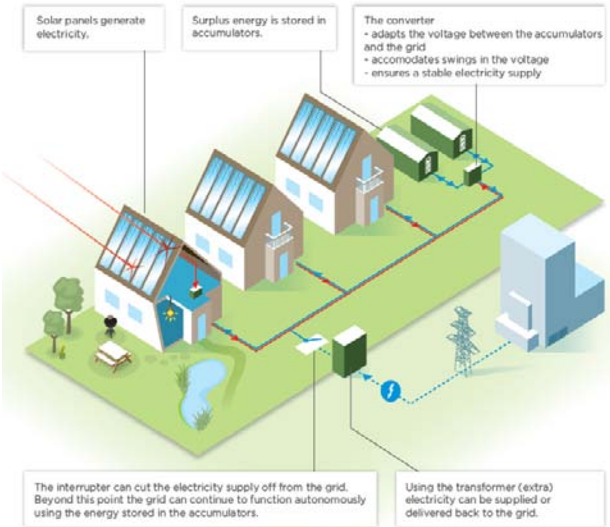

Fig. 1. Bronsbergen microgrid [1]

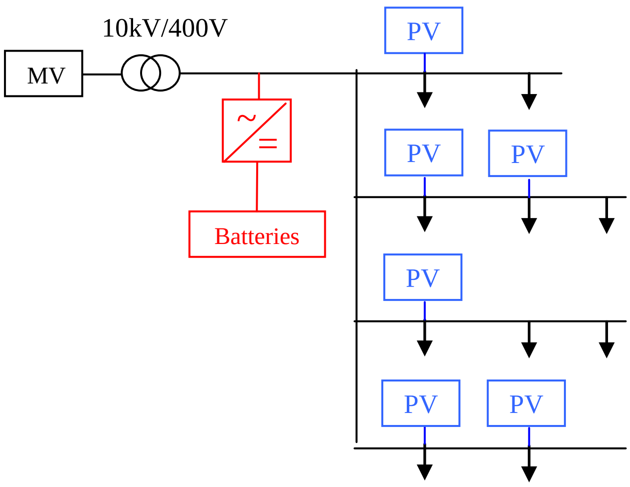

Fig. 2. Bronsbergen single-line diagram

The fundamental and harmonic losses of the Bronsbergen network are considered in three cases.

Case 1: Without PV. Case 1 examines the network situation in the park with only loads connected to the grid via a 10kV/400V, 400 kVA transformer.

Case 2: With PV. Case 2 considers the same networks as described above. In addition, 108 cottages installed with roof-mounted solar panels which can generate a total of 315 kWpeak.

Case 3: With PV and storage. In case 3, two battery banks are connected to the transformer LV side bus through AC/DC inverter. The storage is charged and discharged between 20% and 100% of its capacity, 0.9kAh, and with the efficiency of 85%.

In the following part, section 2 introduces the fundamental frequency losses; section 3 discusses the total losses with effect of harmonics; and section 4 concludes the paper.

2. Fundamental frequency losses

Fundamental frequency losses of the transformer and cables are simulated using DIgSILENT Power Factory software. The total load demand of the network is 820 MWh/year. Simulating results show that the transformer losses are reduced from 8.85 to 6.67 MWh/year with PV and to 6.03 MWh/year after storage is installed. The losses drop slightly with storage because the storage affects the network losses in summer time only, when the PV systems generate more than the demand [2].

The cable losses are reduced from 5.26 to 3.14 MWh/year in case 2, and to 3.13 MWh/year in the third case. The cable losses are almost unchanged with storage because the storage is installed at the transformer LV side; hence, the power flows in the cables are almost unchanged. In another case, instead of one central storage, four dispersed storages are installed at the end of each feeder, the simulated cable losses with decentralized storage are reduced to 2.33 MWh/year [2].

3. Total losses with effect of harmonics

The transformer losses generally are classified into no load and load losses. The load losses are divided into ohmic losses, eddy current losses and other stray losses. The effect of an harmonic voltage on no load losses is negligible. Transformer load losses with current harmonic effects are calculated by a summation of the extra ohmic loss, the adjusted eddy current loss and the adjusted other stray losses [3].

