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Integration of Storage in Electrical Distribution Systems and its Impact on the Depth of Penetration of DG

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Integration of Storage in Electrical Distribution Systems and its Impact on the Depth of Penetration of DG

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Executive Summary

This report provides a set of study results to determine the effect of distributed storage (DS) on the Electric Distribution System (EDS) with emphasis on the depth of penetration of distributed generation (DG) units.

To determine the effect of a DS unit on the distribution system and its effect on the maximum depth of DG penetration, we assume that:

- the efficiency of each DS unit is less than 100%,
- customers with DG and/or DS units do not export reactive power to the system,
- the fault contribution of each DS unit is negligible,
- feeder loading is a mix of industrial, commercial and residential customers,
- typical daily load diagram for each customer group is pre-specified,
- load power factor is between unity and 0.9 at all busses,
- feeder cable ampacity is not exceeded.

Methodology

To determine the maximum depth of DG penetration in a feeder:

1. A typical day is divided into a number of time intervals and within each interval the load and the DG output of the feeder remain constant.
2. A particular load profile (industrial, commercial or residential) is applied at each node, depending on the type of customer connected to the node.
3. All load/DG scenarios are studied with and without DS in service.
4. Three different options for a DS unit are considered:
   a) The DS unit has a minimum storage capacity and power to level the load profile,
   b) The DS unit is a typical 1 MW NaS battery with 7.2 MWh storage capacity and 100% depth of discharge (DOD),
   c) The DS unit is a typical 1 MW NaS battery with 7.2 MWh storage capacity and 90% DOD.
5. Power flow studies are conducted for all load/DG/DS scenarios.
6. Cable loading is checked against ampacity for all possible power flow scenarios.
7. Voltage profile for the most critical power flow scenario is calculated.

The maximum depth of DG penetration with and without DS units, when cable loading is at its limit, is identified for all relevant test cases.

DS Charge/Discharge Strategies

Each DE unit considered in this study is expected first to supply its local load, i.e. the primary purpose of the DE unit is load displacement. If the local load does not consume the total power produced by the DE unit(s), the extra power is exported to the up-stream substation through a feeder or a set of feeders.

The typical DS charge/discharge strategies, adopted for the required studies, are:

1. The first case is the base case where the rated power and the maximum stored energy constraints are not considered. This is equivalent to the case where the storage is large enough so none of these limits are reached. This case always results in a perfectly constant characteristic for the combined load, DS and DG power. Since the maximum stored energy limit is not considered, the DOD level is not considered either. The only parameter of the DS unit considered in this case is the efficiency. The purpose of this study type is to determine the minimum DS rating that provides an ideal distribution system performance. The actual DS rating is practically lower than the maximum power and storage energy calculated in this case.
2. The second case study is based on a realistic 1 MW NaS battery with 7.2 MWh storage capacity and 100% DOD. This case shows the performance that can be achieved based on a commercially available battery storage, without consideration for the life of the battery.
3. The third case is the same 1 MW NaS battery with 7.2 MWh storage capacity at 90% DOD. This effectively reduces the battery capacity to only 6.48 MWh. This case shows the performance that can be achieved by a commercially available DS unit while the battery life expansion is also a consideration.

Feeder types

To determine the effect of DS on the maximum depth of DG penetration, the above methodology is applied to four urban feeder types:

Feeder Type A – Residential/Industrial feeder
Feeder Type B – Residential/Industrial feeder
Feeder Type C - Residential/Commercial/Industrial feeder
Feeder Type D - Industrial feeder

The load mix for each feeder is:

Feeder Type	Contribution to Daily Peak Load (%)		
	Industrial Load	Residential Load	Commercial Load
A	30	70	0
B	37	63	0
C	30	32	38
D	100	0	0

Application of a DS unit in a rural distribution system, where the voltage drop is the main limiting factor for power flow, is presented in Appendix A.

Conclusion

The studies conclude that:

- The allowed net export power from the embedded DG unit is typically increased proportional to the size of a DS unit and fluctuation of the feeder load.
- The presence of the DS unit on the feeder can reduce load fluctuation throughout the day, and depending on the DS characteristics/ratings, the maximum feeder loading can be increased.
- Due to relatively flat industrial load profile, the ability of DS to reduce load fluctuation throughout the day is not as beneficial in the case of purely industrial load as in the case of feeders with larger residential and/or commercial loads.
- The DS unit location with respect to feeder sections with lower ampacity limits is significant. For feeder types that include several critical sections with lower cable ampacity, the DS unit should not be located between the main TS and any of the critical feeder sections.
- The location of the DS unit can change the overall system losses. The most efficient location is as close as possible to the source that charges the DS unit. The loss does not significantly change with the change of the DS unit location.
- In the case of a NaS battery, it is often not justified to run the battery with 100% DOD since a similar performance is achieved with 90% DOD while the battery life is typically doubled.
- The presence of the DS unit in rural distribution system reduces the voltage fluctuation along the feeder and allows for higher feeder loading.

Acknowledgements

We would like to thank Chad Abbey for his assistance, recommendations, evaluation of results, and continuous collaboration to complete this investigation. The authors also would like to thank Toronto Hydro for providing their feeder configurations and data for the system studies.

Introduction

This report summarizes the studies performed to evaluate impact of integration of Distributed Storage (DS) in an Electrical Distribution Systems (EDS) and its impact on the depth of penetration of Distributed Generation (DG).

Increasing the level of DG units is the main purpose of integrating DS in the study system. In general, energy storage systems use electricity during non-peak hours or from intermittent sources, and the stored energy is converted back to electricity for the loads during peak periods. The price difference between energy during peak and off-peak hours is the main motivation for installing DS units.

Presence of DS units reduces the difference between the minimum and the maximum power demand. This results in a better utilization of the distribution system infrastructure and permits higher depth of DG penetration.

To model a DS unit we assume that the storage media is capable of accepting energy, regardless of the state of the charge (SOC) of the battery storage, up to the full capacity. The maximum charging and discharging power levels should not be exceeded, whenever specified.

It is assumed that the DS unit charge/discharge strategy is designed to minimize the difference between the minimum and the maximum combined power of the load, DG units, and the DS unit.

Three types of loads, i.e.: industrial, residential, and commercial are considered.

Four urban feeder types, based on load mix and configuration are considered:

Feeder Type A – Residential/Industrial feeder
Feeder Type B – Residential/Industrial feeder
Feeder Type C - Residential/Commercial/Industrial feeder
Feeder Type D - Industrial feeder

The methodology for analyzing the effect of integration of a DS in an EDS is presented in Section 1.

Based on the methodology presented in Section 1, each feeder type is analyzed and the results are presented in Section 2. Case studies are performed using the CYMDIST software platform to calculate power flow and voltage throughout the distribution system. The results, from each test case, are summarized at the end of the corresponding subsection.

Section 3 of the report provides a list of general conclusions arising from the report.

To address the specific issues specific to rural feeders (voltage drop as a limiting factor), the application of distributed storage in rural distribution system is addressed in Appendix A.

1. Methodology

To determine the effects of DS on the distribution system and the impact on the maximum depth of DG penetration, we assume that:

- the efficiency of each DS unit is less than 100%,
- customers with DG and/or DS units do not export reactive power to the system,
- the fault contribution of each DS unit is negligible,
- feeder loading is a mix of industrial, commercial and residential customers,
- typical daily load diagram for each customer group is pre-specified,
- load power factor is between unity and 0.9 lagging at all busses,
- each feeder cable ampacity is not exceeded.

To determine the maximum depth of DG penetration in each feeder:

1. A typical day is divided into a number of time intervals and within each interval the load and the DG output of the feeder remain constant.
2. A particular load profile (industrial, commercial or residential) is applied at each bus, depending on the type of the customer connected to the bus.
3. All load/DG scenarios are simulated with and without DS units in service.
4. Three different options for DS capacity are considered:
   a) A DS without power and storage capacity constraints,
   b) A DS is a typical 1 MW NaS battery with 7.2 MWh storage capacity and 100% DOD,
   c) A DS is a typical 1 MW NaS battery with 7.2 MWh storage capacity and 90% DOD.
5. Power flow studies are conducted for all possible load/DG/DS scenarios.
6. Cable loading is checked against ampacity for all power flow scenarios.
7. Voltage profile for the most critical power flow scenario is calculated.

The maximum depth of DG penetration with and without DS units, when cable loading is at its limit, is identified for all relevant test cases.

1.1 Typical Load Profiles

Typical spring mid-week load profiles for the three load categories (industrial, commercial and residential) are shown on Figure 1.1. The load profiles are shown as a percentage of the daily peak load for each category, so that the peak power for each curve is 100%. For each feeder, the total load is a mix of these three categories. The percentage for each category depends on the feeder type.

Based on the typical load diagrams from Figure 1.1, the approximate daily load diagrams, using ten constant-load segments, are constructed (ten-interval load curve). The approximated load diagrams, superimposed on the typical load diagrams, are shown on Figures 1.2 to 1.4.

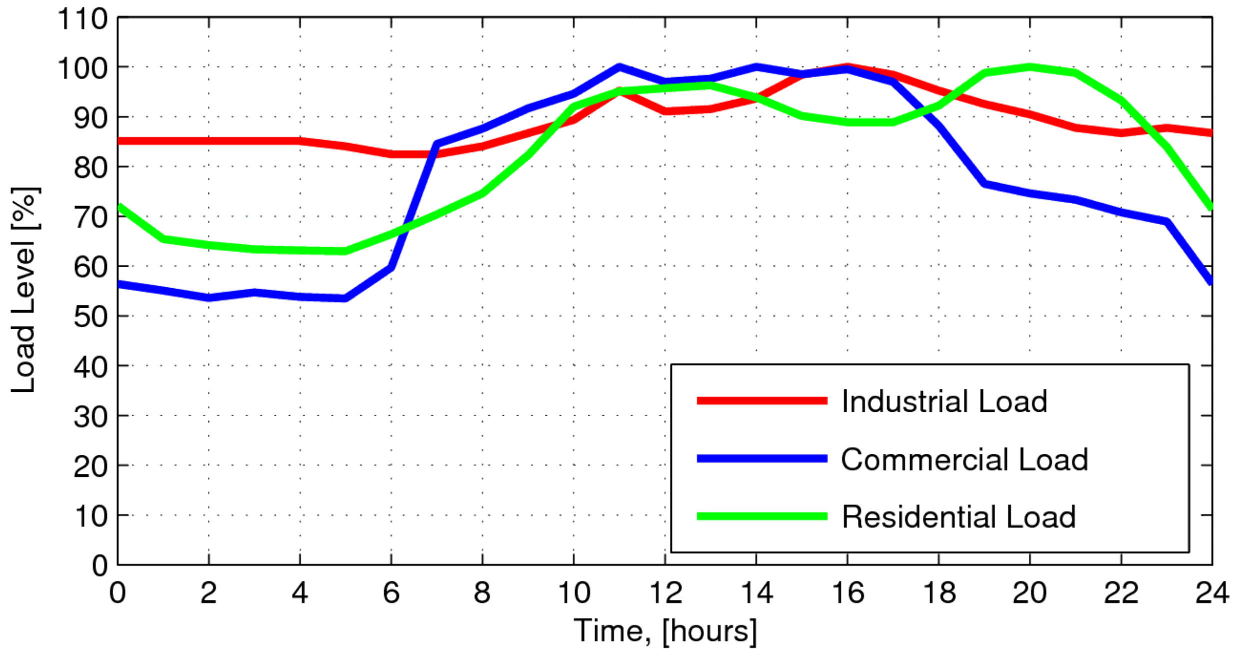

Figure 1.1 Typical spring mid-week load profiles for the three load categories

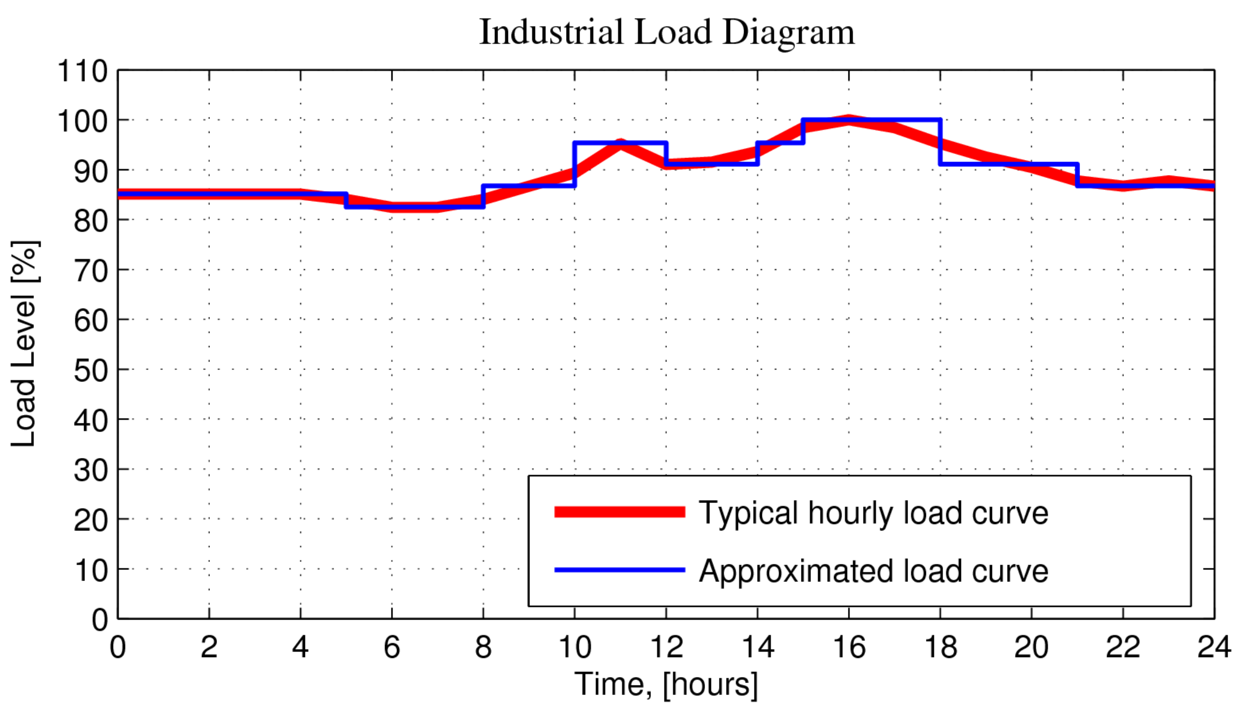

Figure 1.2 The approximated spring mid-week diagram for the industrial load

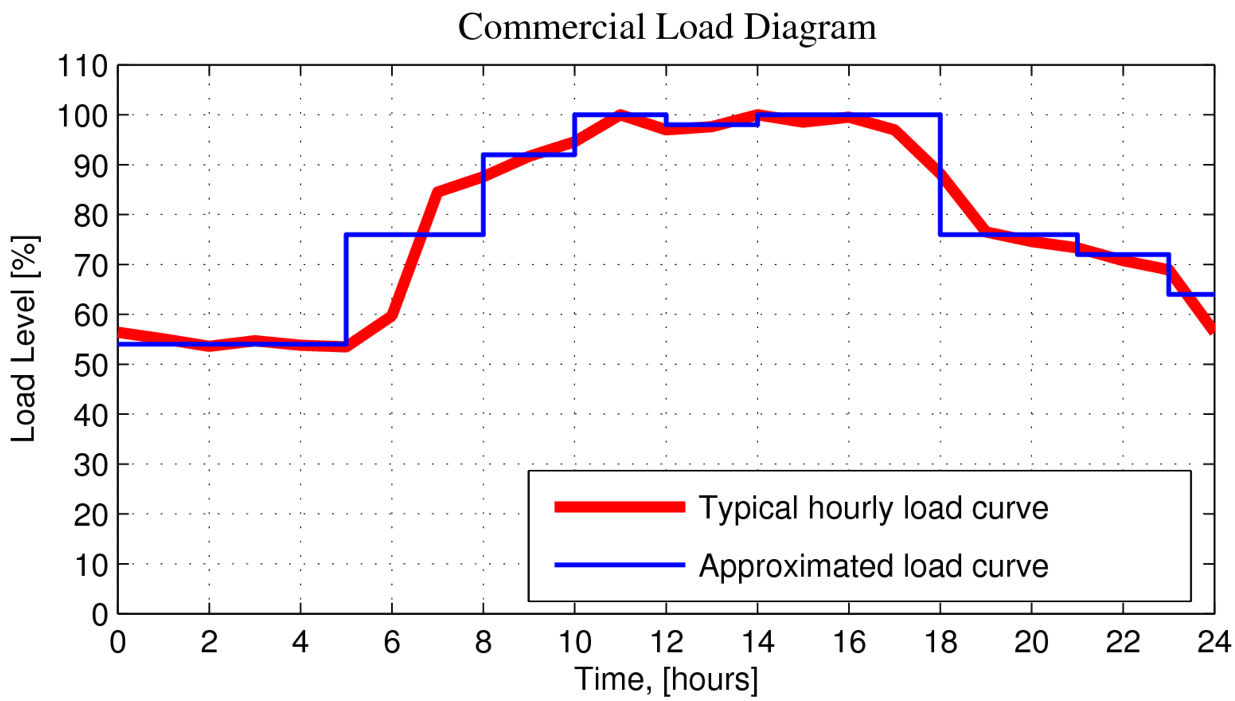

Figure 1.3 The approximated spring mid-week diagram for the commercial load

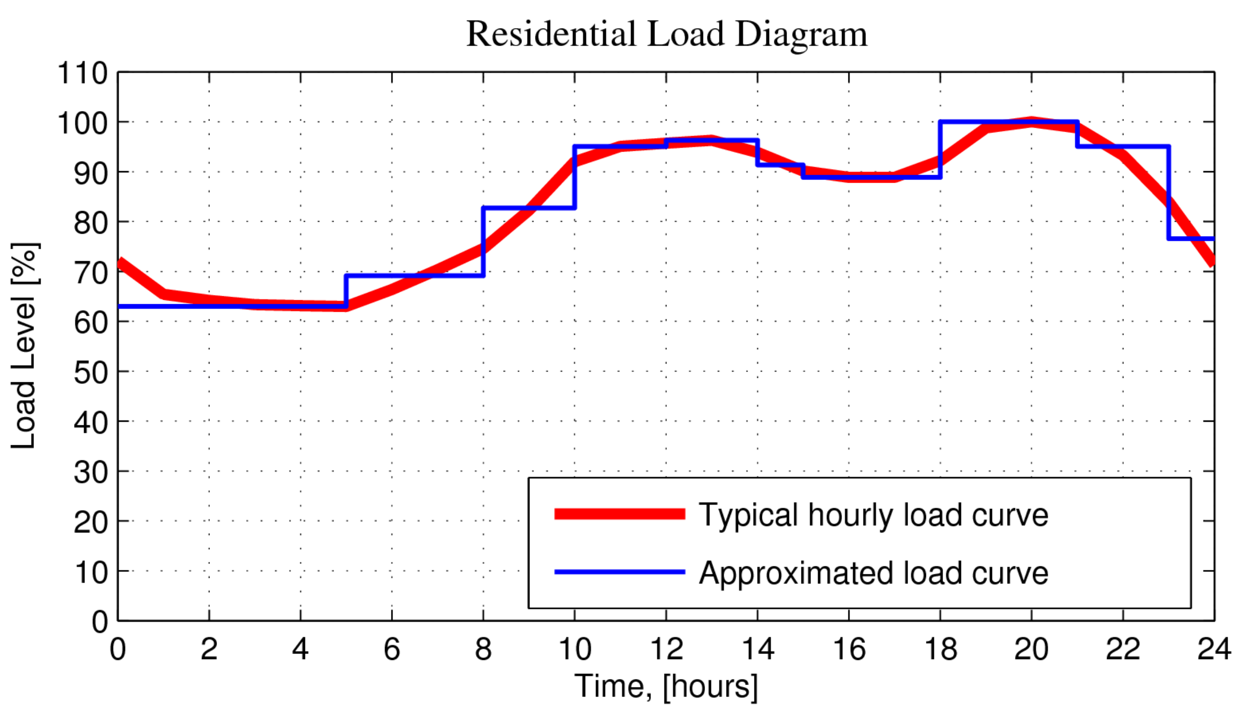

Figure 1.4 The approximated spring mid-week diagram for the residential load

The ten-interval spring mid-week load diagrams, for the industrial, commercial and residential loads, used in this study, are summarized in Table 1.1. The magnitude corresponding to each segment is given as the percentage of the peak value.

Table 1.1 Ten-level relative load diagrams used in the study

Time Period (hours)		Industrial Load, $\mathscr{L}_{\mathbf{I}}(\boldsymbol{t})$	Commercial Load, $\mathscr{L}_{\mathbf{C}}(\boldsymbol{t})$	Residential Load, $\mathscr{L}_{\mathbf{R}}(\boldsymbol{t})$
From	To			
0	5	85.17%	54.00%	62.96%
5	8	82.48%	76.00%	69.14%
8	10	86.73%	92.00%	82.72%
10	12	95.40%	100.00%	95.06%
12	14	91.07%	98.00%	96.30%
14	15	95.40%	100.00%	91.36%
15	18	100.00%	100.00%	88.89%
18	21	91.07%	76.00%	100.00%
21	23	86.73%	72.00%	95.06%
23	24	86.73%	64.00%	76.54%

1.1.1 Procedures to Determine a Combined Load Diagram

Based on the data from Table 1.1 and the pre-specified contribution of each load category to the daily peak, the combined load diagram for each feeder is determined.

Let us assume that the time of the daily load peak is $\boldsymbol{t}_{\max}$ and the contribution of each load category to the daily peak load is $\boldsymbol{P}_{\max\mathbf{I}}$ for the industrial load, $\boldsymbol{P}_{\max\mathbf{C}}$ for the commercial load, and $\boldsymbol{P}_{\max\mathbf{R}}$ for the residential load. The feeder combined load diagram, $\boldsymbol{P}_{\text{Feeder}}(\boldsymbol{t})$, is calculated as:

$$\boldsymbol{P}_{\text{Feeder}}(\boldsymbol{t}) = \frac{\boldsymbol{P}_{\max\mathbf{I}}}{\mathscr{L}_{\mathbf{I}}(\boldsymbol{t}_{\max})} \cdot \mathscr{L}_{\mathbf{I}}(\boldsymbol{t}) + \frac{\boldsymbol{P}_{\max\mathbf{C}}}{\mathscr{L}_{\mathbf{C}}(\boldsymbol{t}_{\max})} \cdot \mathscr{L}_{\mathbf{C}}(\boldsymbol{t}) + \frac{\boldsymbol{P}_{\max\mathbf{R}}}{\mathscr{L}_{\mathbf{R}}(\boldsymbol{t}_{\max})} \cdot \mathscr{L}_{\mathbf{R}}(\boldsymbol{t})$$

In the above equation $\mathscr{L}_{\mathbf{I}}(\boldsymbol{t})$, $\mathscr{L}_{\mathbf{C}}(\boldsymbol{t})$, and $\mathscr{L}_{\mathbf{R}}(\boldsymbol{t})$ are coefficients defined in Table 1.1. For example, if the feeder peak load is experienced at 11am, at 10 MW, and consists of 20% industrial, 50% commercial, and 30% residential load, the feeder daily load diagram is:

$$\boldsymbol{P}_{\text{Feeder}}(\boldsymbol{t}) = \frac{2\text{ MW}}{95.40\%} \cdot \mathscr{L}_{\mathbf{I}}(\boldsymbol{t}) + \frac{5\text{ MW}}{100.00\%} \cdot \mathscr{L}_{\mathbf{C}}(\boldsymbol{t}) + \frac{3\text{ MW}}{95.06\%} \cdot \mathscr{L}_{\mathbf{R}}(\boldsymbol{t})$$

A feeder daily load diagram and the contribution of each load category for this example is shown on Figure 1.5.

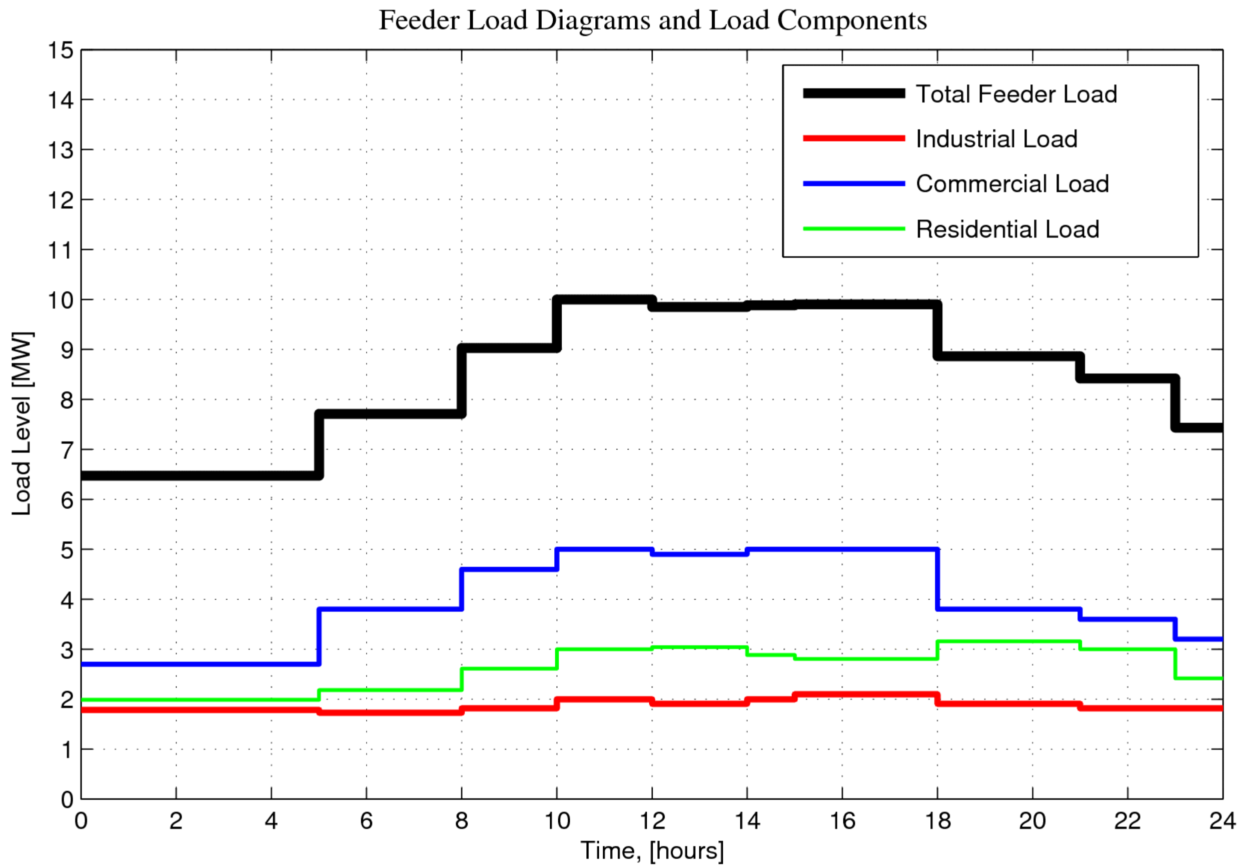

Figure 1.5 Sample feeder daily load diagram

1.2 Distributed Storage Charge/Discharge Strategy

Increasing the level of DG units is the main purpose of integrating a DS unit in the study system. In general, energy storage systems use electricity during non-peak hours or from intermittent sources, and the stored energy is converted back to electricity for the loads during peak periods. The price difference between energy during peak and off-peak hours is the main motivation for installing DS units.

Presence of DS units reduces the difference between the minimum and the maximum power demand. This results in a better utilization of the distribution system infrastructure and permits higher depth of DG penetration.

To model a DS unit we assume that the storage media is capable of accepting energy, regardless of the state of charge (SOC) of the storage, up to the full capacity. The maximum charging and discharging power levels should not be exceeded, whenever specified.

It is assumed that the DS unit is to minimize the difference between the minimum and the maximum combined power of the load, DG units, and the DS unit.

The following technical parameters of a DS unit will be considered as constraints for the DS charge/discharge strategy:

- rated power,
- maximum stored energy,
- efficiency,
- depth of discharge (DOD).

For a given type of battery, the DOD level may significantly affect the maximum number of charge-discharge cycles that the storage device is capable of. For example, the manufacturer of the NaS battery suggests that by lowering the DOD level from the maximum of 100% to 90% the maximum number of charge-discharge cycles over the battery lifetime can be doubled.

The typical DS charge/discharge strategies, adopted for the required studies, are:

1. The first case is the base case where the rated power and the maximum stored energy constraints are not considered. This is equivalent to the case where the storage is large enough so none of these limits are reached. This case always results in a perfectly constant characteristic for the combined load, DS and DG power. Since the maximum stored energy limit is not considered, the DOD level is not considered either. The only technical parameter of the DS unit considered in this case is the efficiency. The purpose of this study type is to determine the minimum DS rating that provides an ideal distribution system performance. The actual DS rating is practically lower than the maximum power and the storage energy calculated in this case.
2. The second case study is based on a realistic 1 MW NaS battery with 7.2 MWh storage capacity and 100% DOD. This case shows the performance that can be achieved based on a commercially available battery storage, without consideration for the life of the battery.
3. The third case is the same 1 MW NaS battery with 7.2 MWh storage capacity at 90% DOD. This effectively reduces the battery capacity to only 6.48 MWh. This case shows the performance that can be achieved by a commercially available DS unit while extending the life of the battery is also a consideration.

For all cases, the load profile from Figure 1.5 is used.

1.2.1 DS Storage Capacity and Power Constraints are not Considered

In this case, the DS unit is considered to be larger, in terms of both energy storage capacity and the maximum power rating, than the amounts required. The average storage AC-to-AC efficiency of 70% is also considered for this case. When such a DS unit is connected to the feeder, it is possible to ideally level the combined power of the load, the DG unit, and the DS unit to a constant power level throughout the day. The daily load diagram of such a system, with and without the DS unit, is shown on Figure 1.6. When the storage is not in service, the load diagram is the same as the profile shown on Figure 1.5. With the presence of the DS unit, the load can be leveled to the constant power level of 9 MW, i.e. effectively reducing the peak power requirement from 10 MW, by 10%.

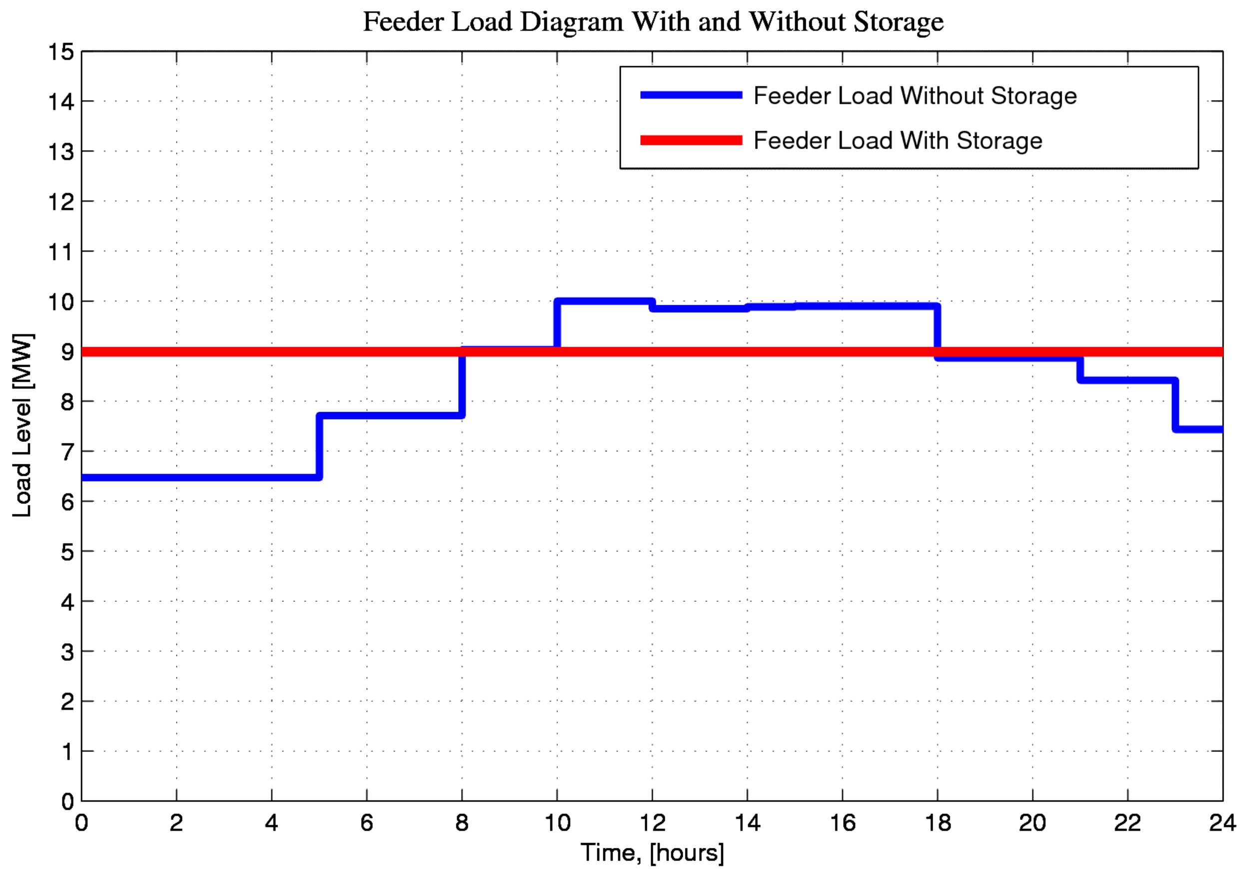

Figure 1.6 Feeder daily load diagram with and without DS (without power and energy constraints)

In this example, the DS unit is charged from 6pm to 8am the next day. The energy stored during the charging period is returned to the system from 10am to 6pm. The ratio between the energy returned to the grid (DS generation) and energy taken from the grid (DS charging) is the storage efficiency, which is 70% for the studied case.

1.2.2 1 MW NaS Battery with 7.2 MWh Storage Capacity (100% DOD)

The 1 MW NaS battery, based on the main technical data as shown in Table 1.2, is connected to the feeder. An average charge/discharge efficiency of 80% for the storage system (on AC side) is considered. This corresponds to a charge/discharge efficiency of 85% at the battery DC terminals.

Table 1.2 Main Electrical Specifications for NGK 1 MW, 7.2 MWh NaS Battery

Rated Power	DC 1.05 MW (nominal)	(AC 1 MW)
	DC 1.26 MW for 3 Hrs	(AC 1.2 MW)
Charge	DC 1.14 MW	(AC 1.2 MW)
Stored Energy	DC 7.2 MWh	

When the battery is connected to the feeder, it is not generally possible to level the combined power of the load, the DG unit, and the DS unit to a constant value throughout the day. The daily peak can be reduced to approximately 9 MW by using the 1 MW NaS battery, Table 1.2. The daily load diagram of such a system, with and without the DS unit in service, is shown on Figure 1.7. When the storage is not used, the load diagram is the same as the one shown on Figure 1.5. The efficiency of the DS unit in this example is significantly higher than that of the previous example. However, because of the power and the energy constraints, the peak reduction is almost the same.

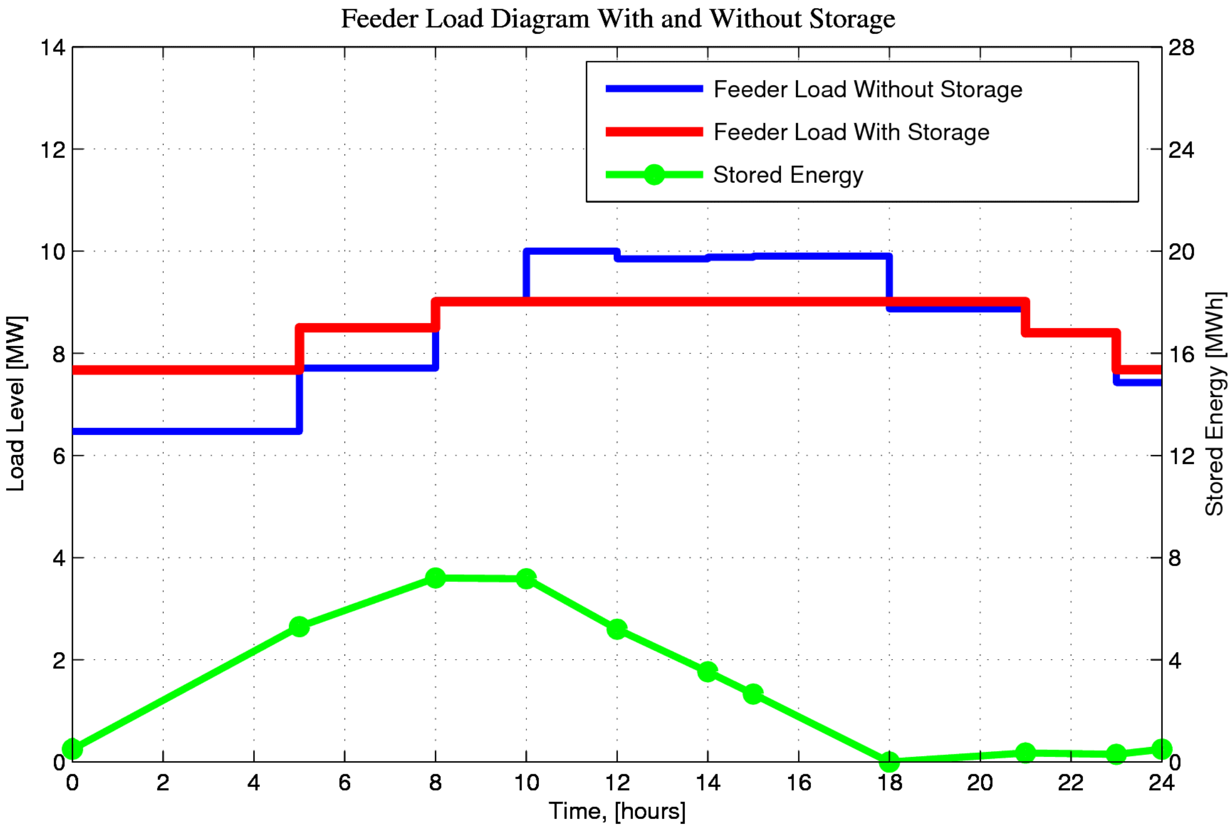

Figure 1.7 Feeder daily load diagram with and without DS (1 MW, 7.2 MWh, 100% DOD)

The storage and generation modes of the DS unit for this example are illustrated on Figure 1.8. From 5am to 8am the DS unit is in the charging mode with a power level that is less than the maximum charging power. The same is true for time periods 6pm to 9pm and 11pm to midnight. Charging power may be shifted from one of these time segments to another without affecting the daily power fluctuations. The final choice of the DS charge/discharge strategy is affected and should be decided based on detailed DS specifications (e.g. impact of charging power on efficiency) or time-of-day price of electric energy.

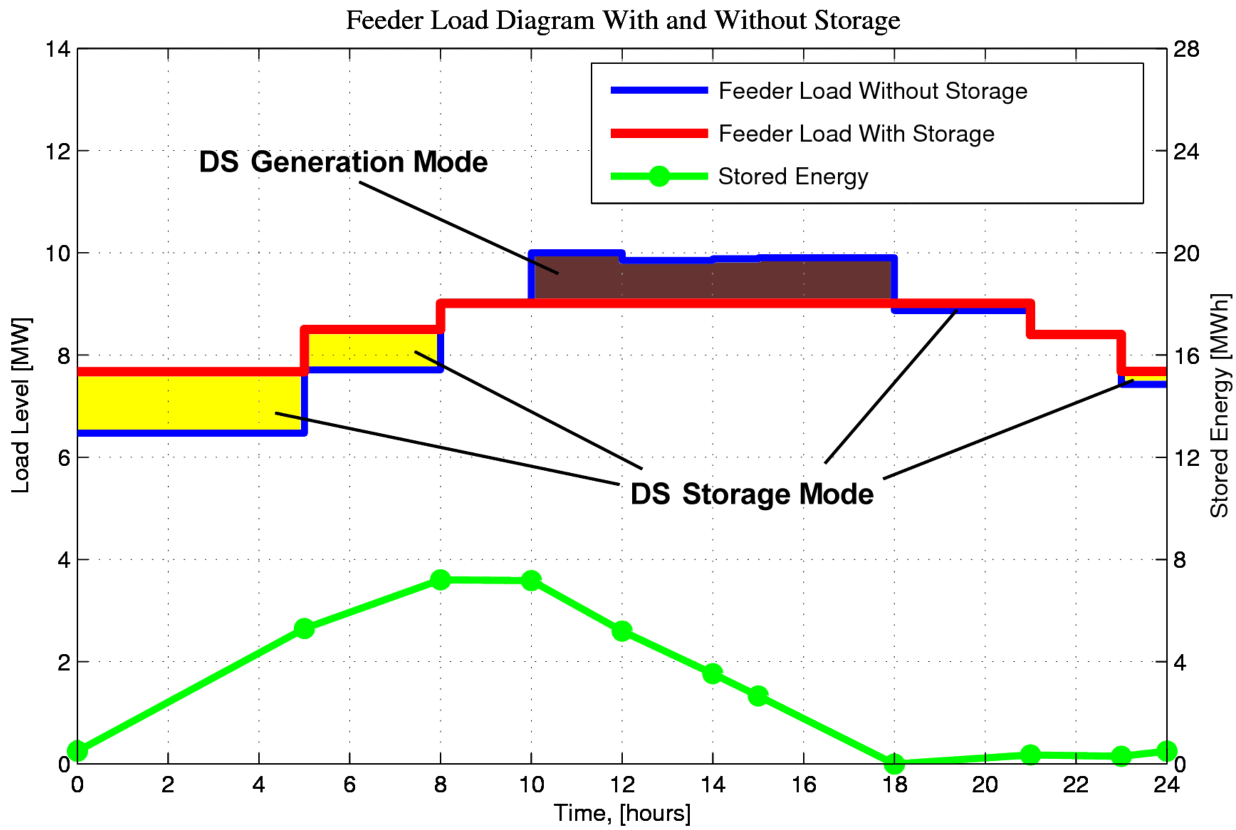

Figure 1.8 DS storage and generation modes (1 MW, 7.2 MWh, 100% DOD)

1.2.3 1 MW NaS battery with 7.2 MWh storage capacity (90% DOD)

The same 1 MW NaS battery described in the previous case is connected to the feeder while its DOD is assumed to be limited to 90%. This case is considered since the lifetime and the number of charge-discharge cycles for the NaS battery is significantly higher if the DOD does not exceed 90%. The available stored energy of the DS unit is thus reduced by 10%, to 6.48 MWh.

In this case study, the equivalent daily peak power is 9.1 MW. The daily load diagrams of the system, with and without the DS unit in service, are shown on Figure 1.9.

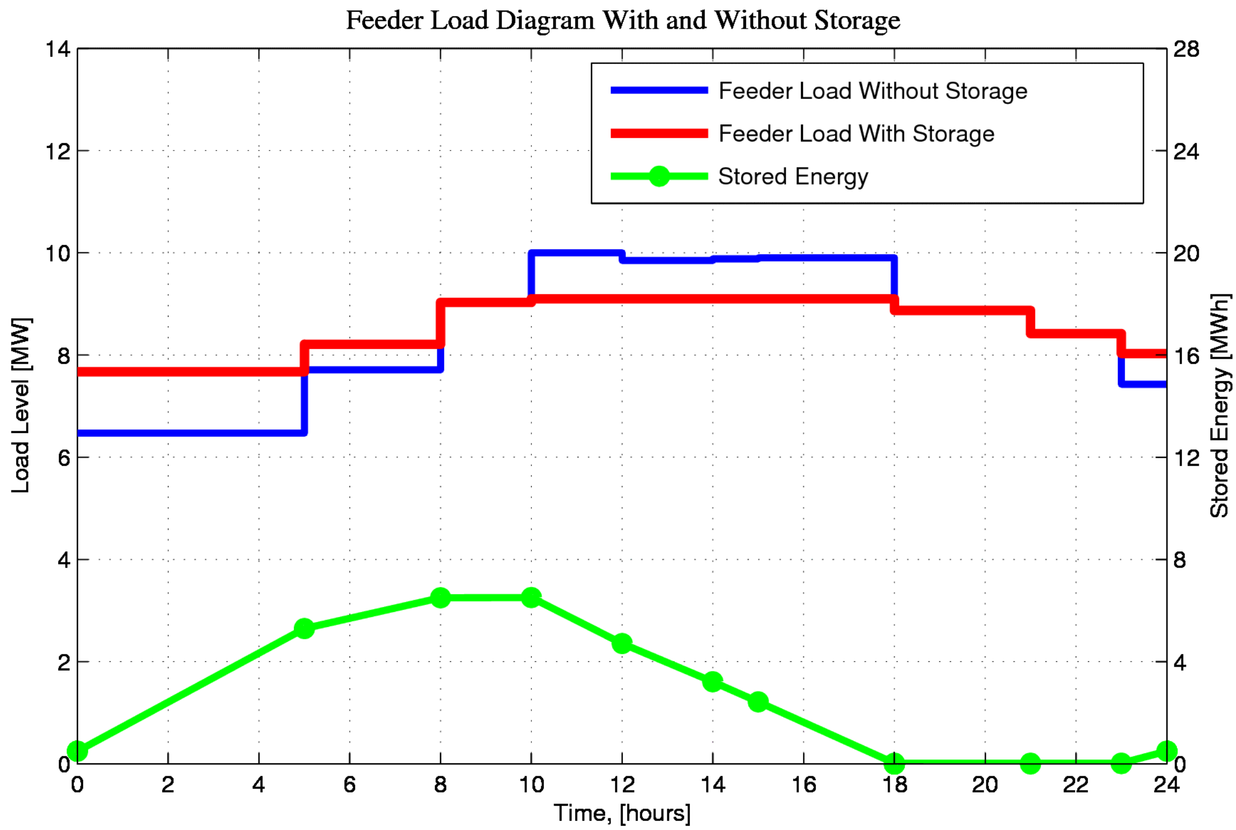

Figure 1.9 Feeder daily load diagram with and without DS (1 MW, 7.2 MWh, 90% DOD)

1.3 Evaluation of DG and DS Impact on Cable Ampacity and Voltage Drop

Each DE unit considered in this study is expected first to supply its local load, i.e. the primary purpose of the DE unit is load displacement. If the local load does not consume the total power produced by the DE unit(s), the extra power is exported to the up-stream substation through a feeder or a set of feeders. This indicates that the total power of the locally installed DG units may exceed the net export power. Under the extreme condition, when there is no local load, the net export power through a feeder (or feeders) is determined by the corresponding cable ampacity limits and voltage drop (negative in this case).

The worst-case power flow scenario with respect to voltage drop and cables ampacity limits is associated with the minimum load, and the maximum voltage of the TS bus. In this scenario real power flows from DE units to the main substation, and voltage at the customer PCC is higher than that of the main substation. If the load(s) are connected to the customer bus, power flow through the cable is reduced and both cable ampacity and voltage drop (increase in this case) become less critical.

2. Case Studies

The methodology described in Section 1, to determine the effect of DS on the maximum depth of DE penetration, is applied to four feeder types:

Feeder Type A - Residential/Industrial feeder
Feeder Type B - Residential/Industrial feeder
Feeder Type C - Residential/Commercial/Industrial feeder
Feeder Type D - Industrial feeder

Typical load diagrams for the industrial, commercial and residential loads are taken from Table 1.1. Each individual load belongs to either the industrial, the commercial or the residential category. The contribution of each load category to the total feeder loading is given in Table 2.1.

Table 2.1 Contribution of Load Categories to Daily Peak Load

Feeder Type	Contribution to Daily Peak Load (%)		
	Industrial Load	Residential Load	Commercial Load
A	30	70	0
B	37	63	0
C	30	32	38
D	100	0	0

The following scenarios are analyzed for each feeder:

Battery Option 1 – No energy storage is available

The first set of studies is performed under the assumption that there is no storage unit in the system. The following scenarios are considered:

Conventional operation

a) ***Normal daily loading*** – A typical daily load diagram based on Tables 1.1 and 2.1 is assumed. No DG units are included in the distribution system.

b) ***The maximum allowable feeder loading*** - Based on the feeder cable ampacity, the maximum allowable feeder loading is determined. The Relative load diagram is the same as the typical load diagram based on Tables 1.1 and 2.1. No DG units are included in the distribution system.

Permissible power export

c) ***Normal daily loading*** - A typical daily load diagram based on Tables 1.1 and 2.1 is assumed. One DG unit is connected to the feeder. The maximum allowed DG capacity is determined, so that the power export from the feeder is less than or equal to the prescribed value of 5 MW at all times.

Maximum power export

d) ***Normal daily loading*** - A typical daily load diagram based on Tables 1.1 and 2.1 is assumed. One DG unit is connected to the feeder. The maximum DG exported power that does not overload the feeder is determined.

Battery Option 2 – Generic case with no power or energy limits

The second set of studies is performed under the assumption that one large distributed DS unit is used, and power and energy limitations are not considered. An AC efficiency of 70% is assumed for this generic case.

Conventional operation

a) ***The maximum allowable feeder loading*** - Based on the feeder cable ampacity, the maximum allowed peak loading is determined. The relative load diagram applicable for a feeder under consideration (based on Tables 1.1 and 2.1) is then scaled so that the peak load is the same as the maximum allowed peak loading. One DS unit is connected to the feeder. The optimal DS location, the required storage power, and the required storage energy to maximize the allowable feeder loading are determined.

Permissible power export

b) ***Normal daily loading*** - A typical daily load diagram based on Tables 1.1 and 2.1 is assumed. One DG unit and one DS unit are connected to the feeder. The maximum power export from the feeder (e.g. 5 MW) is specified by the utility. The optimal DS location, the required storage power, and the required storage energy to maximize the DG export power are determined.

Maximum power export

c) ***Normal daily loading*** - A typical daily load diagram based on Tables 1.1 and 2.1 is assumed. One DG unit and one DS unit are connected to the feeder. The maximum power export from the feeder is obtained when the current reaches the ampacity limit on any one of the feeder section. The optimal DS location, the required storage power, and the required storage energy to maximize the DG export power are determined.

Battery Option 3 – 1 MW NaS Battery (with 7.2 MWh storage capacity), 100% DOD

The third set of studies is performed under the assumption that one large storage unit is used and power and energy limitations are imposed based on a typical 1 MW NaS battery with an AC efficiency of 80%. The DOD is assumed to be 100%, so all 7.2 MWh of the storage is available.

Conventional operation

a) ***The maximum allowable feeder loading*** - Based on the feeder cable ampacity, the maximum allowable feeder loading is determined. The Relative load diagram is the same as the typical load diagram based on Tables 1.1 and 2.1. One DS unit is connected to the feeder. The optimal DS location, the required storage power, and the required storage energy to maximize the allowable feeder loading are determined.

Permissible power export

b) ***Normal daily loading*** - A typical daily load diagram based on Tables 1.1 and 2.1 is assumed. One DG unit and one DS unit are connected to the feeder. The maximum power export from the feeder (e.g. 5 MW) is specified by the utility. The optimal DS location, the required storage power, and the required storage energy to maximize the DG export power are determined.

Maximum power export

c) ***Normal daily loading*** - A typical daily load diagram based on Tables 1.1 and 2.1 is assumed. One DG unit and one DS unit are connected to the feeder. The maximum power export from the feeder is obtained when the current reaches the ampacity limit of at least one feeder section. The optimal DS location, the required storage power, and the required storage energy to maximize the DG export power are determined.

Battery Option 4 – 1 MW NaS Battery (with 7.2 MWh storage capacity), 90% DOD

The fourth set of studies is performed under the assumption that one large storage unit is used and power and energy limitations are imposed based on the 1MW NaS battery with the AC efficiency of 80%. The DOD is assumed to be 90%, thus only 6.48 MWh of storage is available.

Conventional operation

a) ***The maximum allowable feeder loading*** - Based on the feeder cable ampacity, the maximum allowable feeder loading is determined. The Relative load diagram is the same as the typical load diagram based on Tables 1.1 and 2.1. One DS unit is connected to the feeder. The optimal DS location, the required storage power, and the required storage energy to maximize the allowable feeder loading are determined.