The cable losses with harmonics are a summation of three phase and neutral conductor losses. Cable harmonic power losses are calculated by the product of the square of harmonic current and harmonic resistance [3].

A. Harmonic loss approximation in the case without PV

Since the solar panels were already installed and have been operating, the data of harmonic losses in the case without PV cannot be measured anymore. Hence, in this case, the harmonic losses of transformer and cables are approximated.

Based on the simplifications and approximations presented in [4], the total energy harmonic losses of the transformer ($\varepsilon_{h,tran,noPV}$) with respect to fundamental frequency no load losses (P_{Fe}) and load losses (P_{Cu}) can be displayed as equation (1):

$$\varepsilon_{h,tran,noPV} = \sum_{1}^{8760} (0.4 \cdot 10^{-4} P_{Fe} + 0.057 P_{Cu}) \quad (1)$$

The no load (P_{Fe}) and load losses (P_{Cu}) at fundamental frequency are calculated based on power flow simulations, and then the transformer harmonic losses can be approximated.

Similarly, the cable losses at fundamental frequency (P_{cab1}) can be obtained from the results of power flow simulations. Harmonic losses on three phase and neutral conductors are approximated as 2.25% and 3% of the fundamental frequency losses respectively [4]. The total energy harmonic losses of cables ($\varepsilon_{h,cab,noPV}$) are calculated with respect to the known fundamental frequency losses of cables in equation (2).

$$\varepsilon_{h,cab,noPV} = \sum_{1}^{8760} (5.25 \cdot 10^{-2} P_{cab1}) \quad (2)$$

B. Harmonic loss calculation in the case with PV

The effect of harmonic voltage on no load losses is neglected. The transformer load losses with harmonic effects are calculated by a summation of the ohmic loss P_{I^2R}, the adjusted eddy current losses $P_{EC,h}$ and the adjusted other stray losses $P_{OST,h}$ [3].

$$P_{h,tran,PV} = P_{I^2R} + P_{EC,h} + P_{OST,h} \quad (3)$$

where
$P_{h,tran,PV}$ Total transformer losses due to harmonics
P_{I^2R} Ohmic losses
$P_{EC,h}$ Winding eddy current losses with harmonics
$P_{OST,h}$ Other stray losses with harmonics

The adjusted eddy current losses and the other stray losses are calculated by the product of these losses at fundamental frequency and the harmonic factors correspondingly in equations (4) and (5).

$$P_{EC,h} = P_{EC1} \cdot F_{EC} \quad (4)$$

$$P_{OST,h} = P_{OST1} \cdot F_{OST} \quad (5)$$

where P_{EC1} Winding eddy losses at fundamental frequency

P_{OST1}	Other stray losses at fundamental frequency
F_{EC}	Harmonic factor for eddy current losses
F_{OST}	Harmonic factor for other stray losses

From (3), (4), (5), the harmonic losses of transformer are:

$$P_{h,tran,PV} = P_{I^2R} + P_{EC1}\cdot F_{EC} + P_{OST1}\cdot F_{OST} \tag{6}$$

Then, the energy harmonic losses of transformer ($\varepsilon_{h,tran,PV}$) are calculated by a summation over the whole year time of power losses as shown in equation (7).

$$\varepsilon_{h,tran,PV} = \sum_{1}^{8760} P_{h,tran,PV} \tag{7}$$

The yearly energy losses on cables due to the harmonics ($\varepsilon_{h,cab,PV}$) are calculated by the summation of power losses on three phase conductors (P_{hP}) and neutral cconductor (P_{hN}) in the whole year as shown in equation (8).

$$\varepsilon_{h,cab,PV} = \sum_{1}^{8760} P_{hP} + \sum_{1}^{8760} P_{hN} \tag{8}$$

Power loss is the product of square of harmonic current I_h and harmonic resistance R_h. Cable harmonic losses are calculated as equation (9), with assuming that the harmonic resistance on phase conductors is equal to that on neutral conductor, $R_{hP} = R_{hN}$

$$\varepsilon_{h,cab,PV} = \sum_{1}^{8760} \sum_{h=2}^{h_{max}} \left(3\cdot I_{hP}^2 \cdot R_{hP} + I_{hN}^2 \cdot R_{hN}\right) \tag{9}$$

Fig. 3 displays the phase resistance versus harmonic order measured for LV cable used in the Bronsbergen grid [1].

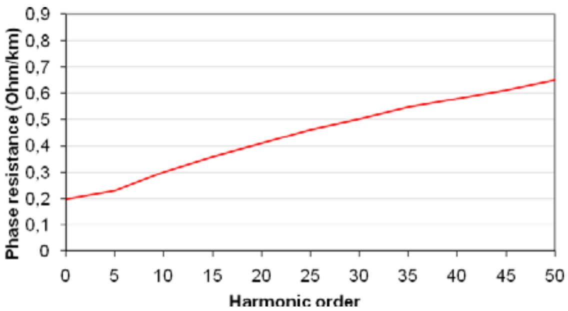

Fig. 3. Phase resistance vs. harmonic order [1]

C. The scenarios

A whole year simulation is implemented, with input data of load and PV generation data in the year 2006. Two scenarios are illustrated to compare among the three cases, consisting of the day with maximum PV generation & minimum load (July 10th) and the day with minimum PV generation & maximum load (December 11th).

Fig. 4 and 5 show the active and reactive power at different points in the network on the two extreme days.

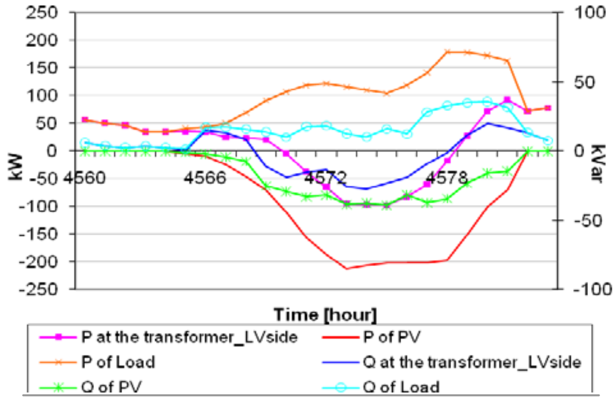

Fig. 4. Active and reactive power on Max PV Min Load day

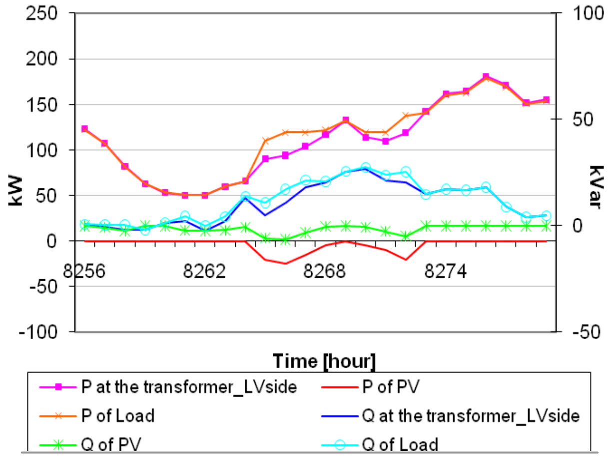

Fig. 5. Active and reactive power on Min PV Max Load day

D. Harmonic data

Fig. 6 and 7 display the current harmonic spectrum on three phase and neutral conductors because of PV, and because of PV and storage inverter.