Permissible power export

b) ***Normal daily loading*** - A typical daily load diagram based on Tables 1.1 and 2.1 is assumed. One DG unit and one DS unit are connected to the feeder. The maximum power export from the feeder (e.g. 5 MW) is specified by the utility. The optimal DS location, the required storage power, and the required storage energy to maximize the DG export power are determined.

Maximum power export

c) ***Normal daily loading*** - A typical daily load diagram based on Tables 1.1 and 2.1 is assumed. One DG unit and one DS unit are connected to the feeder. The maximum power export from the feeder is obtained when the current reaches the ampacity limit on at least one feeder section. The optimal DS location, the required storage power, and the required storage energy to maximize the DG export power are determined.

The feeder details and the study results are given in Sections 2.1 to 2.4.

2.1 Feeder Type A - Residential/Industrial Feeder

The first feeder type analyzed in this study is a mixed Residential/Industrial feeder, Figure 2.1. The feeder includes a large number of small residential loads distributed along the feeder and one large industrial load at the middle of the feeder. The industrial load can include one large DG unit.

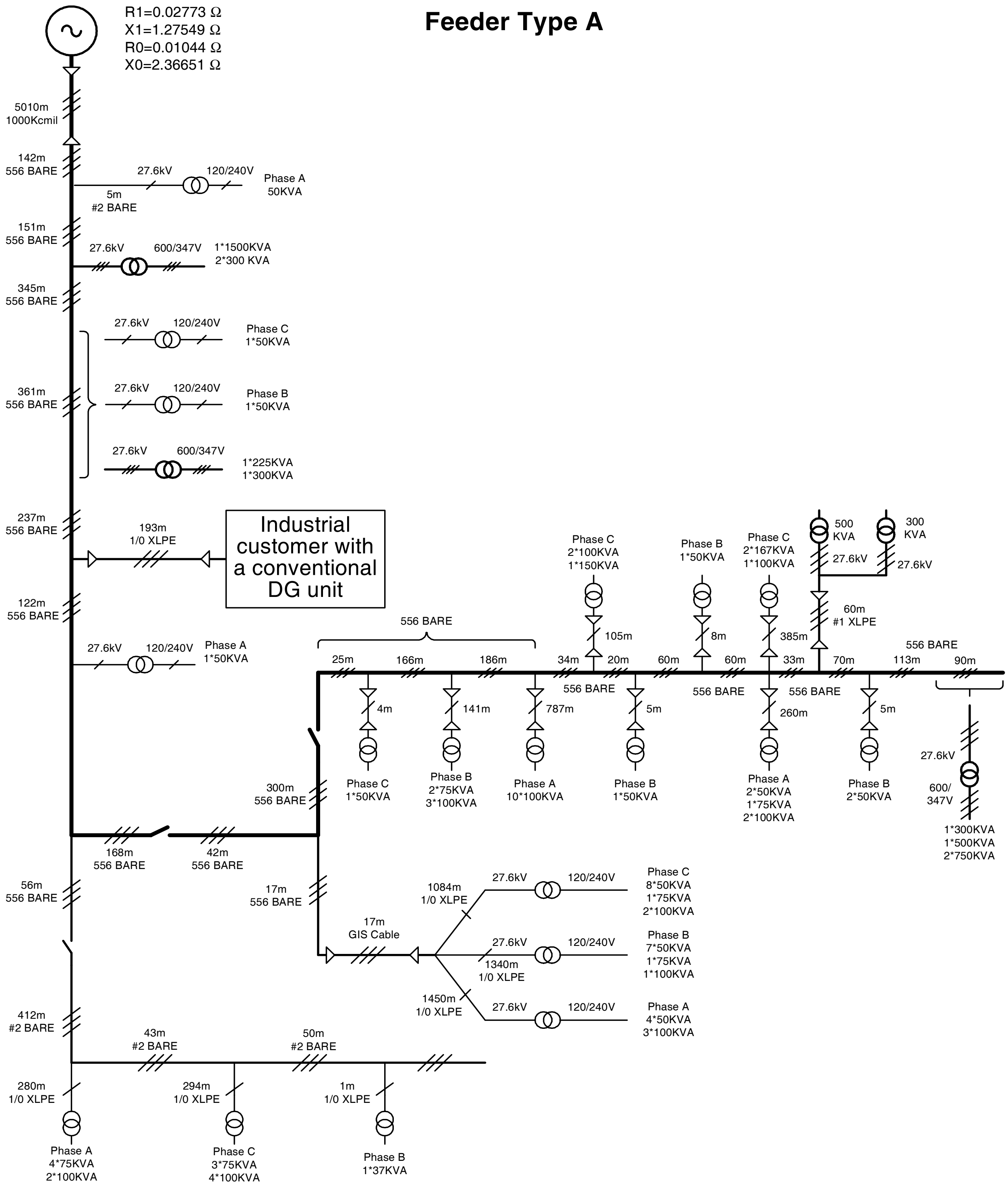

Figure 2.1 One-line diagram of Feeder Type A - Residential/Industrial Feeder

To identify the cable ampacity limits and to specify potential DS unit locations, the feeder of Figure 2.1 is divided in multiple sections, as shown in Figure 2.2. The feeder is sectionized so that there is at least one feeder section between any two major loads or a group of loads. Seven sections are used for feeder type A. The maximum feeder loading for each section is based on the cable ampacity as shown in Table 2.2. The significant part of the feeder section A1, closest to the transformer station, is the 1000 kcmil cable with the maximum current of 500 A. The minimal currents for all other sections are higher (777 A), therefore section A1 is the critical section for all cable ampacity studies.

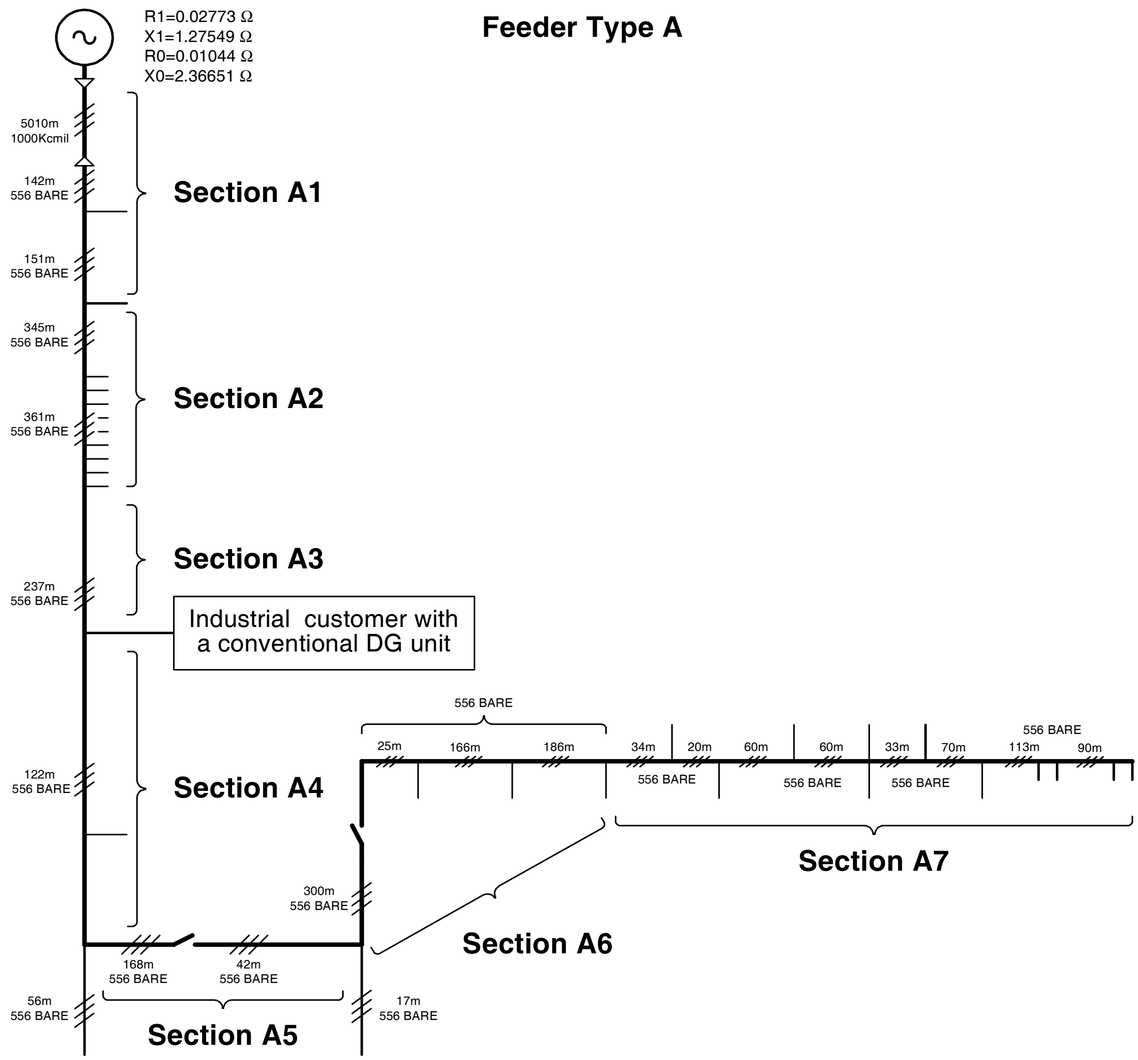

Figure 2.2 Sections of Feeder Type A - Residential/Industrial Feeder

The industrial customer that includes a conventional DG unit is located between sections A3 and A4. Three potential locations for placing a DS unit are analyzed:

- end of section A7 (at the feeder end), the extreme case where the highest losses due to DS are expected,
- end of section A3, where the major industrial load with a DG unit is located,
- end of section A1, since section A1 has the lowest cable ampacity limit (500 A).

The typical daily peak load for this feeder is 7.08 MW and the normal daily load diagram based on the typical load data from Tables 1.1 and 2.1, is given in Table 2.3.

Table 2.2 Feeder cable ampacity per section

Section number	Cable Type	Cable Ampacity (A)	Maximum Power (MW)	Section Resistance (mΩ)
A1	1000kcmil	500	23.9	618
A2	556 Bare	777	37.1	72
A3	556 Bare	777	37.1	24
A4	556 Bare	777	37.1	12
A5	556 Bare	777	37.1	21
A6	556 Bare	777	37.1	69
A7	556 Bare	777	37.1	47

Table 2.3 Normal daily load diagram for Feeder Type A - Residential/Industrial Feeder

Time Period (hours)			Industrial Load, MW	Residential Load, MW	Total Feeder Load, MW
Period #	From	To			
1	0	5	1.95	3.11	5.07
2	5	8	1.89	3.42	5.31
3	8	10	2.01	4.09	6.10
4	10	12	2.20	4.70	6.90
5	12	14	2.14	4.76	6.90
6	14	15	2.20	4.52	6.72
7	15	18	2.32	4.40	6.72
8	18	21	2.14	4.94	7.08
9	21	23	2.01	4.70	6.72
10	23	24	2.01	3.78	5.80

2.1.1 Battery Option 1 – No energy storage is available

The first set of studies is performed under the assumption that there is no storage unit in the system. The results from this case study are used as the benchmark to evaluate the study results when the system includes DS.

Conventional operation

a) ***Normal daily loading*** **-** The total feeder loading is equal to the normal daily loading from Table 2.3. The Industrial load is distributed among three-phase transformers, while the residential load is distributed among three-phase and single-phase transformers. No DG units are connected to the feeder.

   The study results provide the feeder loading (in Amperes) for each of the seven sections of Feeder Type A (as defined in Figure 2.2), and for all 10 time periods (as specified in Table 2.3). The study results are presented in Figure 2.3.

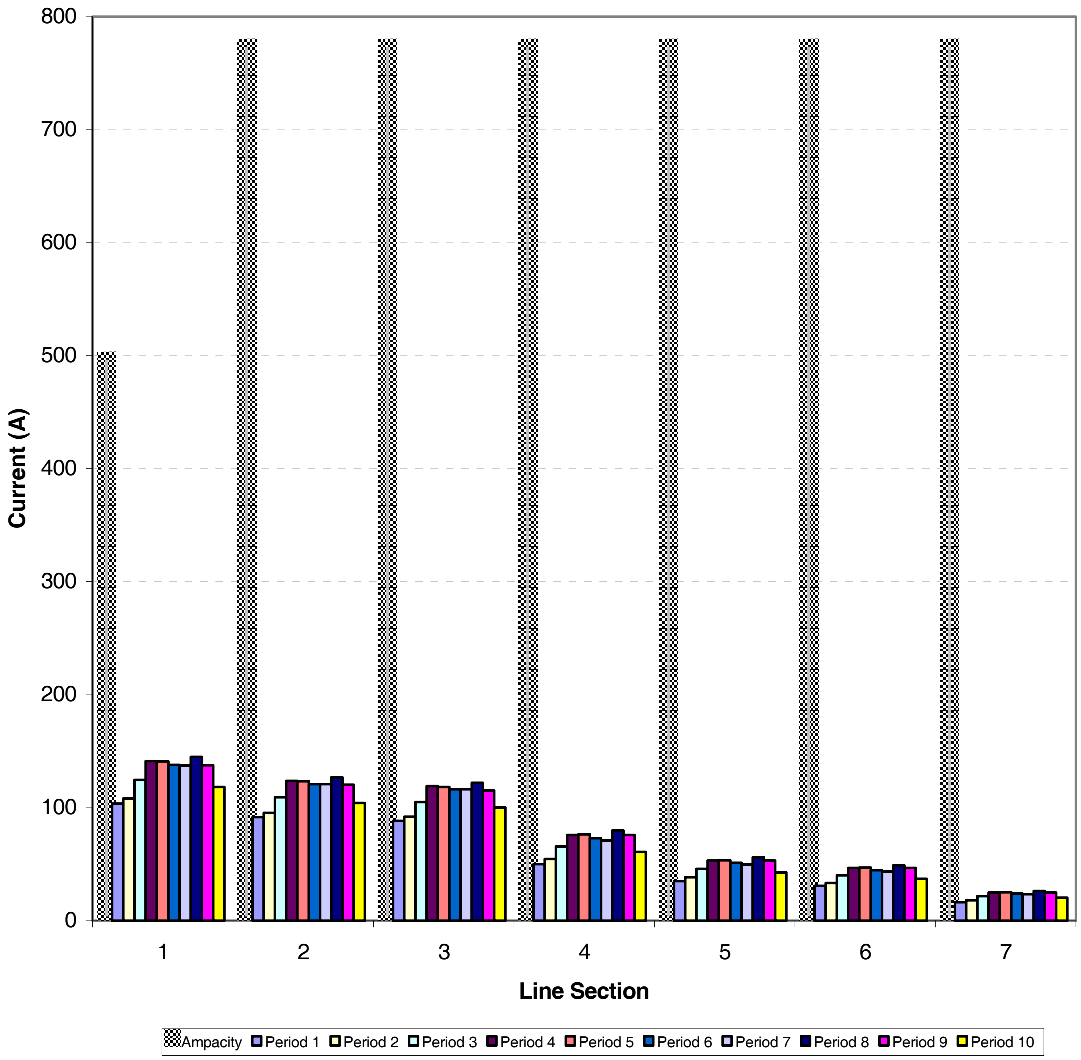

Figure 2.3 Feeder loading per section for normal loading (no DS or DG in the system)

Figure 2.3 shows a comparison of the current associated with the normal daily loading with the cable ampacity in each feeder section. All cable sections are loaded with less than 30% of the ampacity limits.

b) ***The maximum allowable feeder loading*** – The load for this case study is obtained by scaling up all individual loads of case (a) until one of the cable ampacity limits is reached. The study results for this test case are presented on Figure 2.4.

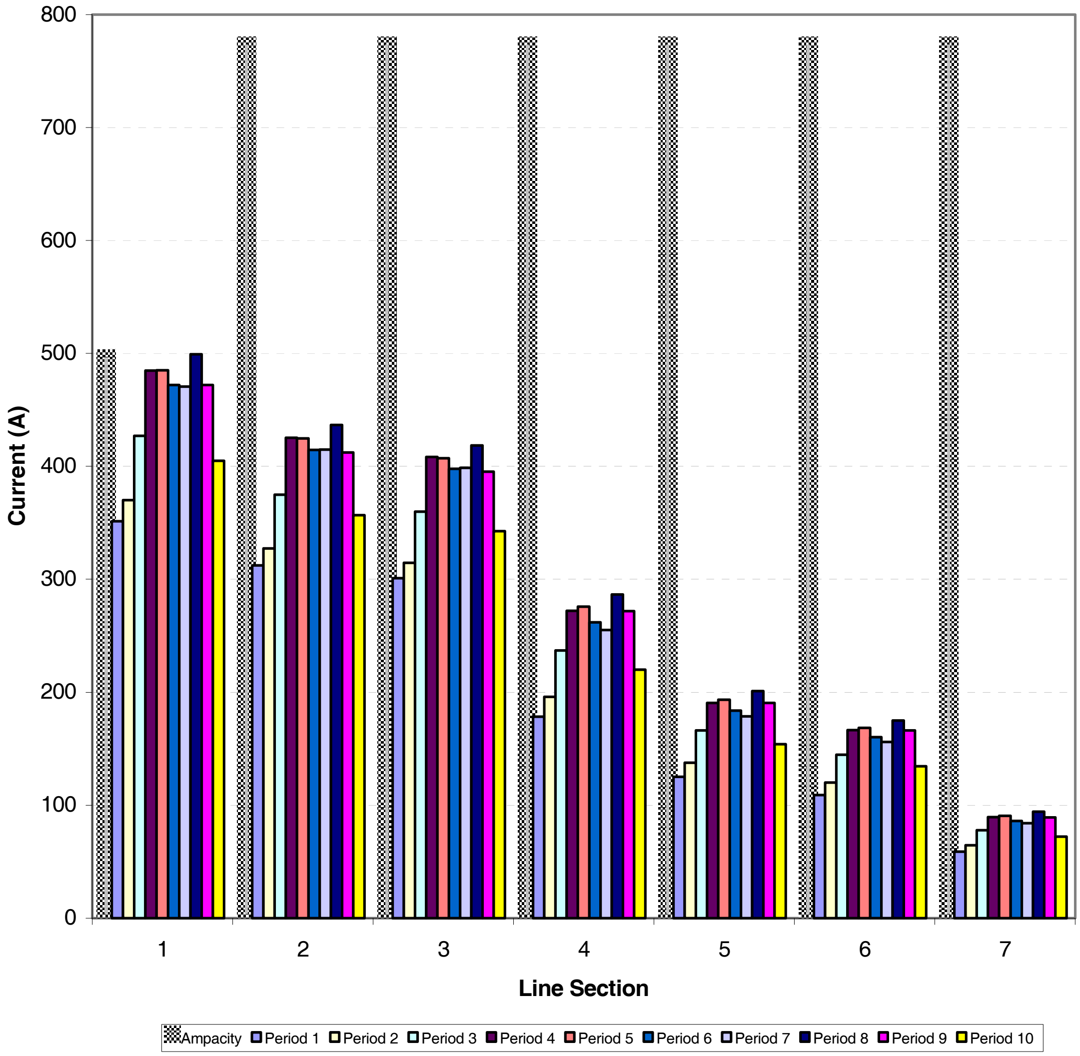

Figure 2.4 Feeder loading per section for cable ampacity loading and no DS or DG in the system

The results from Figure 2.4 show that the maximum cable loading in this case occurs on feeder section A1, during the peak power period (period #8, between 18:00 and 21:00). The total load peak power that brings the cable ampacity of the feeder section A1 to the limit is 23.9 MW, as specified in Table 2.2. The maximum voltage drop for this case is 2.6%. It is calculated at the end of Section 7, during time period #8, between 18:00 and 21:00. This scenario is associated with the highest possible voltage drop for this feeder. Since 2.6% is significantly less than the maximum allowed 6% voltage drop, we conclude that voltage drop is not a factor in any of the case studies for this feeder.

Permissible power export

A normal daily loading is assumed for the feeder of Figure 2.1. The typical daily load diagram is given in Table 2.3. One DG unit is connected to the feeder. The maximum allowed DG capacity is determined such that the power export from the feeder is either less than or equal to the value specified by the utility (e.g. 5 MW) at all times. The simulation results for this test case are presented on Figure 2.5.

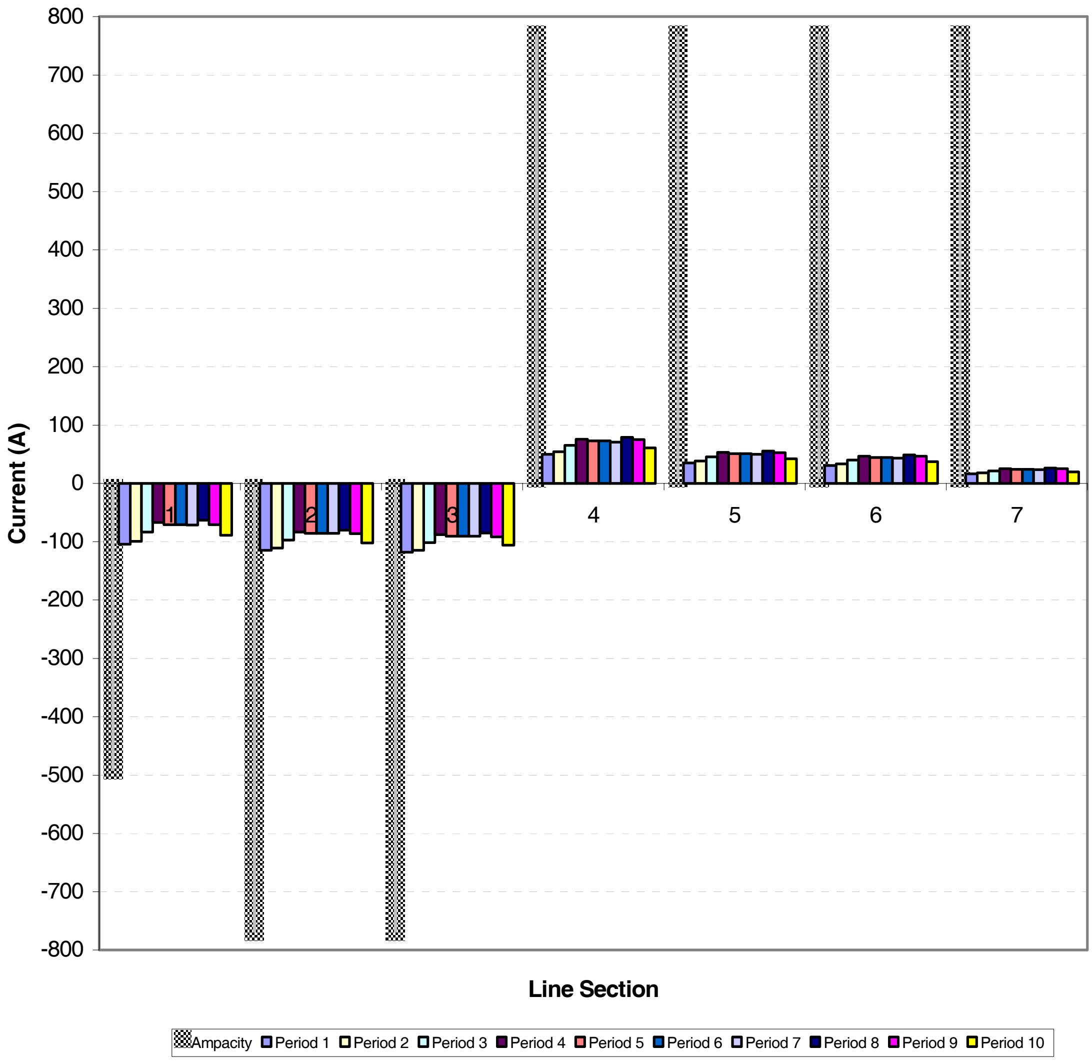

Figure 2.5 Feeder loading per section when 9.9 MW DG is installed after Section A3 and no DS is connected to the feeder

The results of Figure 2.5 show that when 9.9 MW produced by the DG unit, under the normal daily load condition, the maximum power export is 5 MW, as specified by the utility. The critical time period when the maximum power export limit is reached at night (period #1, between midnight and 5:00).

Maximum power export

A normal daily loading is assumed for the feeder of Figure 2.1. The typical daily load diagram is given in Table 2.3. One DG unit is connected to the feeder at the end of feeder section A3. The maximum allowed DG capacity is determined such that the power export from the feeder is less than the cable ampacity of the 1000 kcmil cable of the section A1 feeder. The study results for this test case are presented on Figure 2.6.

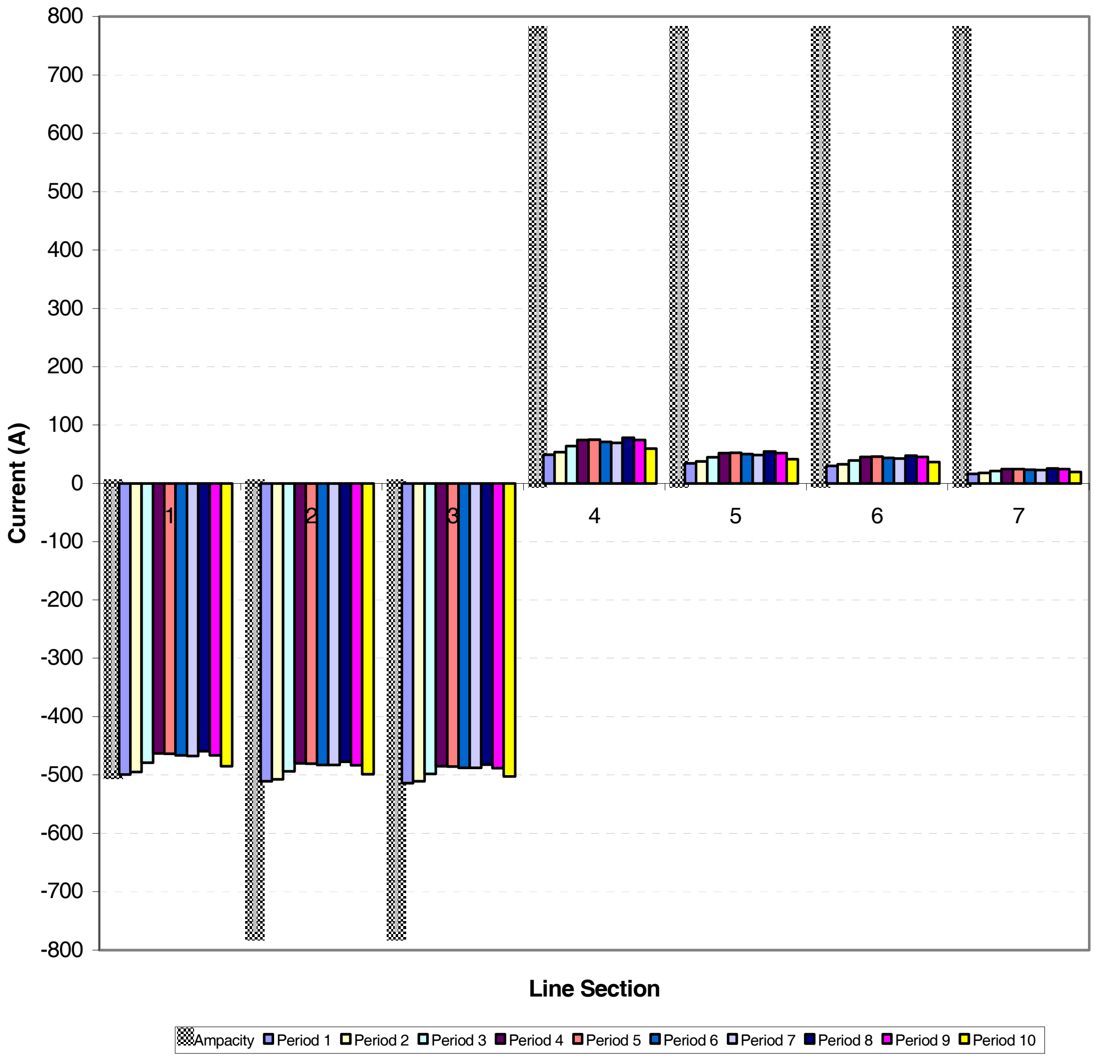

Figure 2.6 Feeder loading per section when 29.6 MW DG is installed after Section A3 and no DS is connected to the feeder

The results of Figure 2.6 show that when 29.6 MW produced by the DG unit, under the normal daily load condition, the maximum power export is 23.9 MW, which is equal to the cable ampacity of the section A1 feeder (Table 2.2). The critical time period when the maximum power export limit is reached is at night (period #1, between midnight and 5:00).

2.1.2 Battery Option 2 – Generic case with no power or energy limits

The second set of studies is performed under the assumption that one large DS unit is used and no power and energy constrains were imposed. An AC efficiency of 70% is assumed for this generic case.

Conventional operation

Based on the feeder cable ampacity (Table 2.2), the maximum permissible power in section A1 is 23.9 MW. In the case study of Figure 2.4, without storage the daily peak is equal to the maximum permissible power in section A1 (23.9 MW). By placing the DS unit on the feeder, the maximum load can be increased. Figure 2.7 shows the effect of storage charge/discharge control strategy based on the procedure of Section 1.2.1.

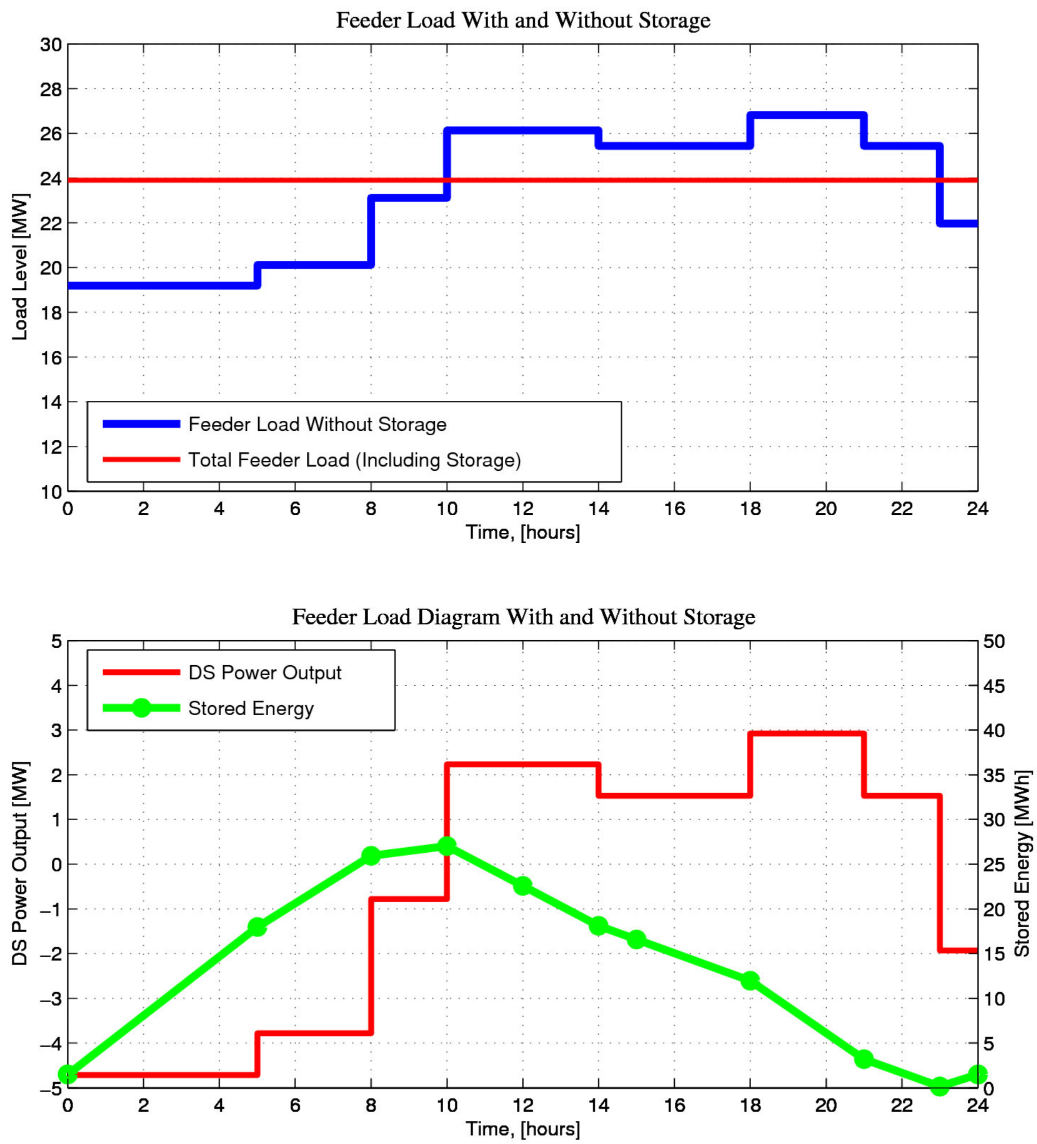

Figure 2.7 DS charge/discharge strategy and the effect of DS unit on feeder loading

On Figure 2.7, the permissible daily peak load in the presence of the DS unit can be increased to 26.8 MW, compared to 23.9 MW for the case without the storage. The total energy produced by the DS unit during the battery discharge period is 70% of the consumed energy during the battery charge period. To achieve the storage charge/discharge performance characteristic of Figure 2.7, the DS unit rating should be:

- the maximum charging power of 4.71 MW,
- the maximum discharging power of 2.92 MW,
- the storage capacity of 27.02 MWh.

As explained before, three locations are considered for the DS unit:

- end of section A7, the case where the highest losses due to DS are expected (Figure 2.8),
- end of section A3, where the major industrial load with a DG is located (Figure 2.9),
- end of section A1, since it has the lowest cable ampacity limit (Figure 2.10).

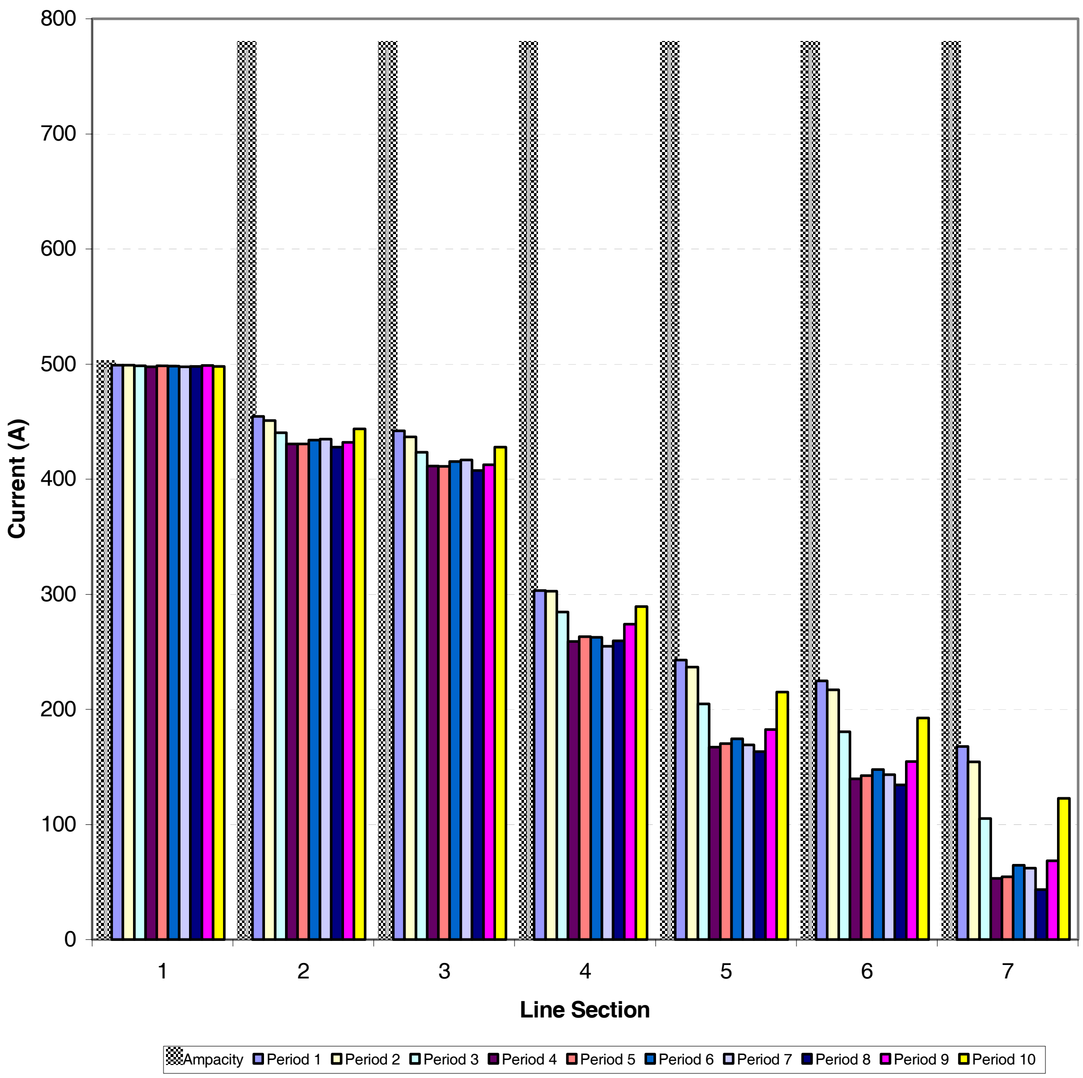

Figure 2.8 Feeder loading per section for cable ampacity loading with one DS unit (70% efficiency and no power/energy limits), located after section A7 and no DG in the system

Figure 2.8 shows that locating the DS unit at the end of the feeder (after section 7) reduces the feeder loading on all feeder sections during the mid-day period. This results in a higher total load limit (26.8 MW), compared to the case without the storage (23.9 MW). The feeder loading at night is increased on all sections (due to the DS charging).

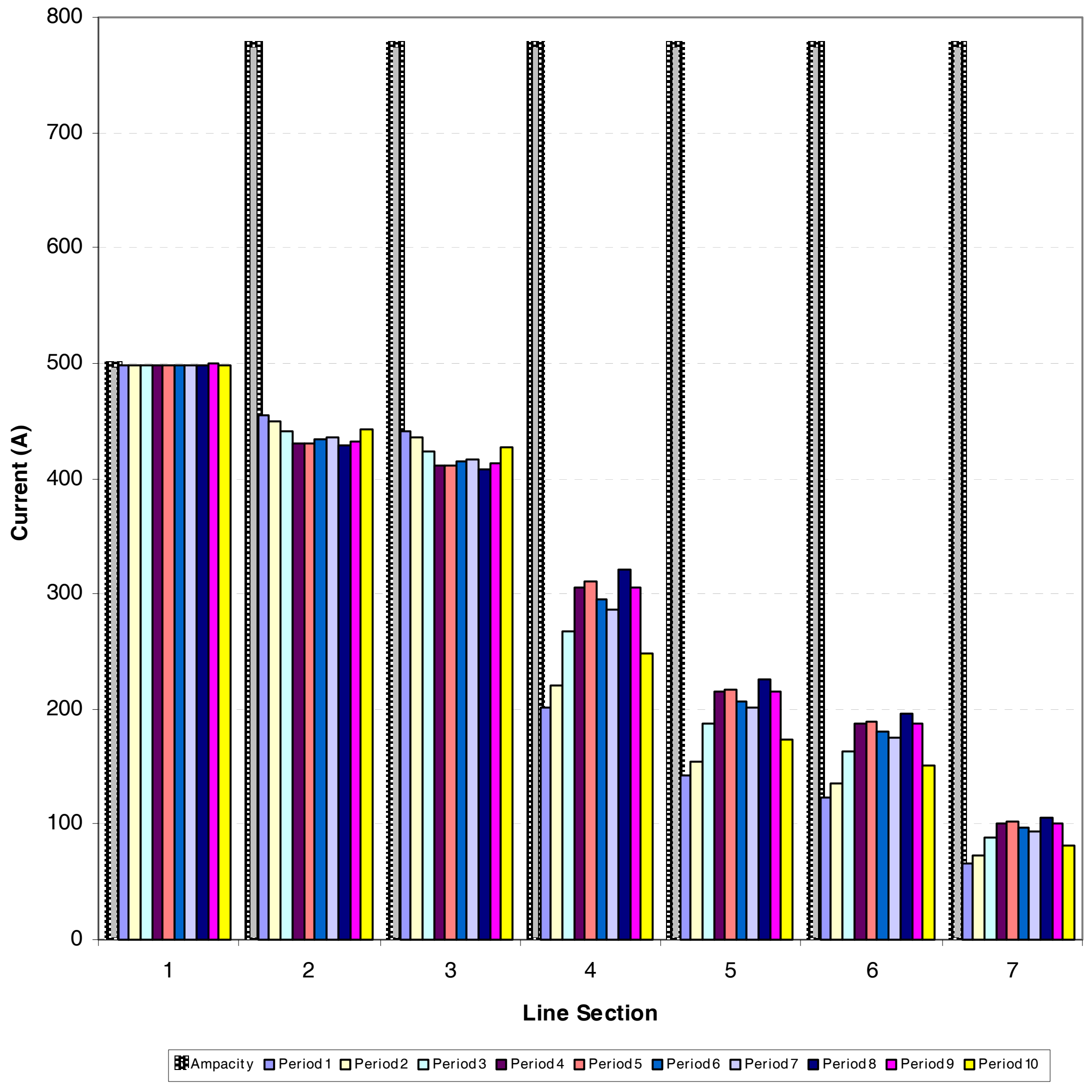

Figure 2.9 Feeder loading per section for cable ampacity loading with one DS unit (70% efficiency and no power/energy limits), located after section A3 and no DG in the system

Figure 2.9 shows that locating the DS unit after section A3 reduces the loading of feeder sections A1, A2, and A3 during the mid-day. Sections A1, A2, and A3 experience higher loading at night (due to the DS charging), in a similar way as in the previous case. Loadings of section A4, A5, A6 and A7 are not affected by the presence of the DS unit.

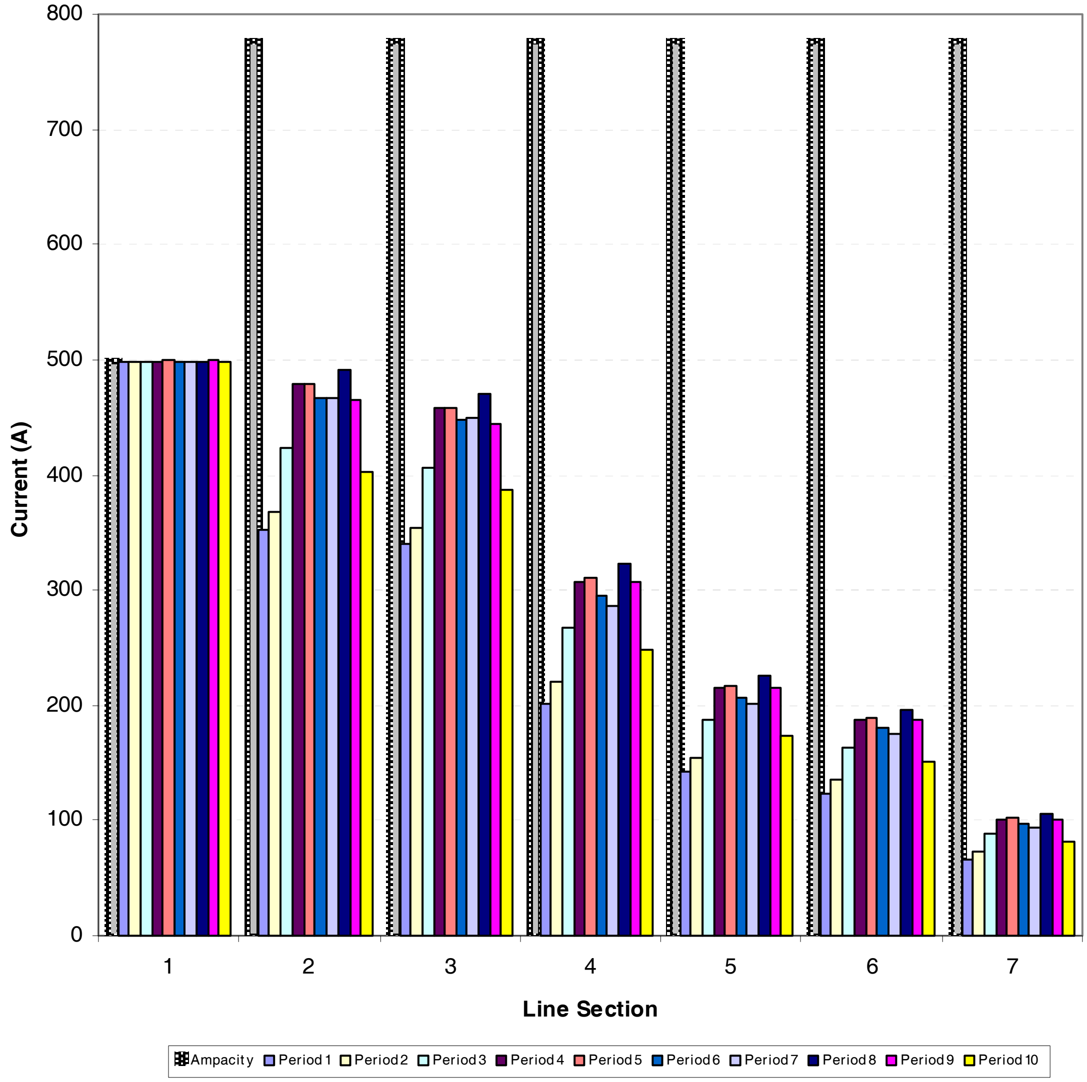

Figure 2.10 Feeder loading per section for cable ampacity loading with one DS unit (70% efficiency and no power/energy limits), located after section A1 and no DG in the system

Figure 2.10 shows that locating the DS unit after section A1 reduces the feeder loading on feeder section A1 only. The loadings of the downstream sections (A2, A3, A4, A5, A6 and A7) are not affected by the presence of the DS unit. The feeder loading of section A1 at night is increased (due to the DS charging), in a similar way as in the previous case.

The study results from Figures 2.8 to 2.10 show that in all case studies the presence of the DS unit allows for higher load levels (26.8 MW vs. 23.9 MW) without overloading the critical feeder section (A1).

To evaluate the effect of the DS unit location, the detailed analysis of system losses for all three scenarios has been performed. The system losses for three scenarios, corresponding to various DS unit locations and all ten time periods, are presented in Table 2.4. Distribution of power losses throughout the day for all three DS unit locations is given on Figure 2.11.

Table 2.4 System losses for all three DS unit location scenarios

Time Period	**Hours**	Power loss (kW)			Energy loss per day (kWh)		
		DS after A1	DS after A3	DS after A7	DS after A1	DS after A3	DS after A7
1	5	594	615	642	2970	3073	3209
2	3	611	628	650	1832	1883	1949
3	2	665	669	673	1330	1337	1346
4	2	723	712	700	1447	1425	1401
5	2	728	717	705	1456	1434	1410
6	1	709	701	693	709	701	693
7	3	703	695	687	2108	2086	2062
8	3	744	729	713	2231	2187	2140
9	2	717	710	701	1434	1419	1402
10	1	641	650	660	641	650	660
				Total	16156	16195	16273

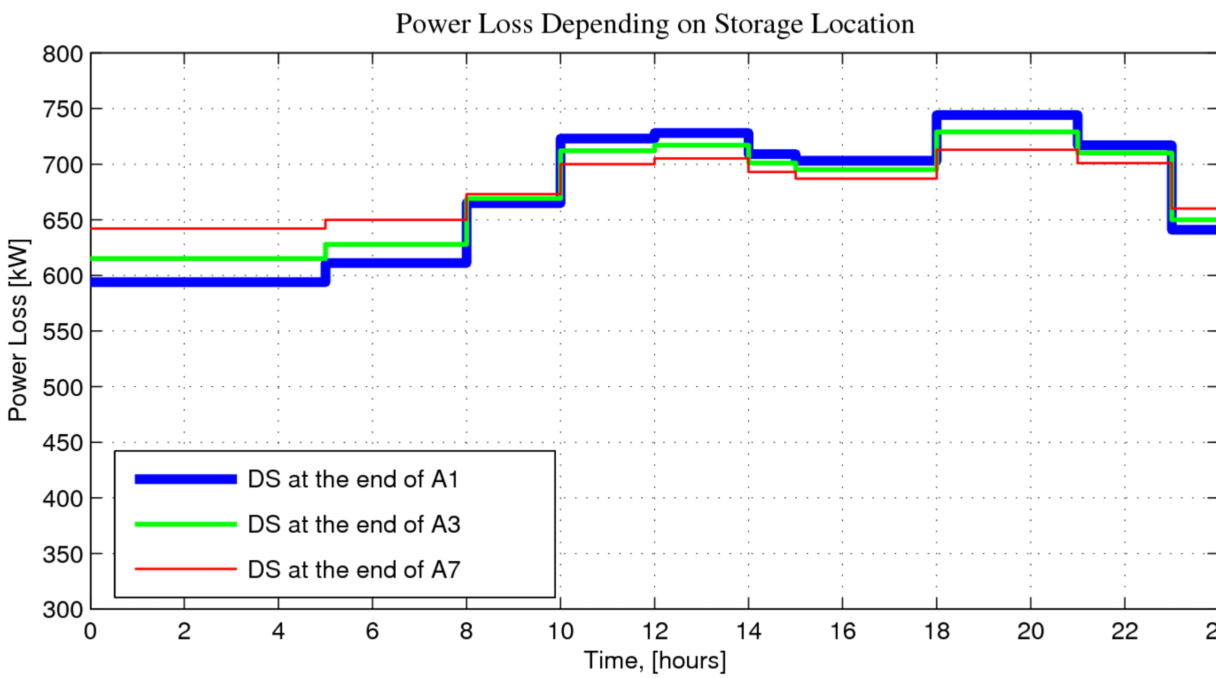

Figure 2.11 Distribution of system losses for all three DS unit location scenarios

Table 2.4 and Figure 2.11 show that the most efficient operation is when the DS unit is located just after the critical section (A1 in this case). The reason is that the charging current is higher than the discharging current (due to the DS efficiency). The difference between the lowest and the highest loss values is 0.72%. This indicates that from the point of view of the maximum allowable feeder loading, the DS unit should be located as close to the critical feeder section as possible. If this is not possible due to other constraints, placing the DS unit at any other location after the critical section is acceptable.

Permissible power export

A typical daily load diagram based on Table 2.3 is assumed. One DG unit and one DS unit are connected to the feeder. The criterion for the DS charge/discharge strategy is to enable the DG unit to export maximum constant power throughout the day. Figure 2.12 shows the loading of the feeder section A1, the required DS charging/discharging power, and the energy stored in the DS (so that the combined power of the load and the DS is constant).