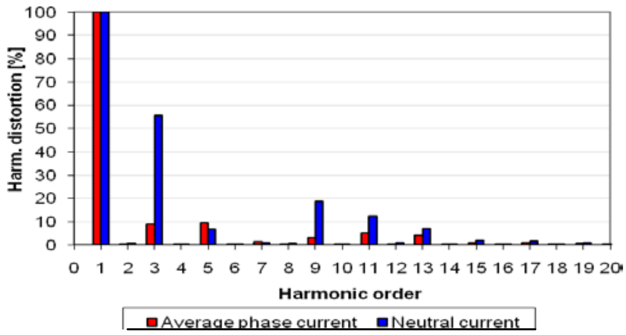

Fig. 6. Current harmonic spectrum with PV

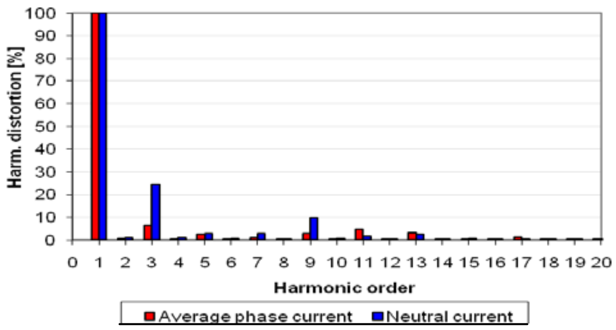

Fig. 7. Current harmonic spectrum with PV and storage including inverter

The even harmonics are much smaller than the odd ones, therefore, the even harmonics can be negligible. The inverter connecting the storage and the transformer LV bus reduces the current harmonics on three phase and neutral conductors.

E. Results

Fig. 8 and 9 show the transformer loading in three cases (without PV, with PV and with PV and storage) on the two extreme days.

In case 1, the maximum transformer loading is nearly 50% in both extreme scenarios at peak hours in late evening.

On the maximum PV – minimum load day, the maximum loading level decreases from about 50% to about 20% after PV systems are installed. In case 2, the maximum loading level is reduced smoothly in the morning, but then from 10hr. to 19hr., there is a rise caused by the reversed flow to the MV grid. In case 3, the transformer loading reduces strongly during afternoon, when the additional PV generation charges the storage instead of flowing back to the grid, and during the peak hours in late evening, when the missing demand is fed by discharging the storage, instead of requiring from the grid. The storage has enabled the autonomous ability of Bronsbergen network by reducing the exchange with the external grid.

On the minimum PV - maximum load day, the curve is almost unchanged among the three cases since PV and storage are not in use during low irradiation season.

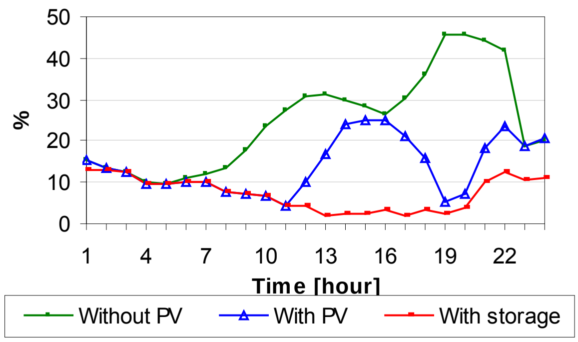

Fig. 8. Transformer loading on the ‘Max PV Min Load’ day

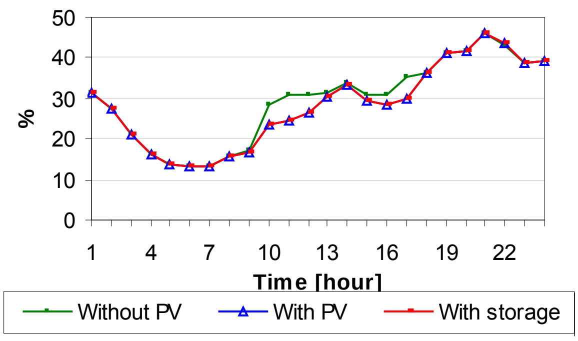

Fig. 9. Transformer loading on the ‘Min PV Max Load’ day

The transformer loading level affects the transformer losses under load condition. Therefore, the transformer load losses at fundamental frequency are reduced in case 2 and further more in case 3.

Fig. 10 shows the yearly transformer loss components, including no load losses, fundamental frequency load losses and harmonic losses for the three cases.

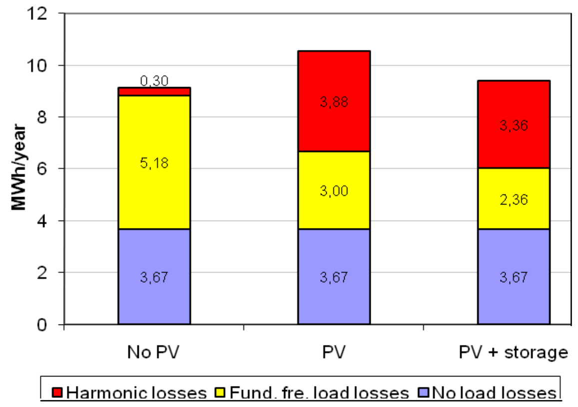

Fig. 10. Transformer losses with harmonics

The fundamental frequency load losses are reduced gradually from case 1 to case 3. However, the large extra harmonic losses make the total transformer losses increased in case 2 and 3.

Cable loss components, including fundamental frequency losses and harmonic losses on three phases and neutral conductor are shown in Fig. 11. The effects of current harmonics on cable losses are not as significant as on transformer losses.

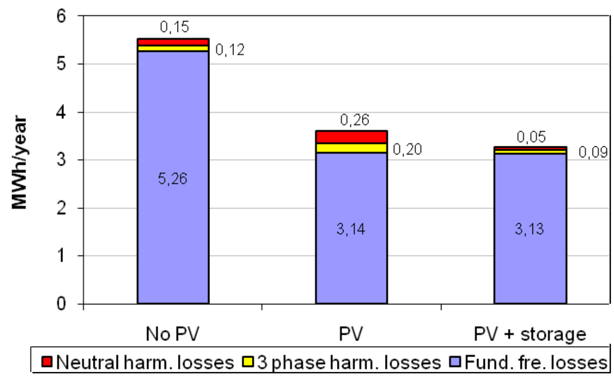

Fig. 11. Cable losses with harmonics

The total losses (for transformer and cables), consisting of fundamental and harmonic losses, are illustrated in Fig. 12.

The total losses are reduced slightly from 14.68 MWh/year to 14.15 MWh/year with PV, and to 12.66 MWh/year with PV and storage, which are equivalent to 1.8%, 1.72%, and 1.54% of the total demand respectively.

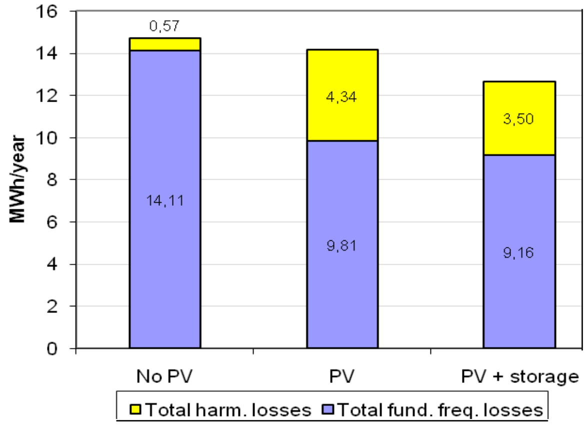

Fig. 12. Total losses

However, in case 3, the storage with 85% efficiency causes an extra loss of 8.75 MWh/year, which is much larger than the network loss reduction when it is applied.

4. Conclusions

For the transformer, the losses at fundamental frequency are reduced after PV systems, or PV systems and storage are implemented. However, the large extra harmonic losses due to PV and battery inverters make the total transformer losses increased.

For the cable, the losses at fundamental frequency are reduced after PV systems are installed, but almost keep unchanged after storage is applied. The current harmonics have small effect on cable losses. At the result, the total cable losses are reduced with PV, and a little bit more with PV and storage.

Totally, for the two main network components, which are transformer and cables, the implementation of PV or PV and storage can reduce the network fundamental frequency losses. However, electronic devices in PV system and storage cause extra harmonic losses, which finally make the total losses reduced very slightly. In the case with storage, the storage loss itself is much larger than this loss reduction. Methods for reducing harmonic losses could be applied to reduce the total network losses.

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