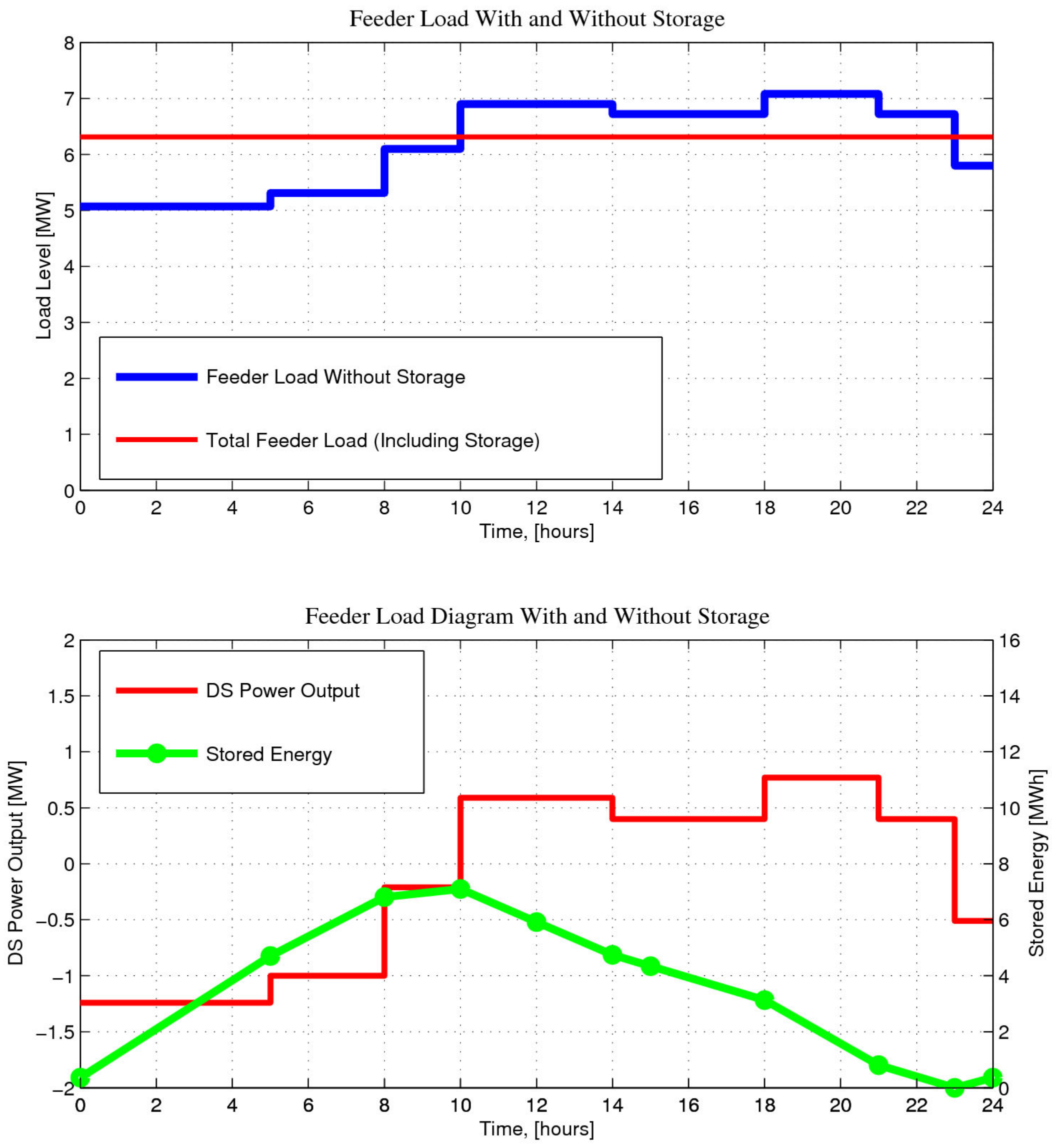

Figure 2.12 DS charge/discharge strategy and the effect of DS unit on feeder loading

Figure 2.12 shows that a constant power of 6.31 MW can be achieved for the mixture of the load and the DS unit. The parameters of the DS unit that satisfy the charge/discharge strategy of Figure 2.12 are:

- the maximum charging power of 1.24 MW,
- the maximum discharging power of 0.77 MW,
- the storage capacity of 7.1 MWh.

The total power export from the feeder is the difference between the exported power from the DG unit and the combined power of the load and the DS unit. From Figure 2.12, to keep the maximum power export at the utility at the permissible value of 5 MW, the exported power from the DG should be 11.3 MW. This is an approximate value, as it does not take into consideration that DG reverses the power flow in feeder sections A1, A2, and A3, and thus losses in the system are different with and without the DG unit in service. The realistic DG power limit is determined from the power flow studies and is slightly smaller, 11.1 MW. This is 1.2 MW more than it would be allowed if the DS unit is not in the system.

In power flow studies, three locations are considered for the DS unit:

- end of section A7, the case where the highest losses are expected (Figure 2.13),
- end of section A3, where the major industrial load with a DG is located (Figure 2.14),
- end of section A1, since section A1 has the lowest cable ampacity limit (Figure 2.15).

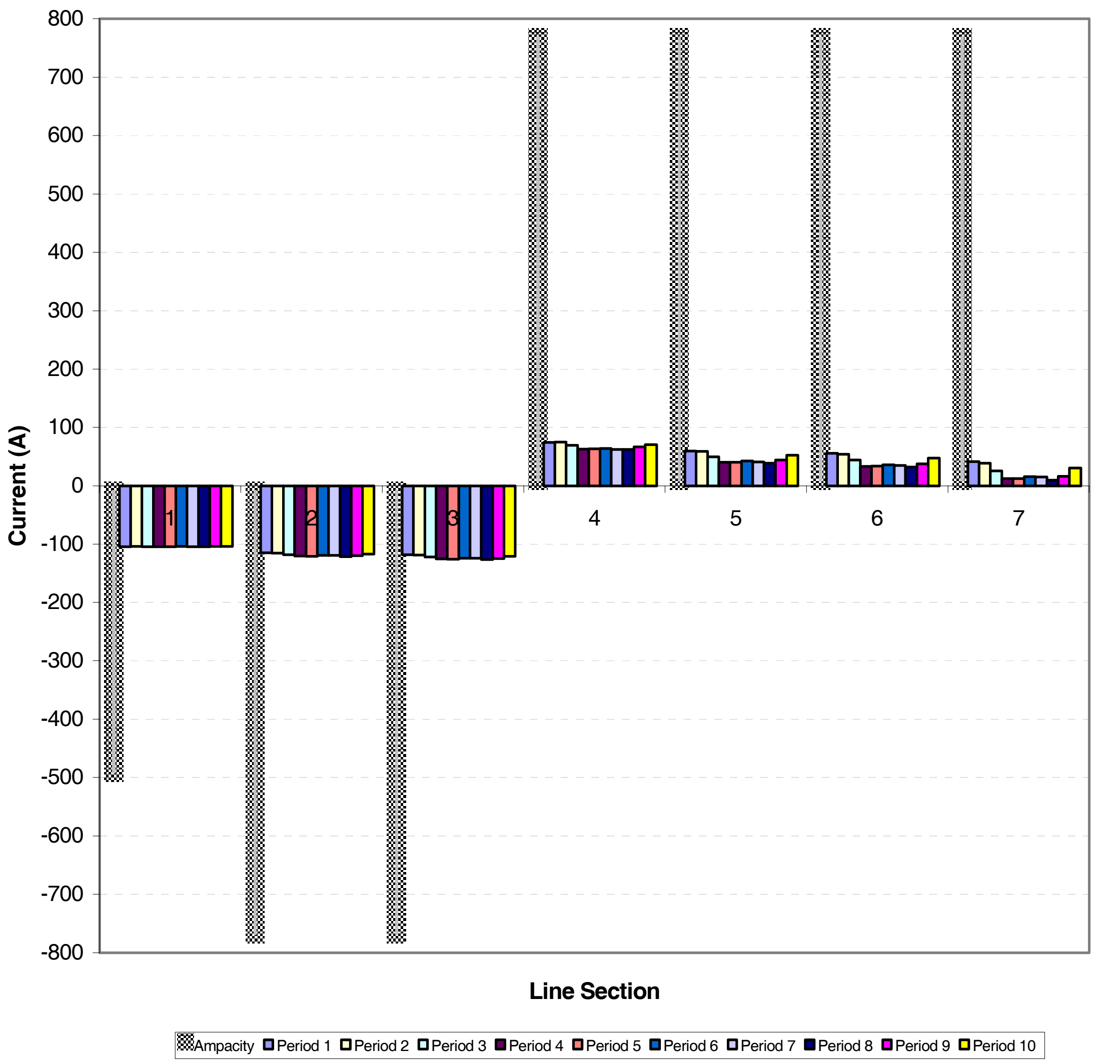

Figure 2.13 Feeder loading per section when 11.1 MW DG is installed after Section A3 and DS is connected of the feeder (after Section A7)

In the case of Figure 2.13, the DS unit is located at the end of the feeder (after section A7), the power generated by the DS unit, during the mid-day period, reduces the feeder loading of feeder sections A4, A5, A6, and A7. The same feeder sections have to carry additional current for charging the DS unit during the period of light load. The feeder loadings at all times are much lighter than the cable ampacity limits.

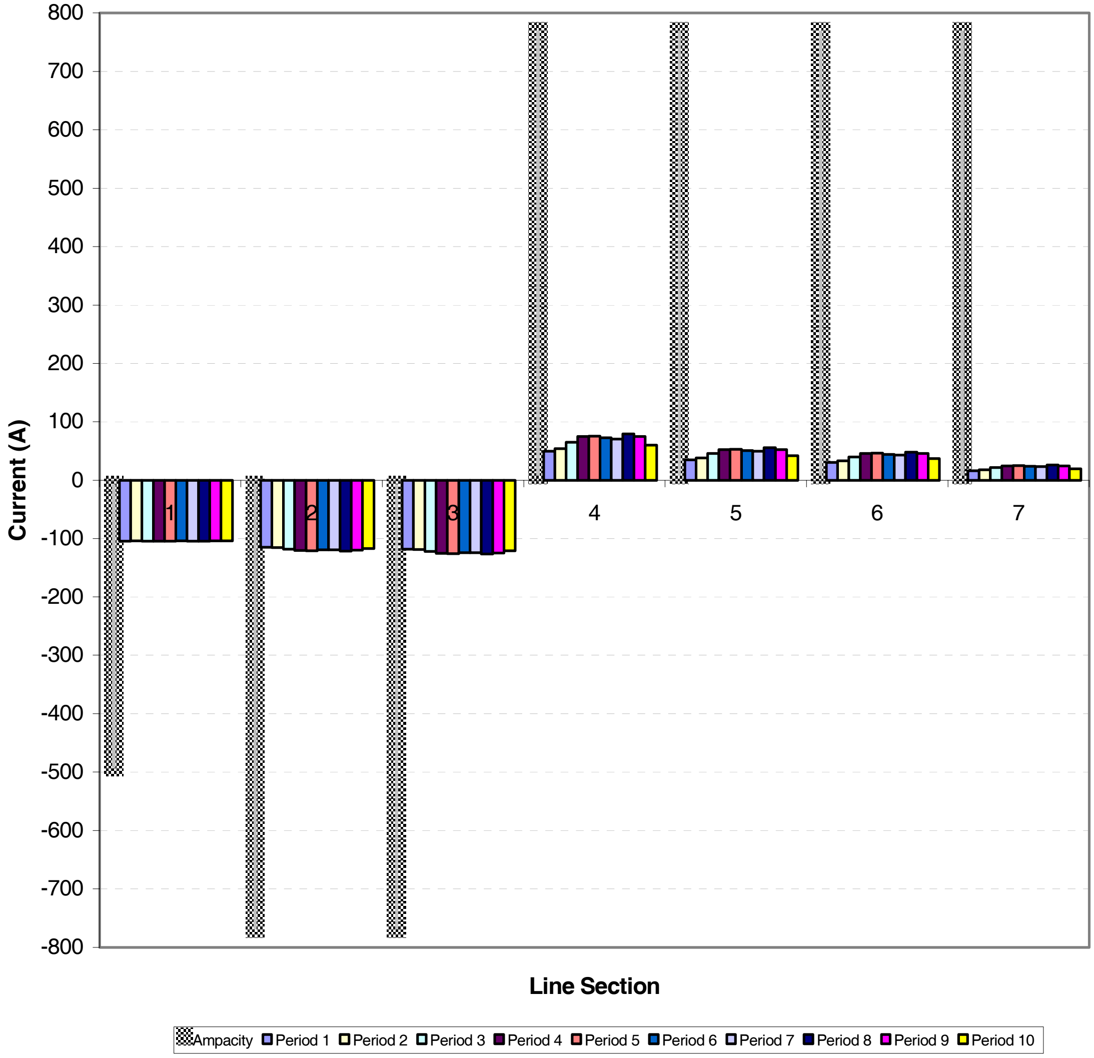

Figure 2.14 Feeder loading per section when 11.1 MW DG is installed after Section A3 and DS is connected of the feeder (after Section A3)

In the case of Figure 2.14, the DS unit is located after section A3 and during the period of light load the DS unit absorbs a portion of the power generated by the DG unit. This reduces the loadings of feeder sections A1, A2, and A3. Loadings of feeder sections A4, A5, A6 and A7 are not affected by the presence of the DS unit or the DG unit. The feeder loadings at all times are much less than the cable ampacity limits.

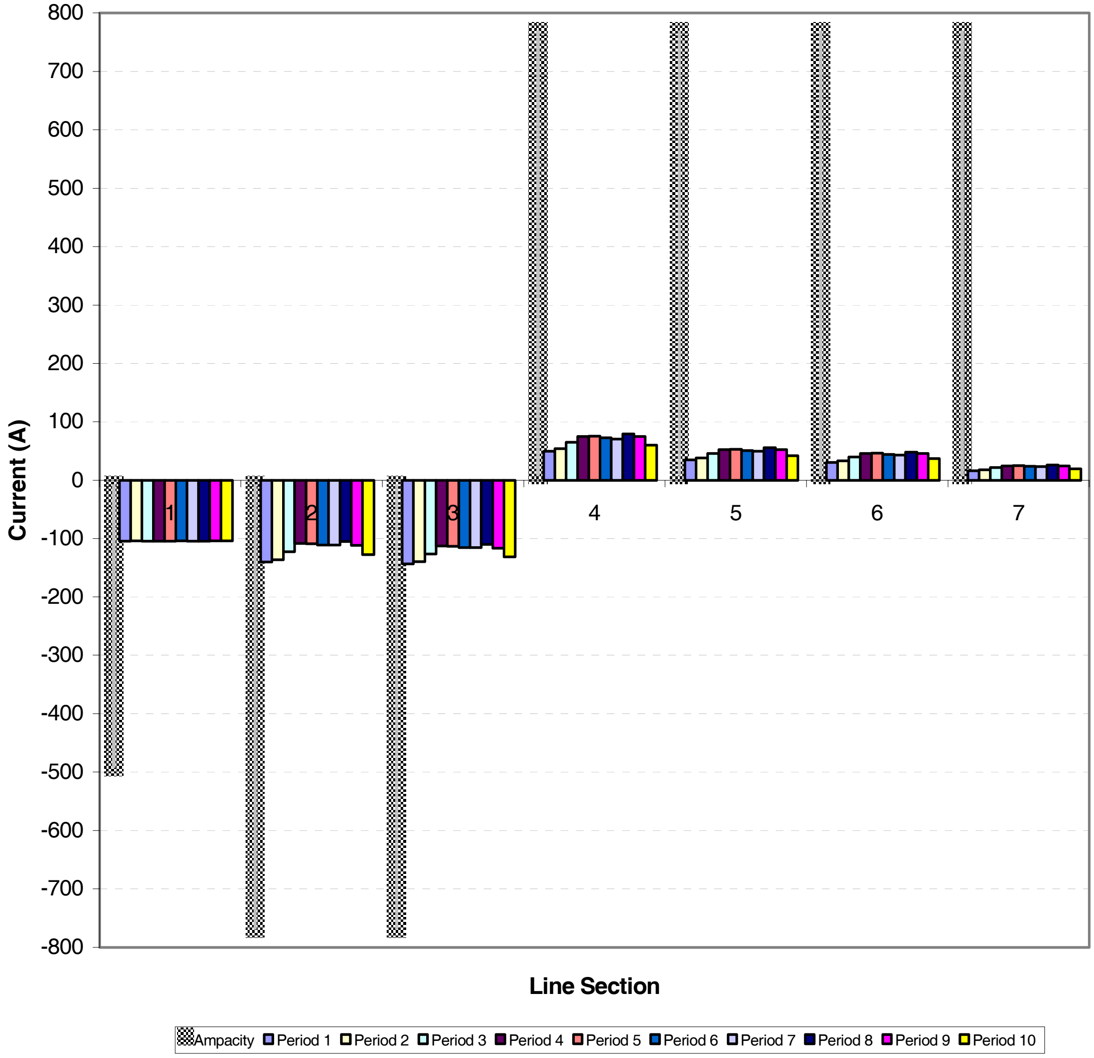

Figure 2.15 Feeder loading per section when 11.1 MW DG is installed after Section A3 and DS is connected of the feeder (after Section A1)

In the case of Figure 2.15, the DS unit is located immediately after feeder section A1 and during the period of the light load the DS unit absorbs a portion of the power generated by the DG unit. Similar to the previous two study cases, this reduces the feeder power export to the permissible limit of 5 MVA. The loadings of sections A4, A5, A6 and A7 are not affected by the presence of the DS unit or the DG unit. The loadings of sections A2 and A3 are reduced during the heavy-load period (discharging the DS unit) but increased during the light-load period (charging the DS unit). The feeder loadings at all times are much less than the cables ampacity limits.

The study results show that in all cases the presence of the DS unit allows for a larger DG unit to be installed at the industrial customer's site (11.1 MW vs. 9.9 MW) without violating the prescribed power export limit of 5 MW.

To evaluate the effect of the DS unit location, a detailed loss analysis for all three scenarios has been performed. The system losses for all three DS unit location scenarios and all ten time periods are presented in Table 2.5. Distribution of power losses throughout the day for the three DS unit location scenarios is given on Figure 2.16.

Table 2.5 System losses for all three DS unit location scenarios

Time Period	Hours	Power loss (kW)			Energy loss per day (kWh)		
		DS after A1	DS after A3	DS after A7	DS after A1	DS after A3	DS after A7
1	5	75	74	75	377	370	377
2	3	76	75	76	229	225	229
3	2	77	77	77	154	153	154
4	2	77	78	77	154	155	154
5	2	78	79	78	156	157	156
6	1	76	77	76	76	77	76
7	3	75	75	75	225	226	225
8	3	79	80	79	236	239	236
9	2	79	79	79	157	158	157
10	1	76	75	76	76	75	76
				Total	1840	1836	1840

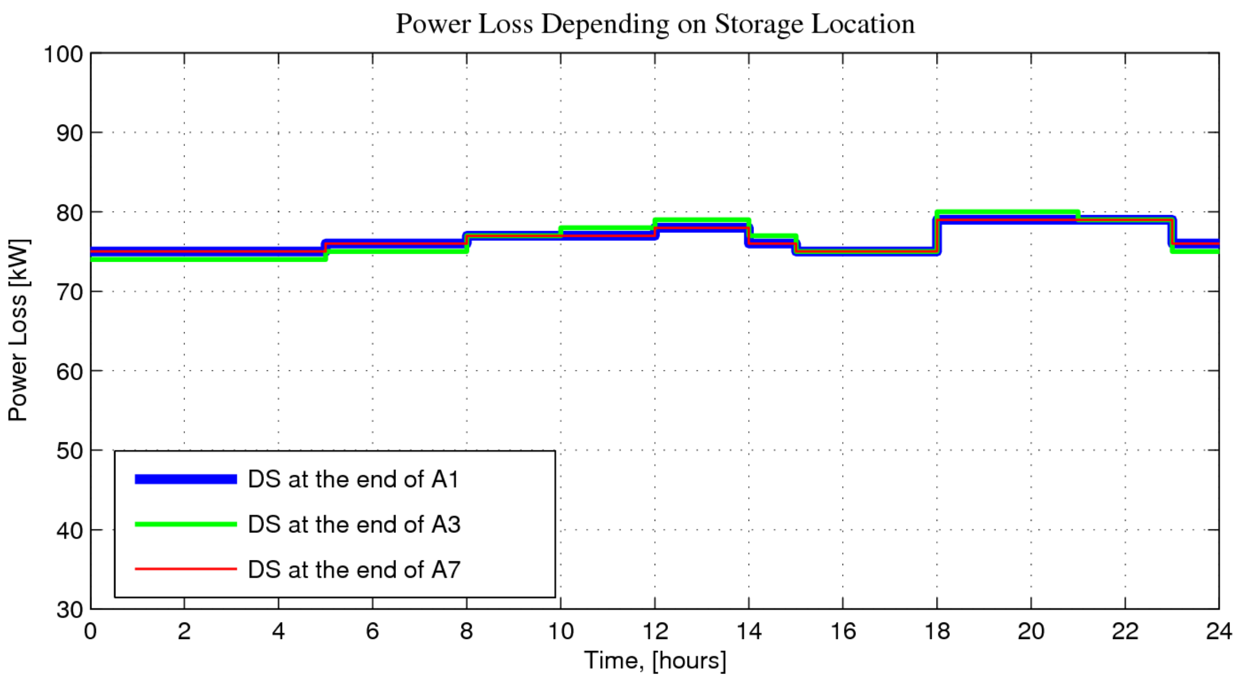

Figure 2.16 Distribution of system losses for all three DS unit location scenarios

Table 2.5 and Figure 2.16 show that the most efficient operation is when the DS unit is located after section A3. The reason is that the charging current is higher than the discharging current and locating the DS unit at the same location of the DG unit minimizes losses during charging. The difference between the lowest and the highest loss values is 0.2%. This indicates that in this case the DG location is not a significant factor in the system energy loss.

Maximum power export

A typical daily load diagram based on Table 2.3 is assumed. One DG unit and one DS unit are connected to the feeder. The same DS unit charge/discharge strategy as shown on Figure 2.12 is adopted to keep the combined power of the load and the DS unit constant. It is assumed that the DG unit export-power is limited so that the feeder current is less than or equal to the feeder ampacity limit. To keep the critical feeder section (A1 in this case) from overloading, the DG power limit is determined from the power flow studies at 30.8 MW. This is 1.2 MW more than it would be allowed if the DS unit is not in the system.

In power flow studies, three locations are considered for DS unit:

- end of section A7, the case where the highest losses are expected (Figure 2.17),
- end of section A3, where the major industrial load with a DG is located (Figure 2.18),
- end of section A1, since section A1 has the lowest cable ampacity limit (Figure 2.19).

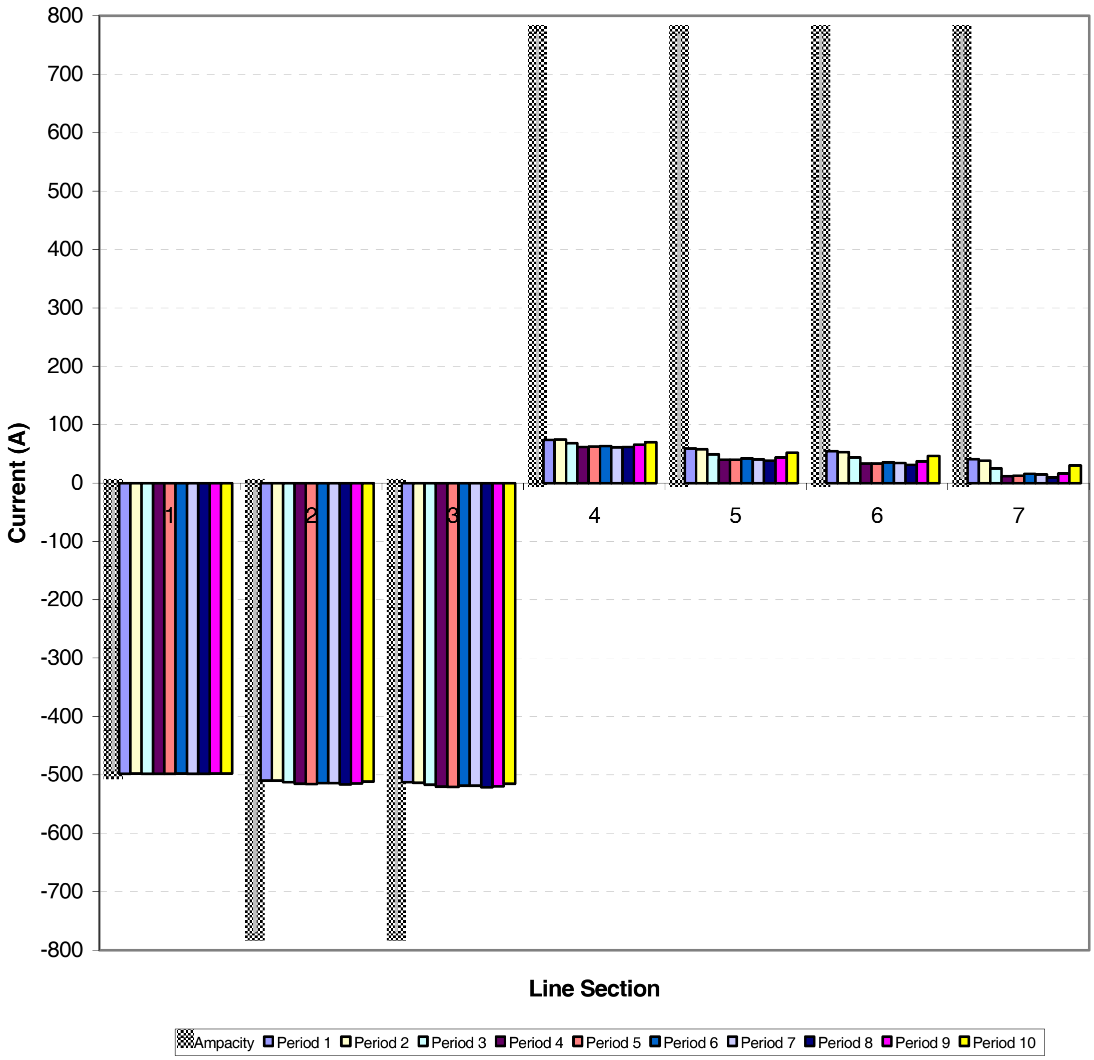

Figure 2.17 Feeder loading per section when 30.8 MW DG is installed after Section A3 and DS is connected of the feeder (after Section A7)

In the case of Figure 2.17, the DS unit is located at the end of the feeder (after section A7), the power generated by the DS unit during the mid-day period reduces the feeder loading on feeder sections A4, A5, A6, and A7. The same feeder sections have to carry additional currents for charging the DS unit during the light load periods.

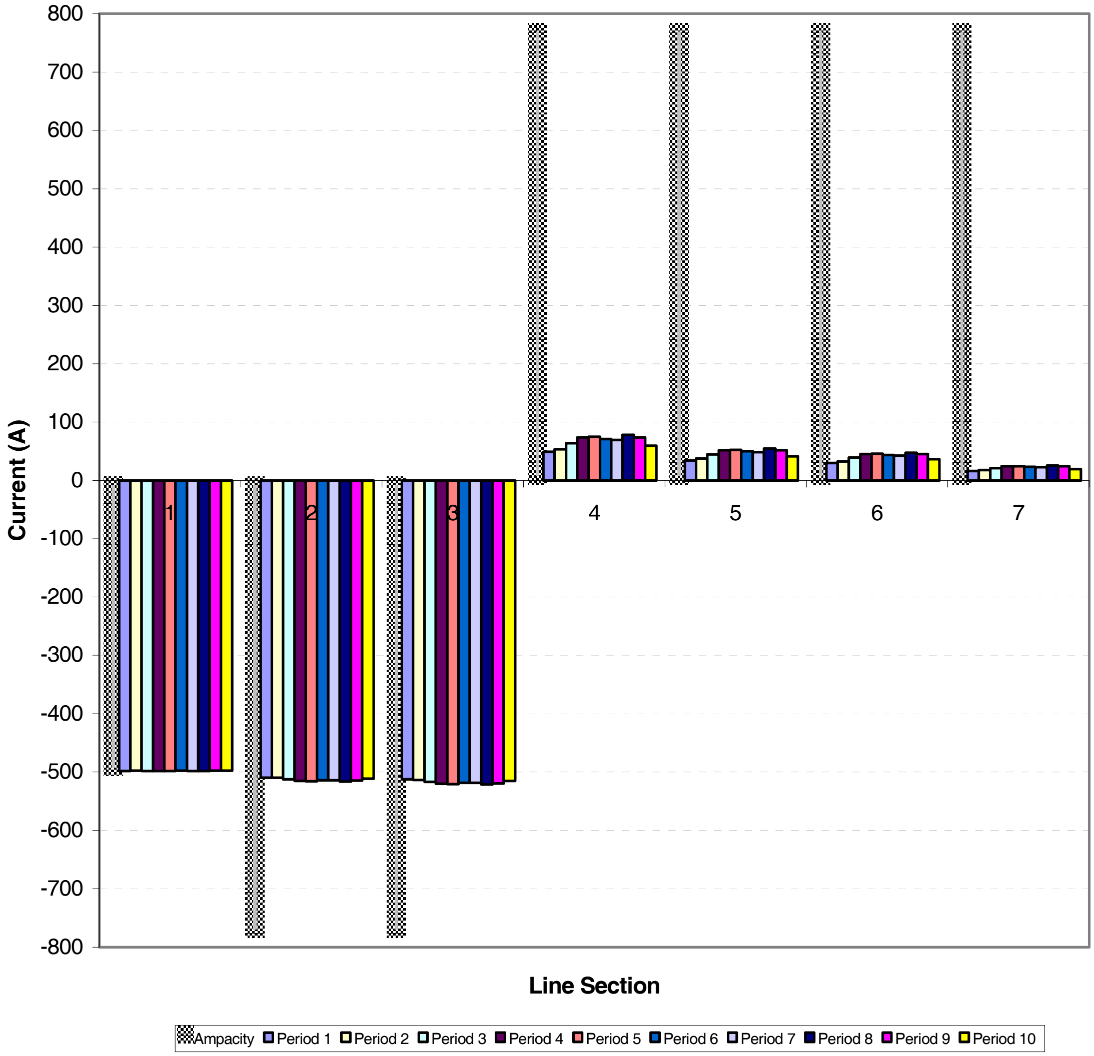

Figure 2.18 Feeder loading per section when 30.8 MW DG is installed after Section A3 and DS is connected of the feeder (after Section A3)

In the case of Figure 2.18, the DS unit is located after section A3 and during the period of light load the DS unit absorbs a portion of the power generated by the DG unit. This reduces the loadings of feeder sections A1, A2, and A3. The loadings of feeder sections A4, A5, A6 and A7 are not affected by the presence of the DS or the DG unit.

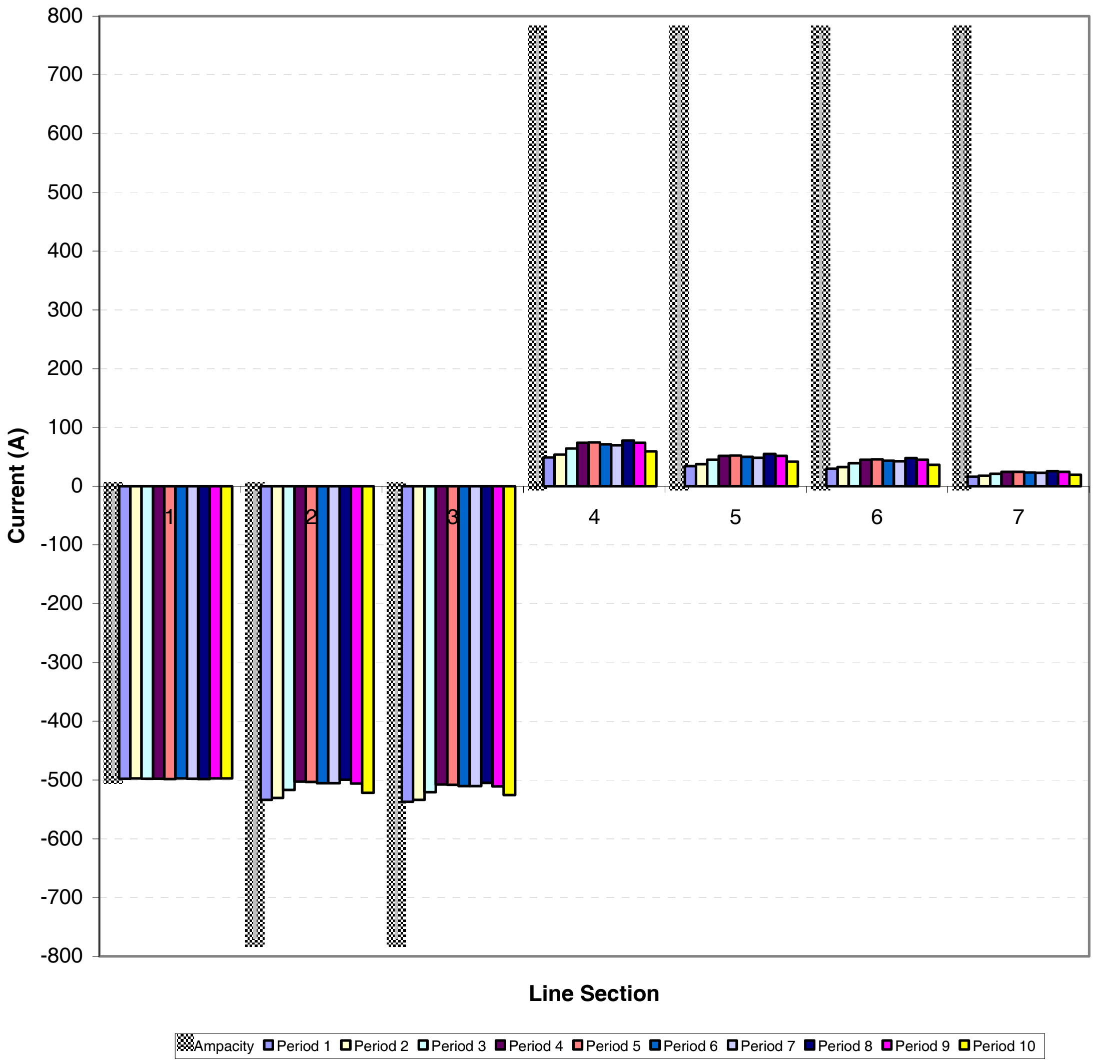

Figure 2.19 Feeder loading per section when 30.8 MW DG is installed after Section A3 and DS is connected of the feeder (after Section A1)

In the case of Figure 2.19, the DS unit is located immediately after section A1 and during light load periods the DS unit absorbs a portion of the power generated by the DG unit. This reduces section A1 current to the cable ampacity limit of 500 A (Table 2.2). The loadings of the downstream feeder sections A4, A5, A6 and A7 are not affected by the presence of the DS or the DG unit. The feeder loadings of sections A2 and A3 are reduced during heavy-load periods but increased, due to the DS charging, during the light-load periods.

The most efficient operation is when the DS unit is located after section A3. The reason is that the charging current is higher than the discharging current (due to storage efficiency) and locating DS in the same place as the DG unit exists minimizes losses during charging.

To evaluate the effect of the DS unit location, a detailed analysis of system losses for all the three scenarios was performed. The system losses for the three DS unit locations and all ten time periods are presented in Table 2.6. Distribution of power losses throughout the day for the three DS unit location scenarios is given on Figure 2.20.

Table 2.6 System losses for all three DS unit location scenarios

Time Period	Hours	Power loss (kW)			Energy loss per day (kWh)		
		DS after A1	DS after A3	DS after A7	DS after A1	DS after A3	DS after A7
1	5	849	843	844	4247	4216	4221
2	3	850	845	846	2550	2535	2537
3	2	846	845	845	1693	1691	1691
4	2	841	844	843	1682	1688	1687
5	2	843	846	846	1686	1692	1691
6	1	840	842	841	840	842	841
7	3	837	839	839	2512	2518	2517
8	3	843	847	846	2529	2541	2539
9	2	846	848	847	1691	1695	1695
10	1	846	844	844	846	844	844
				Total	20276	20261	20264

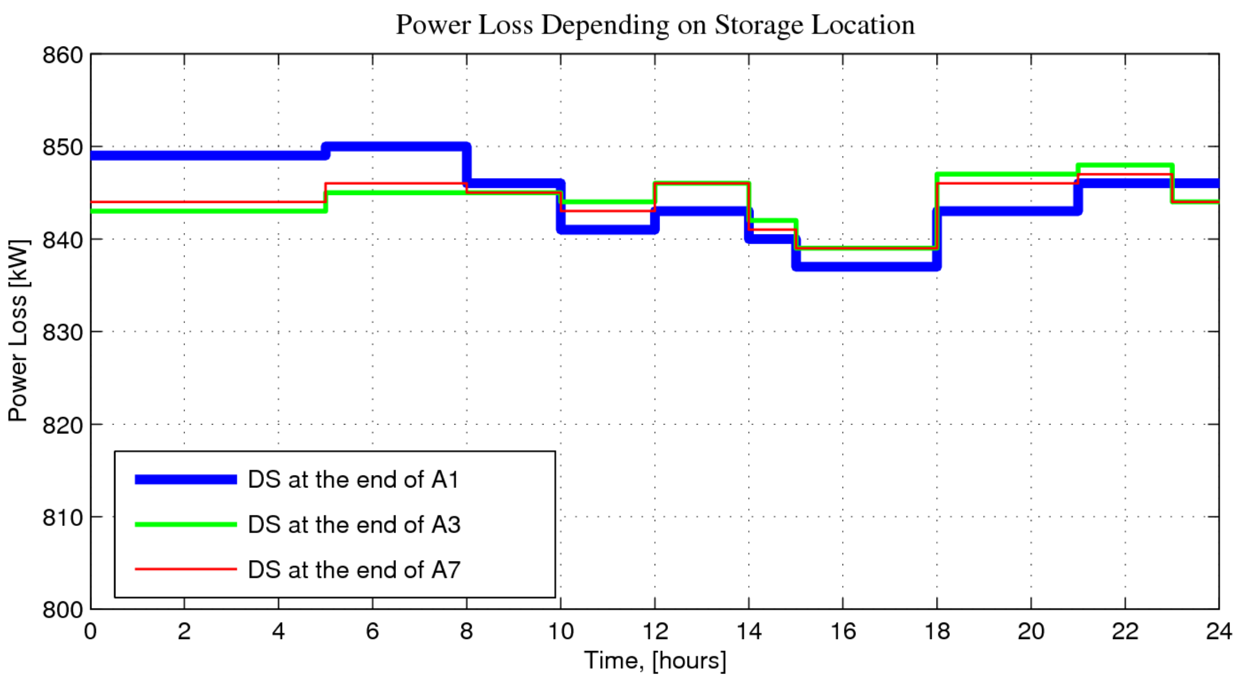

Figure 2.20 Distribution of system losses for all three DS unit location scenarios

Table 2.6 and Figure 2.20 show that the most efficient operation is when the DS unit is located after section A3, but the differences between the three scenarios are fairly insignificant.

2.1.3 Battery Option 3 – 1 MW NaS Battery with 100% DOD

The third set of studies is performed under the assumption that one large 1 MW NaS battery-based on the main technical data from Section 1.2.2 is used. The charging power (on the AC side) is limited to 1.2 MW, while the discharging power limit (on the AC side) is 1.2 MW for up to 3 hours and 1 MW perpetually. The available stored energy is up to 7.2 MWh (100% DOD). An AC efficiency of 80% is assumed for this case.

Conventional operation

Based on the feeder cable ampacity (Table 2.2), the maximum permissible power in section A1 is 23.9 MW. In the case study that analyzes the maximum permissible feeder loading without storage (Figure 2.4), the daily peak is equal to the maximum permissible power in section A1 (23.9 MW). By placing the DS unit on the feeder, the maximum load can be increased. Figure 2.21 shows the effect of storage charge/discharge control strategy based on the procedures of Section 1.2.2.

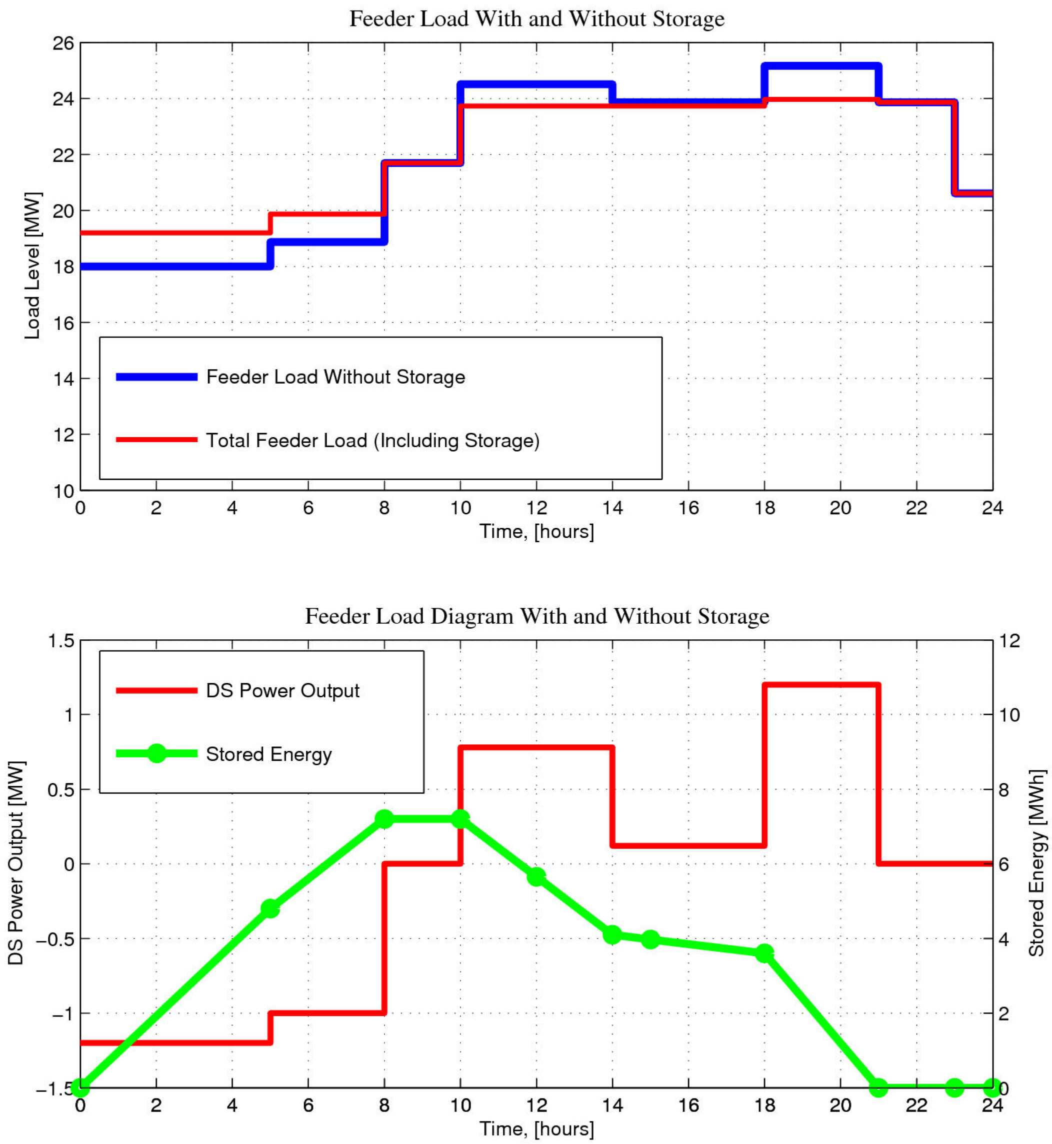

Figure 2.21 DS charge/discharge strategy and the effect of DS unit on feeder loading

On Figure 2.21, the permissible daily peak load in the presence of the 1 MW NaS battery-based DS unit can be increased to 25.1 MW, compared to 23.9 MW for the case without storage. The total energy produced by the DS unit during discharging period is 80% of the consumed energy during charging period.

Based on the analysis from Section 2.1.2, the DS unit location associated with the minimal losses is considered (end of section A1). The loadings and the cable ampacities for all sections are shown on Figure 2.22.

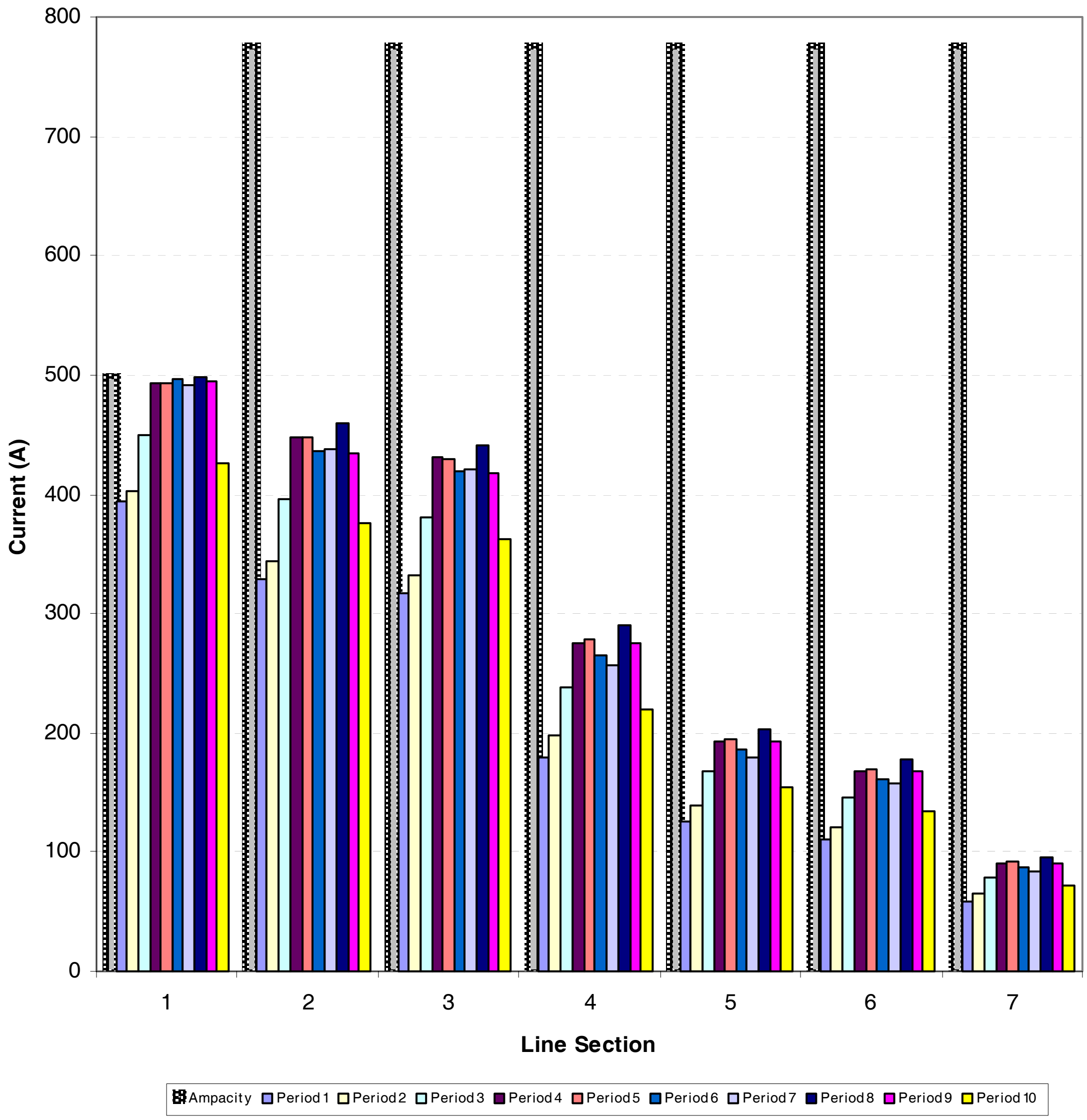

Figure 2.22 Feeder loading per section for cable ampacity loading with one DS unit (1 MW NaS battery with 100% DOD), located after section A1 and no DG in the system

The study results of Figure 2.22 confirm that with the presence of the 1 MW NaS battery-based DS unit, the cable ampacity limits are not violated even if the load peak is as high as 25.1 MW.

Permissible power export

A typical daily load diagram based on Table 2.3 is assumed. One DG unit and one 1 MW NaS battery-based DS unit are connected to the feeder. Without the DG unit, Figure 2.23 shows the loading of section A1 feeder, the DS charging/discharging power, and the energy stored in the DS (so that the combined power of the load and the DS is as level as possible). For exporting power from the feeder, the critical period is during the night when the combined load and the DS unit power is 6.2 MW. The stored energy limit is reached at 10:00 am to 7.2 MWh. On Figure 2.23, the DS output power during charging period is shown as a negative value.

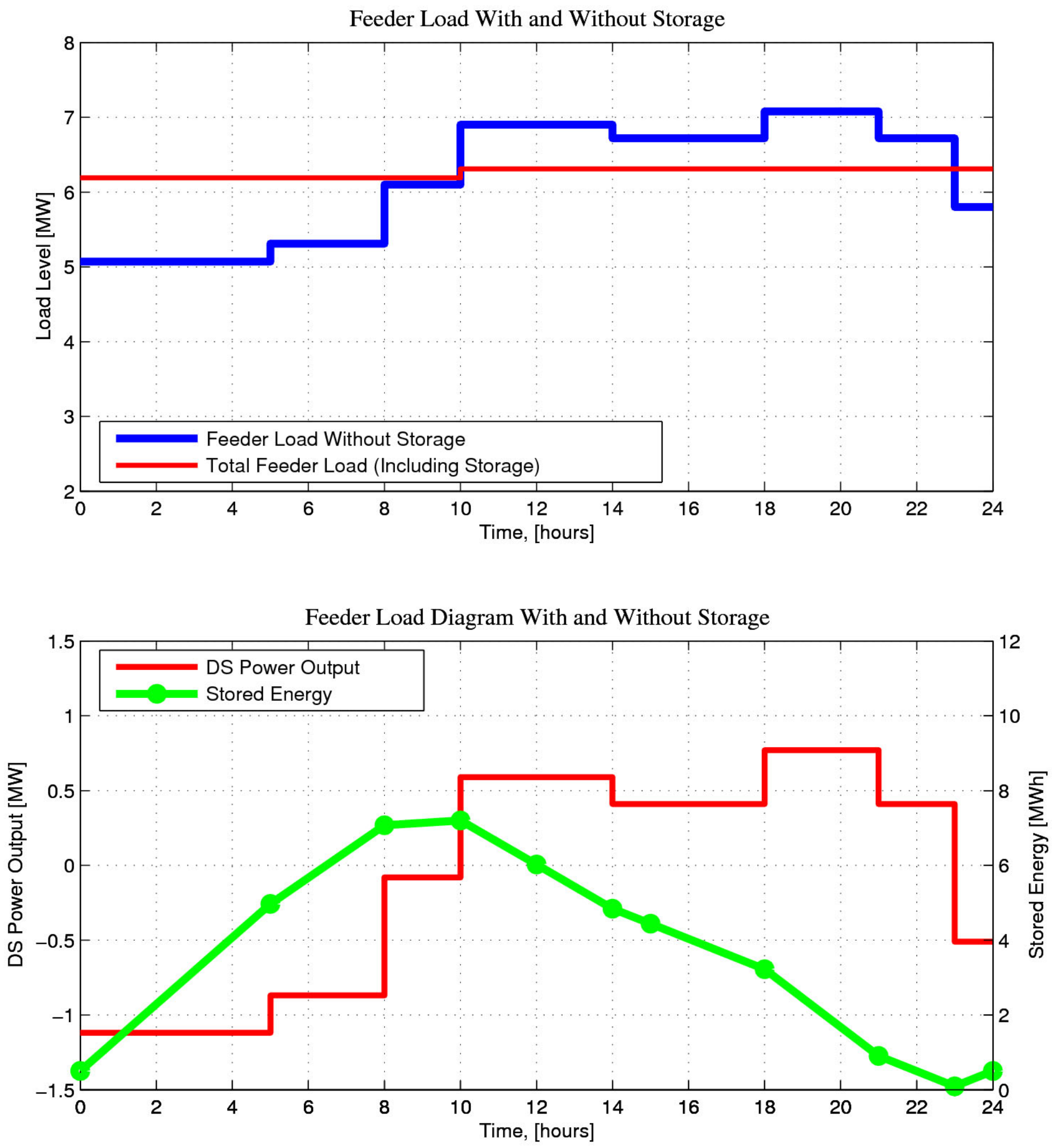

Figure 2.23 DS charge/discharge strategy and the effect of DS unit on feeder loading

The total power export from the feeder is the difference between the exported power from the DG unit and the combined power of the load and the DS during the period of minimal load (6.2 MW). To keep the maximum power export at the prescribed value of 5 MW, the exported power from the DG unit should be 11.2 MW. This is an approximate value, as it does not take into consideration that due to reversed power flow in the first three sections, losses in the system are changed. The actual DG power limit is determined from the power flow studies and is slightly smaller, 11.0 MW. This is 1.1 MW more than it would be allowed if the DS unit is not included in the system. The study results, with the DS unit connected to the feeder after section A3, are shown on Figure 2.24.

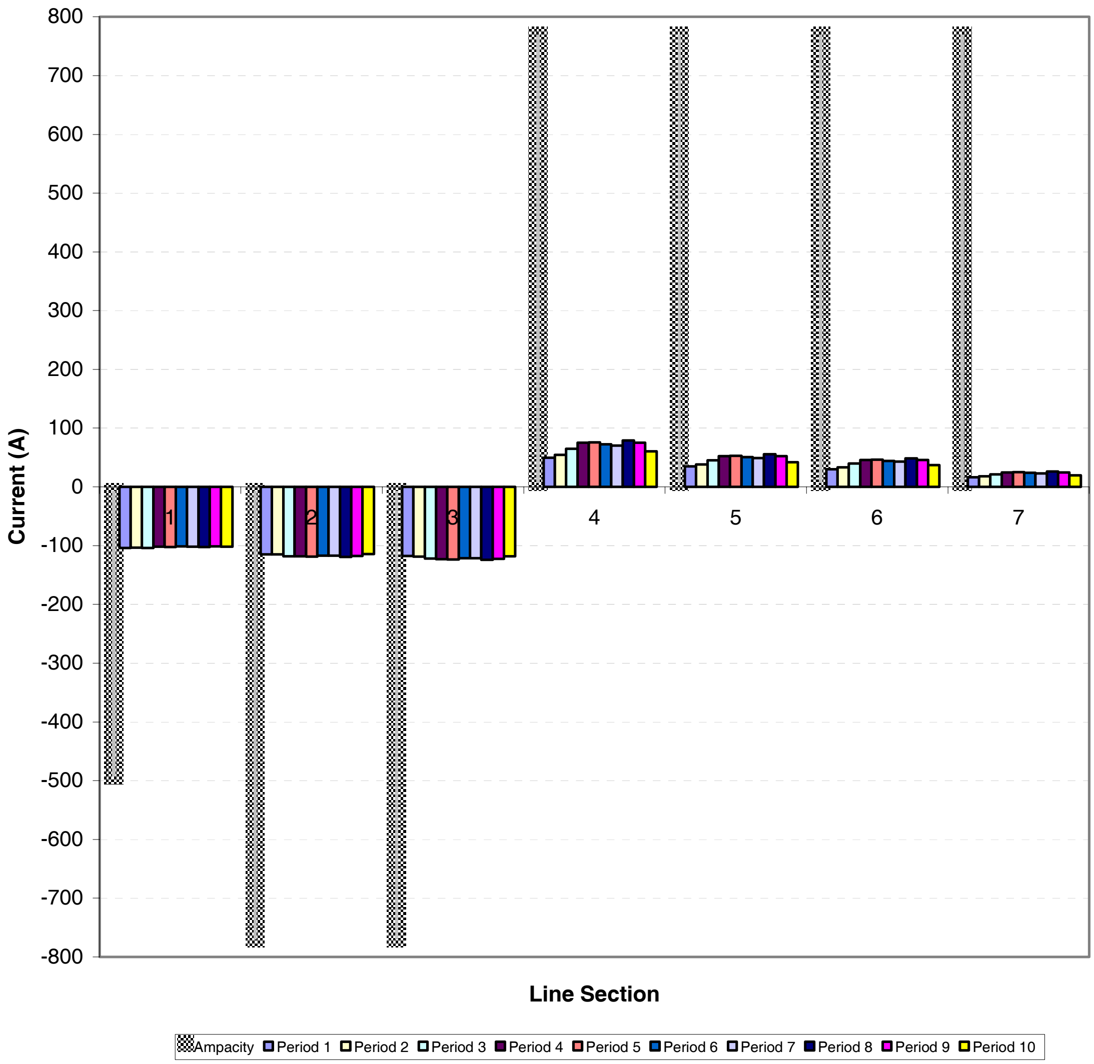

Figure 2.24 Feeder loading per section when 11 MW DG is installed after Section A3 and DS is connected of the feeder (after Section A3)

The study results show that the presence of the DS unit allows for a larger DG unit to be installed at the industrial customer's site (11.0 MW vs. 9.9 MW), without violating the prescribed power export limit of 5 MW.

Maximum power export

A typical daily load diagram based on Table 2.3 is assumed. One DG unit and one 1 MW NaS battery-based DS unit are connected to the feeder. The same charge/discharge strategy, shown on Figure 2.23, is assumed for the DS unit. It is assumed that the DG export power is limited so that the feeder current is less than or equal to the feeder ampacity limit. The study results for the case when the DS unit is in the same location as the DG unit (at the end of section A3) are shown on Figure 2.25.

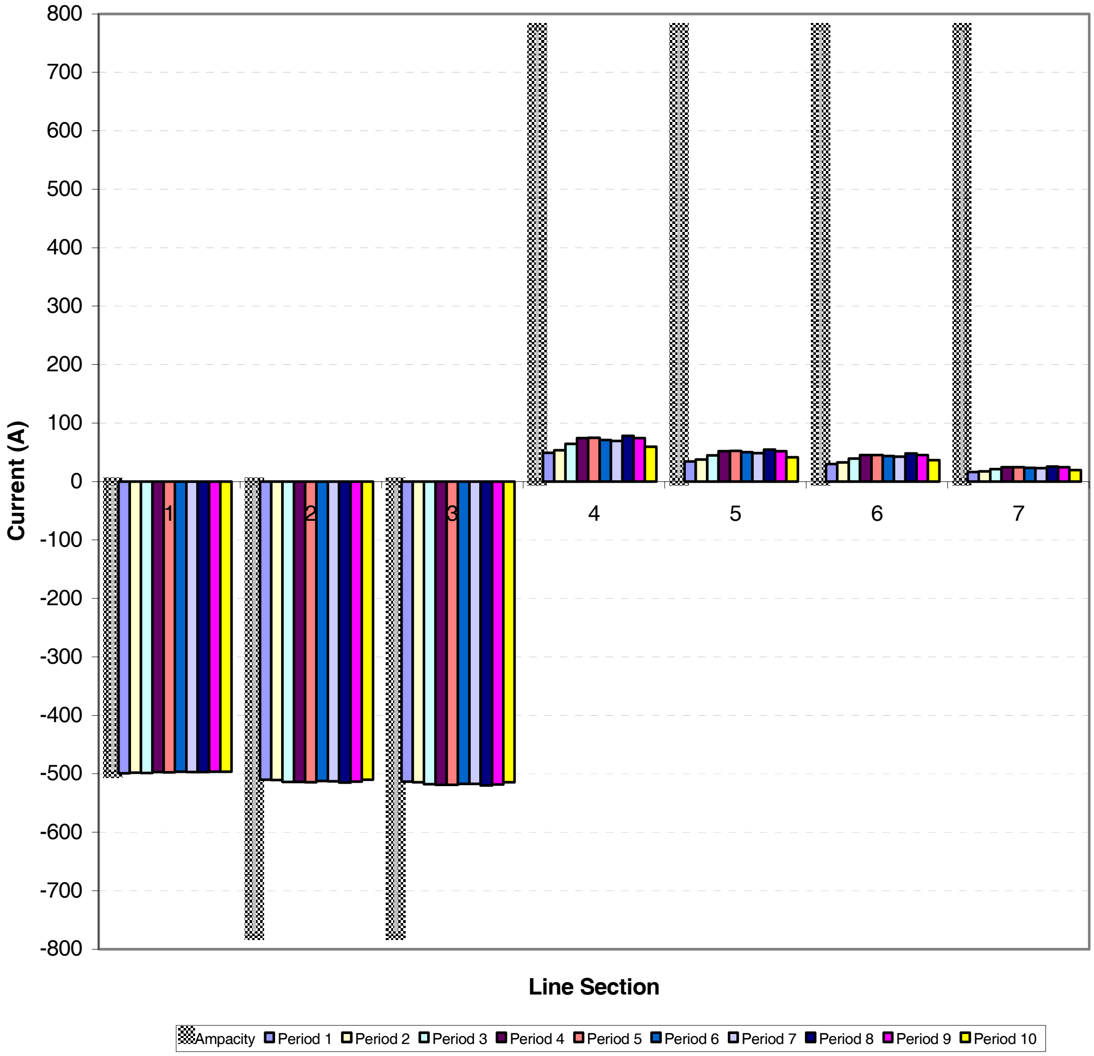

Figure 2.25 Feeder loading per section when 30.8 MW DG is installed after Section A3 and DS is connected of the feeder (after Section A3)

In the case of Figure 2.25, the DG power limit that does not overload the critical feeder section (A1 in this case) is 30.8 MW. This is 1.2 MW more than it would be allowed if the DS is not in the system.

2.1.4 Battery Option 4 – 1 MW NaS Battery with 90% DOD

The fourth set of simulations is performed under the assumption that the same 1 MW NaS battery of Section 2.1.3 is used. The charging power (on the AC side) is limited to 1.2 MW, while the discharging power limit (on the AC side) is 1.2 MW for up to 3 hours and 1 MW perpetually. The available stored energy is up to 6.48 MWh (battery capacity is 7.2 MWh, but only 90% DOD is allowed to increase the life of the battery). An AC efficiency of 80% is assumed for this case.

Conventional operation

Based on the feeder cable ampacity (Table 2.2), the maximum allowed power in section A1 is 23.9 MW. If we implement a storage charge/discharge control strategy based on the procedures from Section 1.2.3, the peak load in the presence of the 1 MW NaS battery (90% DOD) is 25.1 MW. The relative load diagram applicable for Feeder A is scaled up so that the peak load is the same as the maximum allowed peak loading. Figure 2.26 shows the loading of the section A1 feeder, the DS charging/discharging power, and the energy stored in the DS. On Figure 2.26, the DS output power during charging period is shown as a negative value.

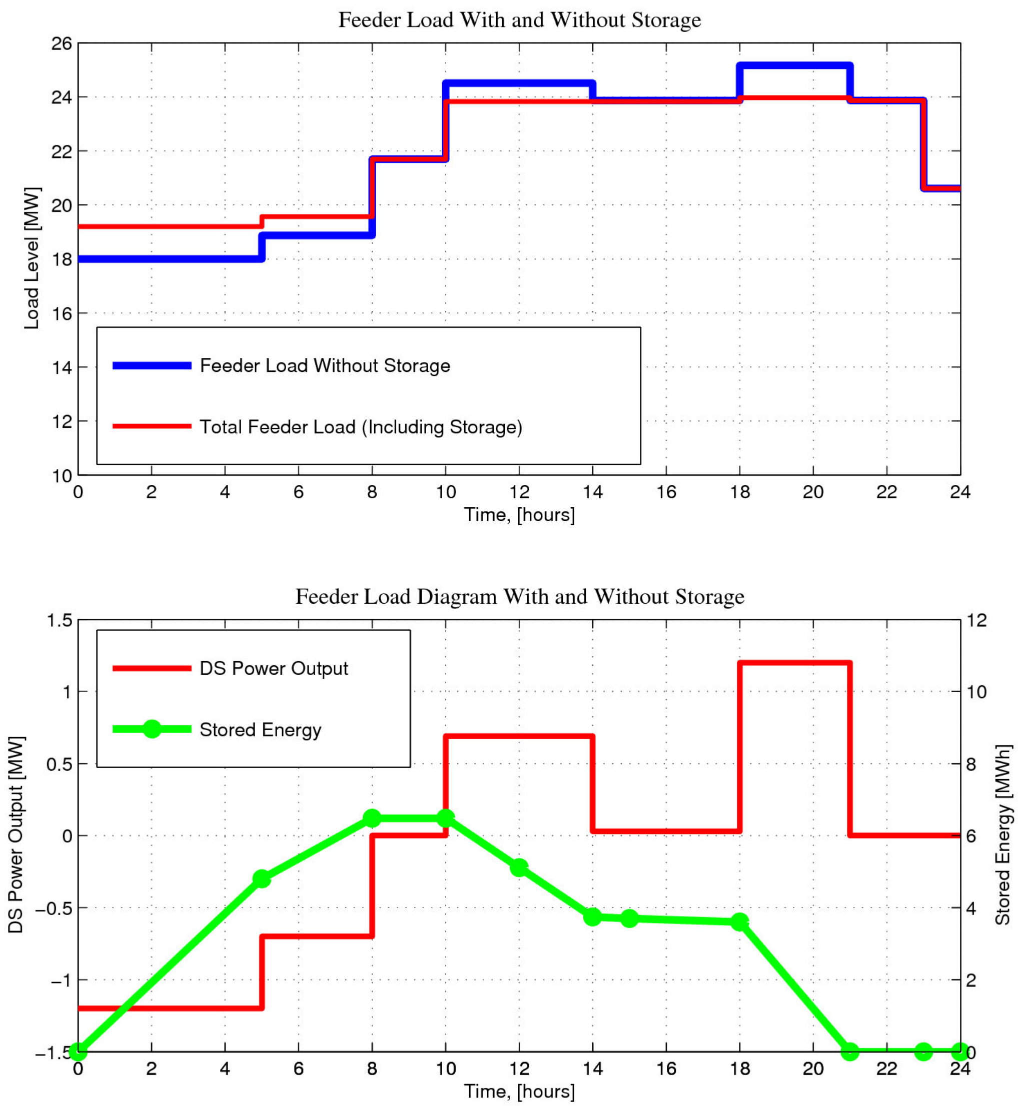

Figure 2.26 DS charge/discharge strategy and the effect of DS unit on feeder loading

Based on the analysis of Section 2.1.2, the DS unit location associated with the minimal losses is considered (after section A1). The loadings of all sections throughout the day are shown on Figure 2.27.

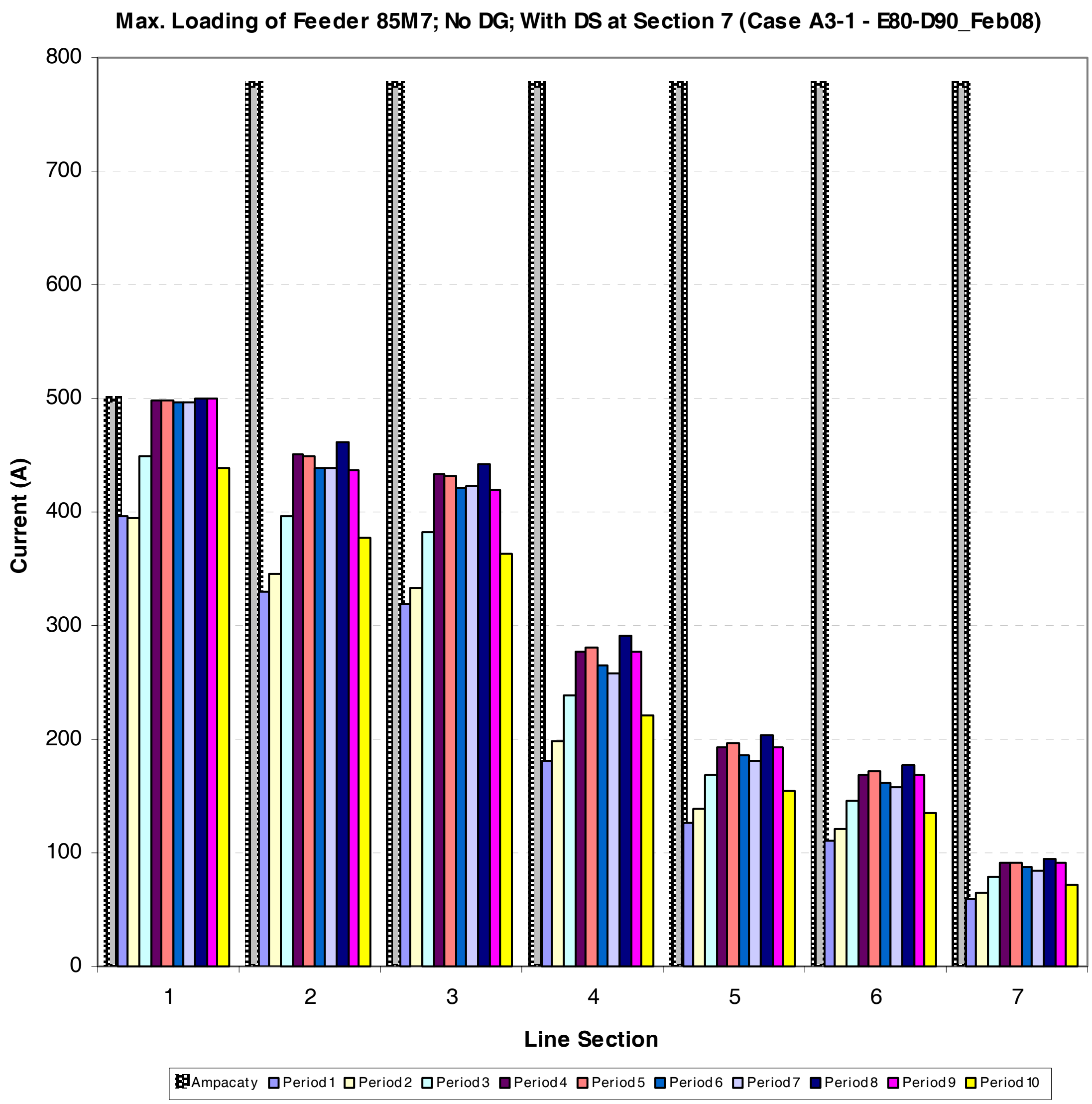

Figure 2.27 Feeder loading per section for cable ampacity loading with one DS unit (1 MW NaS battery with 90% DOD), located after section A1 and no DG in the system

The study results from Figure 2.24 confirm that with the presence of the 1 MW NaS battery-based DS unit, the cable ampacity limits are not violated even if the load peak is as high as 25.1 MW. Under the conventional operation of feeder A1, the critical parameter is not the maximum stored energy but the maximum output power. Therefore, the effect of reducing DOD from 100% to 90% is negligible.

Permissible power export

A typical daily load diagram based on Table 2.3 is assumed. One DG unit and one 1 MW NaS battery-based DS unit are connected to the feeder. Without the DG unit, Figure 2.28 shows the loading of the section A1 feeder, the DS charging/discharging power, and the energy stored in the DS (so that the combined power of the load and the DS is as level as possible). For exporting power from the feeder, the critical period is during the night when the combined load and the DS unit power is 6.1 MW. The stored energy limit is reached at 8:00 at 6.48 MWh. On Figure 2.28, the DS output power during charging period is shown as a negative value.

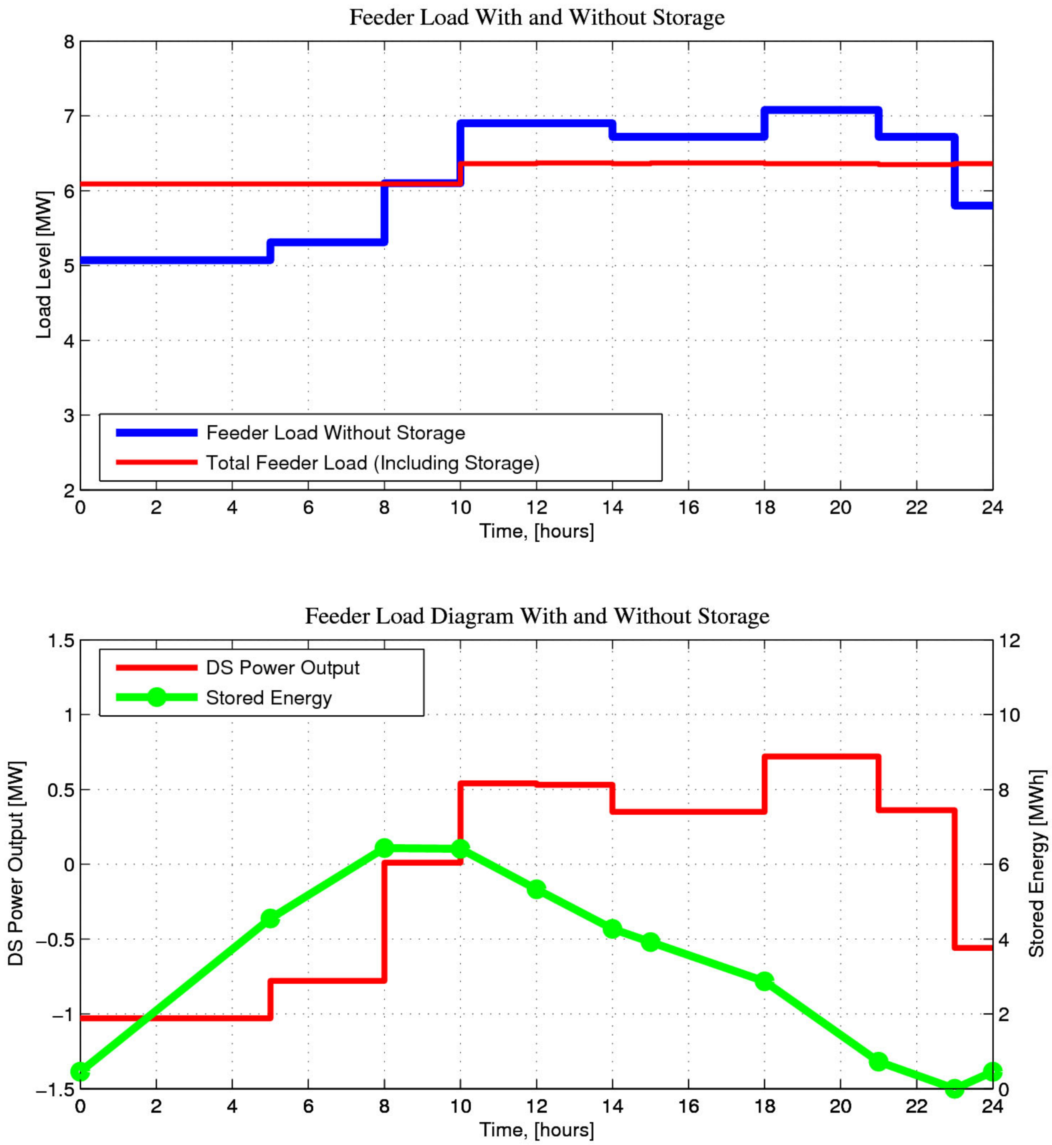

Figure 2.28 DS charge/discharge strategy and the effect of DS unit on feeder loading

The total power export from the feeder is the difference between the exported power from the DG unit and the combined power of the load and the DS during the period of minimal load (6.1 MW). To keep the maximum power export at the prescribed value of 5 MW, the exported power from the DG should be 11.1 MW. This is en approximate value, as it does not take into consideration that due to reversed power flow in the first three sections, losses in the system are changed. The actual DG power limit is determined from the power flow studies and is slightly smaller, 10.9 MW. This is 1.0 MW more than it would be allowed if the DS unit is not included in the system. The study results, with the DS unit connected to the feeder after section A3, are shown on Figure 2.29.

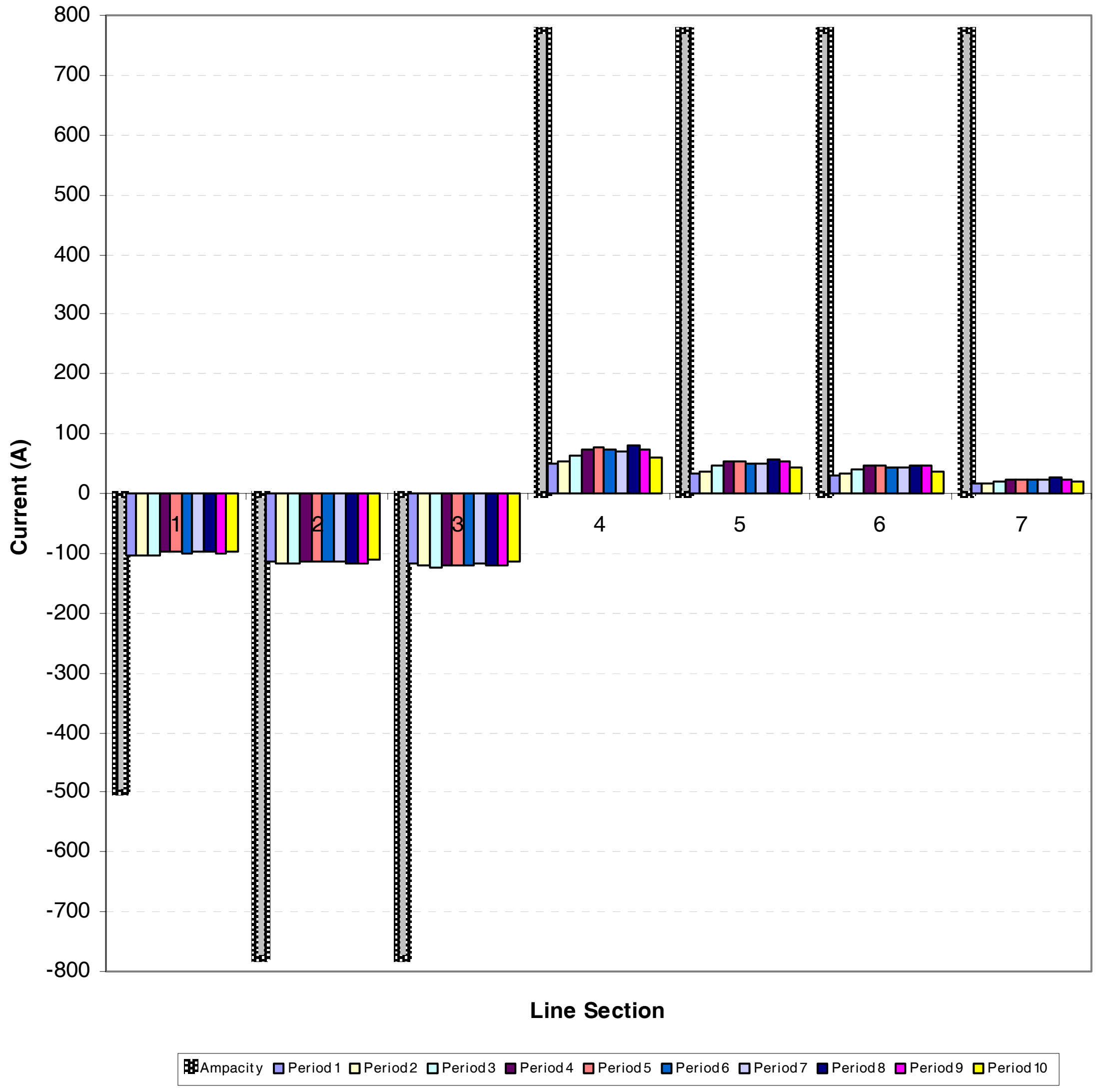

Figure 2.29 Feeder loading per section when 10.9 MW DG is installed after Section A3 and DS is connected of the feeder (after Section A3)

The study results show that the presence of the DS unit allows for a larger DG unit to be installed at the industrial customer's site (10.9 MW vs. 9.9 MW), without violating the prescribed power export limit of 5 MW. This is 0.1 MW less then when the same 1 MW NaS battery operates with 100% DOD.

Maximum power export

A typical daily load diagram based on Table 2.3 is assumed. One DG unit and one 1 MW NaS battery-based DS unit are connected to the feeder. The same charge/discharge strategy, shown on Figure 2.28, is assumed for the DS unit. It is assumed that the DG export power is limited so that the feeder current is less than or equal to the feeder ampacity limit. The study results for the case when the DS unit is in the same location as the DG unit (at the end of section A3) are shown on Figure 2.30.

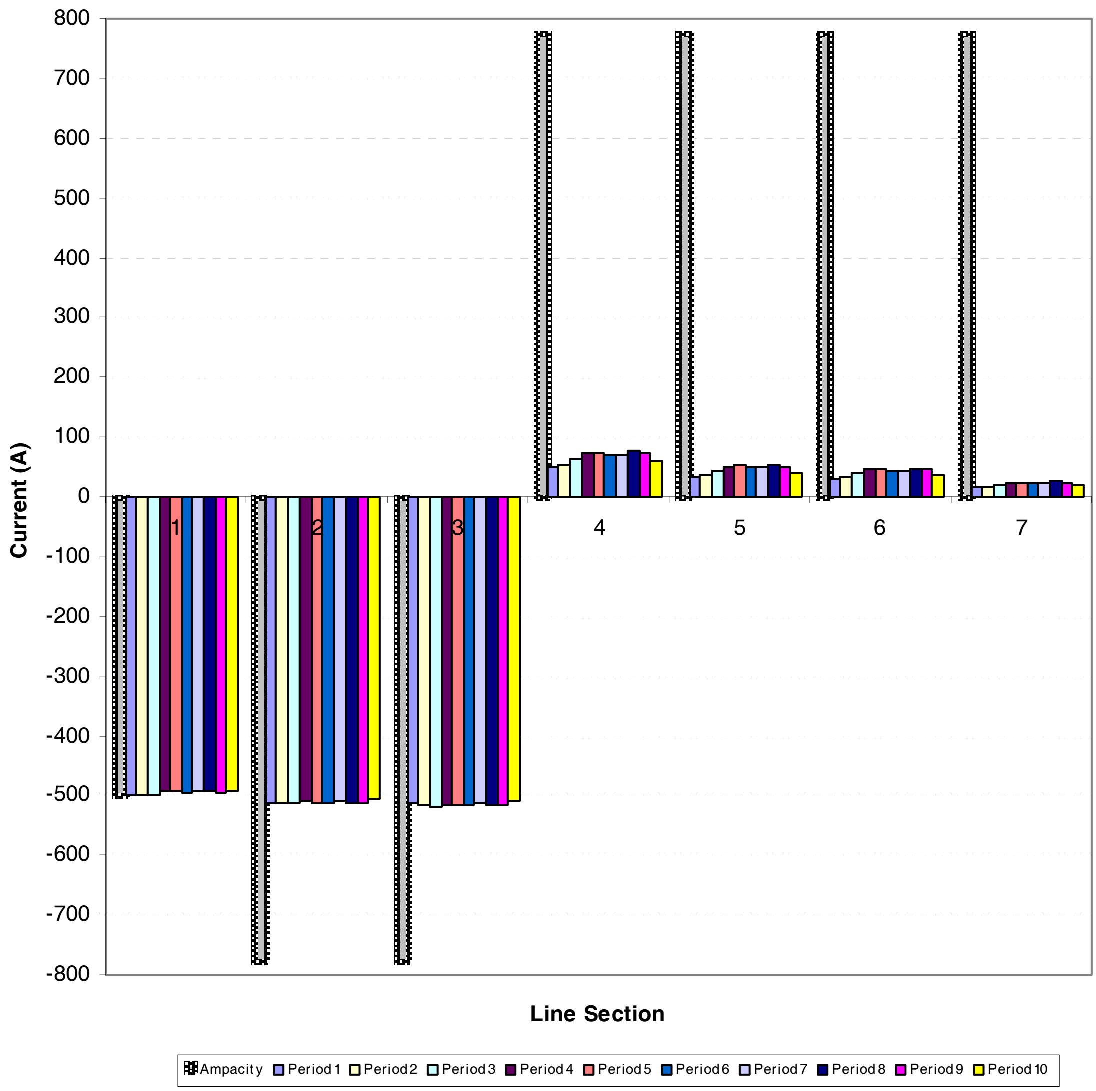

Figure 2.30 Feeder loading per section when 30.6 MW DG is installed after Section A3 and DS is connected of the feeder (after Section A3)

In the case of Figure 2.30, the DG power limit that does not overload the critical feeder section (A1 in this case) is 30.6 MW. This is 1.0 MW more than it would be allowed if the DS is not in the system. This is 0.2 MW less then when the same 1 MW NaS battery operates with 100% DOD.

2.1.5 Summary

The study results show the effect of integration of distributed storage (DS) on a typical industrial/residential feeder loading. It is demonstrated that the presence of the DS unit can reduce the load fluctuations throughout the day, and depending on the DS characteristics/ratings, the maximum feeder loading can be increased as follows:

- When a DS unit with the AC efficiency of 70% and without power and storage capacity constraints is used, the maximum allowed load peak power on the feeder is increased from the 23.9 MW to 26.8 MW. The DS parameters required for this case are: (i) the maximum charging power of 4.71 MW, (ii) the maximum discharging power of 2.92 MW, and (iii) the storage capacity of 27.02 MWh.
- When a DS unit of 1 MW NaS battery with 7.2 MWh storage capacity and 100% DOD is used, the maximum allowed load peak power on the feeder is increased from 23.9 MW to 25.1 MW.
- When the DS unit is a 1 MW NaS battery with 7.2 MWh storage capacity and 90% DOD, the maximum allowed load peak power on the feeder is increased from the 23.9 MW to 25.1 MW.

The effect of the NaS battery on the maximum allowed load peak power is not affected by the change of DOD from 100% to 90%. The reason is that the limiting factor for reducing the peak load is the maximum discharging power.

When the feeder includes DG units, the DS unit allows for a higher level of DG power export:

- When a DS unit with the AC efficiency of 70% and without power and storage capacity constraints is used, the maximum allowed DG power export is increased by 1.2 MW. The DS unit parameters required for this case are: (i) the maximum charging power of 1.24 MW, (ii) the maximum discharging power of 0.77 MW, and (iii) the storage capacity of 7.1 MWh.
- When the DS unit is a typical 1 MW NaS battery with 7.2 MWh storage capacity and 100% DOD, the maximum allowed DG power export is increased up to 1.2 MW. The actual value is between 1.1 MW and 1.2 MW and depends on the permissible power export from the feeder.
- When the DS unit is a typical 1 MW NaS battery with 7.2 MWh storage capacity and 90% DOD, the maximum allowed DG power export is increased up to 1.1 MW. The actual value is between 1.0 MW and 1.1 MW and depends on the allowed power export from the feeder.

The study results show that the location of the DS unit can change the overall system losses but in all cases this effect is less than 1%. The most efficient location is a location as close as possible to the source for DS unit charging.

2.2 Feeder Type B - Residential/Industrial feeder

The second type of feeder analyzed in this study is a mixed Residential/Industrial feeder, Figure 2.31. The feeder supplies a large number of small residential loads distributed along the feeder and one large industrial load at the end of the feeder. The industrial load can include one large DG unit.

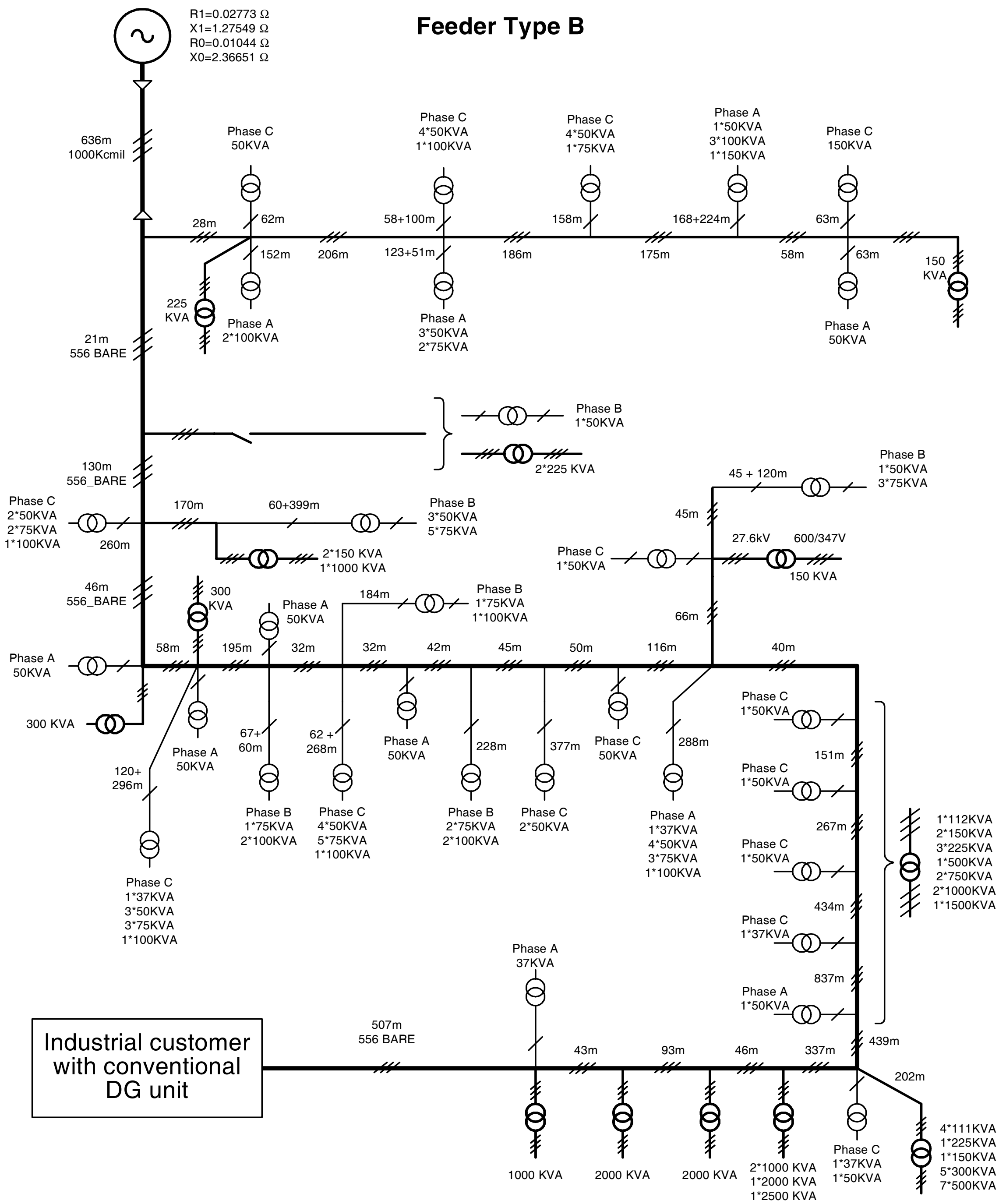

Figure 2.31 One-line diagram of Feeder Type B - Residential/Industrial feeder

To identify the cable ampacity limits and to specify potential DS unit locations, the feeder of Figure 2.31 is divided in multiple sections, as shown in Figure 2.32. The feeder is sectionized so that there is at least one feeder section between any two major loads or a group of loads. Seven sections are used for Feeder Type B. The maximum feeder loading for each section is based on the cable ampacity as shown in Table 2.7. The feeder section B1, closest to the transformer station, is the 1000 kcmil cable with the maximum current 500 A. The minimal currents for the remaining sections are higher (777 A), therefore section B1 is the critical section for all cable ampacity studies.

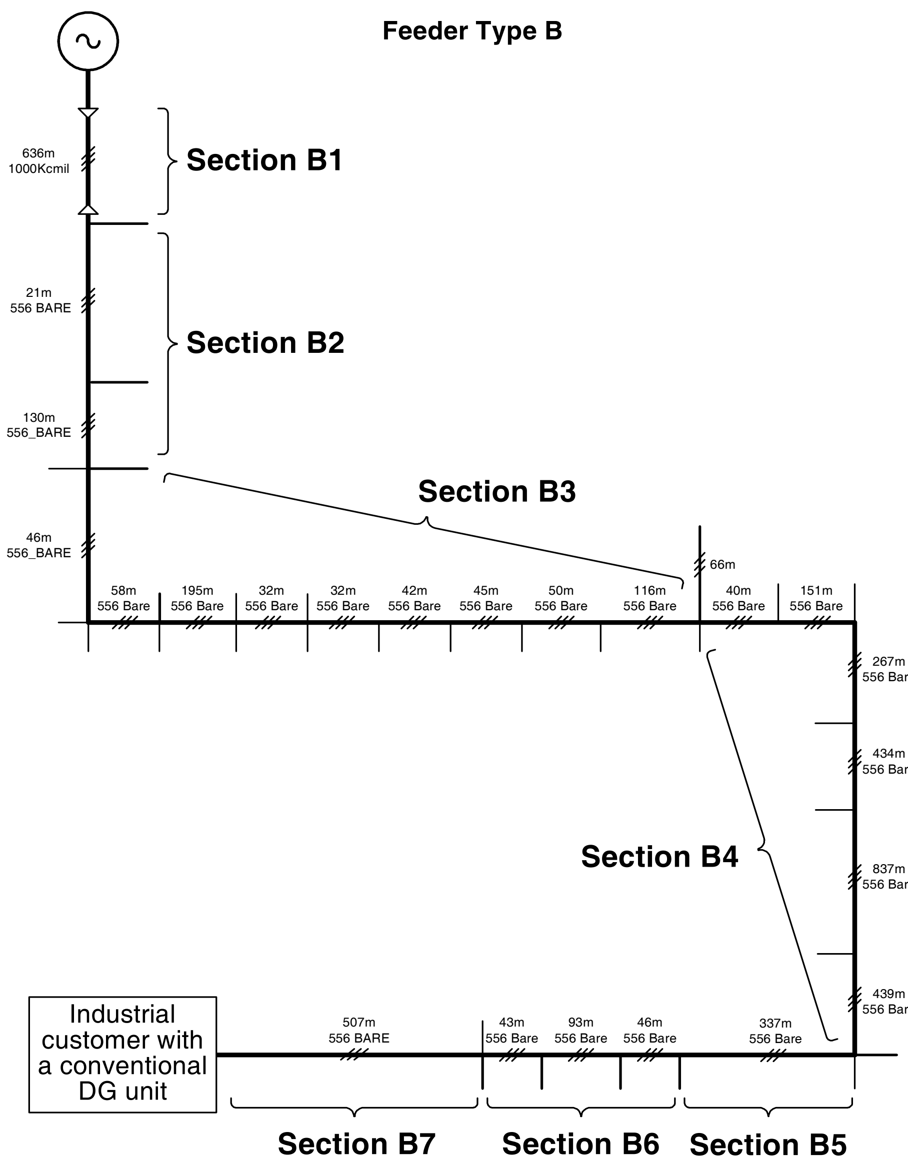

Figure 2.32 Sections of Feeder Type B - Residential/Industrial feeder

The industrial customer that includes a conventional DG unit is located after Section B7, at the end of the feeder. Three potential locations for placing a DS unit are analyzed:

- end of section B7 (at the feeder end), where the major industrial load with a DG is located,
- end of section B4, at the middle of the feeder, where a large cluster of residential loads is located,
- end of section B1, since it has the lowest cable ampacity limit (500 A).

The typical daily peak load for this feeder is 9.79 MW and the normal daily load diagram based on the typical load data from Tables 1.1 and 2.1, is given in Table 2.8.

Table 2.7 Feeder cable ampacity per section

Section number	Cable Type	Cable Ampacity (A)	Maximum Power (MW)	Section Resistance (mΩ)
B1	1000kcmil	500	23.9	75
B2	556 Bare	777	37.1	15
B3	556 Bare	777	37.1	63
B4	556 Bare	777	37.1	221
B5	556 Bare	777	37.1	34
B6	556 Bare	777	37.1	20
B7	556 Bare	777	37.1	52

Table 2.8 Normal daily load diagram for Feeder Type B - Residential/Industrial feeder

Time Period (hours)			Industrial Load, MW	Residential Load, MW	Total Feeder Load, MW
Period #	From	To			
1	0	5	3.35	3.91	7.26
2	5	8	3.25	4.29	7.53
3	8	10	3.41	5.13	8.54
4	10	12	3.75	5.90	9.65
5	12	14	3.58	5.97	9.56
6	14	15	3.75	5.67	9.42
7	15	18	3.93	5.51	9.45
8	18	21	3.58	6.20	9.79
9	21	23	3.41	5.90	9.31
10	23	24	3.41	4.75	8.16

2.2.1 Battery Option 1 – No energy storage is available

The first set of studies is performed under the assumption that there is no storage unit in the system. The results from this case study are used as the benchmark to evaluate the study results when the system includes DS.

Conventional operation

a) ***Normal daily loading*** **-** The total feeder loading is equal to the normal daily loading from Table 2.8. The industrial load is distributed among three-phase transformers, while the residential load is distributed among three-phase and single-phase transformers. No DG units are connected to the feeder.

The study results provide the feeder loading (in Amperes) for each of the seven sections of Feeder Type B (as defined in Figure 2.32), and for all 10 time periods (as specified in Table 2.8). The study results are presented in Figure 2.33.

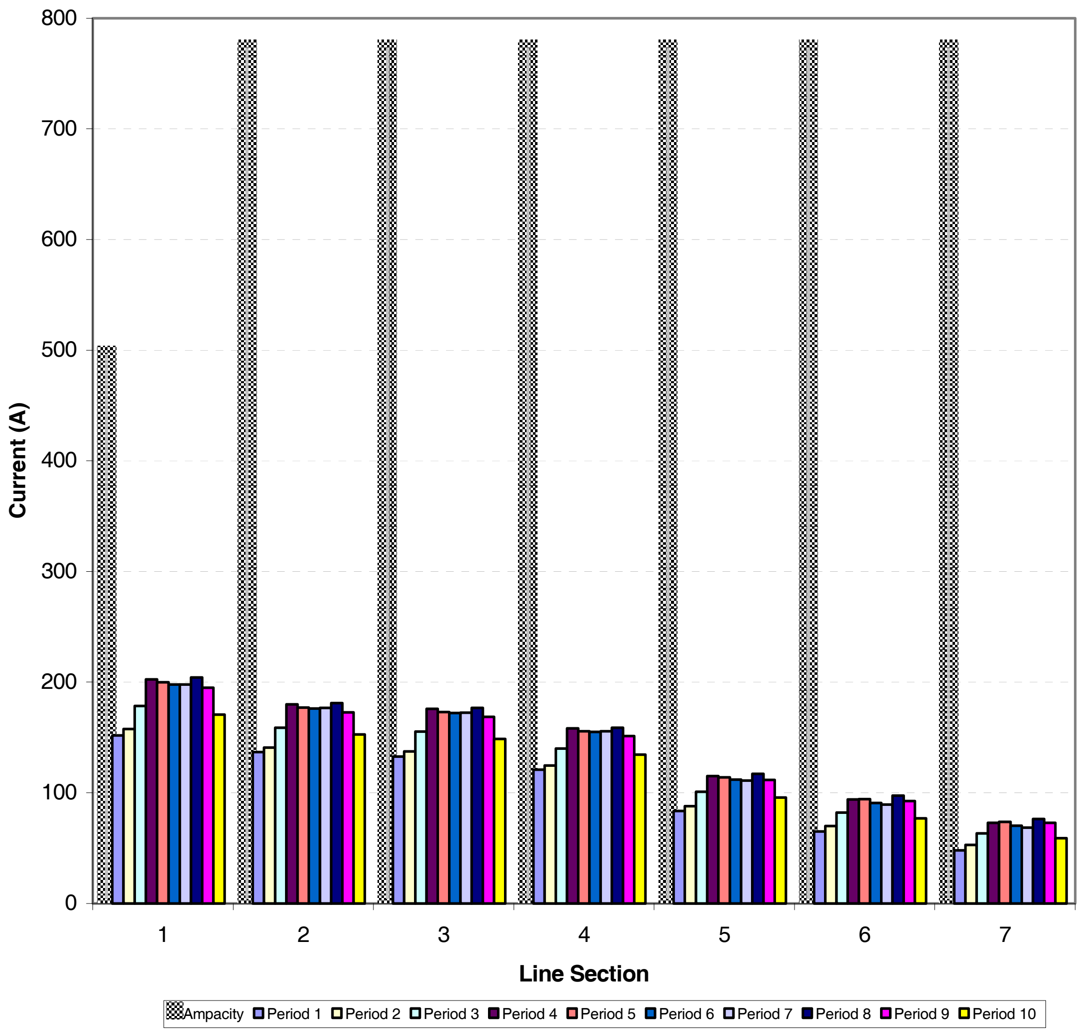

Figure 2.33 Feeder loading per section for normal loading (no DS or DG in the system)

Figure 2.33 compares how the current associated with the normal daily loading compares with the cable ampacity in each feeder section. All cable sections are loaded with less than 40% of the ampacity limits.

b) ***The maximum allowable feeder loading*** – The load for this case study is obtained by scaling up all individual loads of case (a) until one of the cable ampacity limits is reached. The study results for this test case are presented on Figure 2.34.

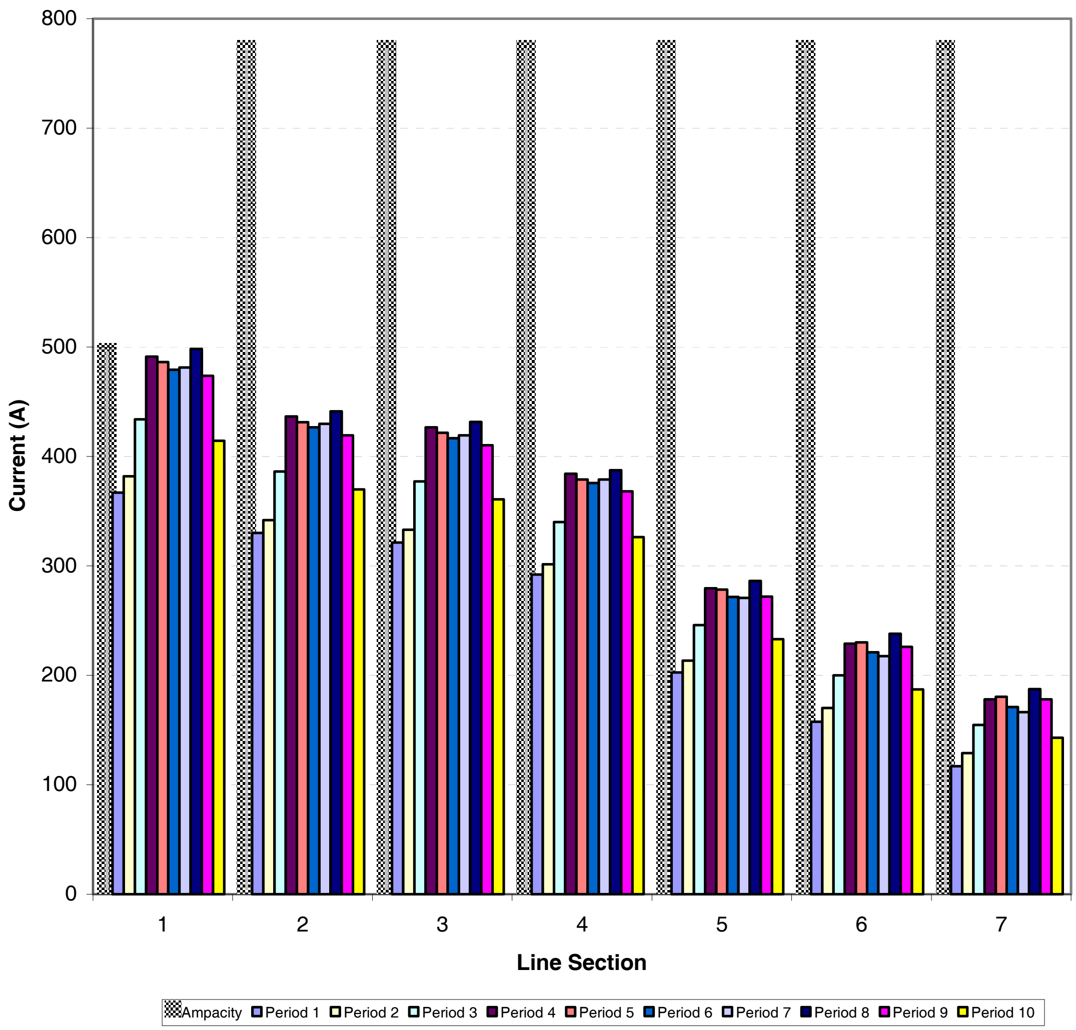

Figure 2.34 Feeder loading per section for cable ampacity loading and no DS or DG in the system

The results from Figure 2.34 show that the maximum cable loading in this case occurs on feeder section B1, during the peak power period (period #8, between 18:00 and 21:00). The total load peak power that brings the cable ampacity of feeder section B1 to the limit is 23.6 MW. The maximum voltage drop for this case is 1.2%. It is calculated at the end of Section 7, during time period #8, between 18:00 and 21:00. This scenario is associated with the highest possible voltage drop for this feeder. Since 1.2% is significantly less than the maximum allowed 6% voltage drop, we conclude that voltage drop is not a factor in any of the case studies for this feeder.

Permissible power export

A normal daily loading is assumed for the feeder of Figure 2.31. The typical daily load diagram is given in Table 2.8. One DG unit is connected to the feeder. The maximum allowed DG capacity is determined such that the power export from the feeder is either less than or equal to the value specified by the utility (e.g. 5 MW) at all times. The study results for this test case are presented on Figure 2.35.

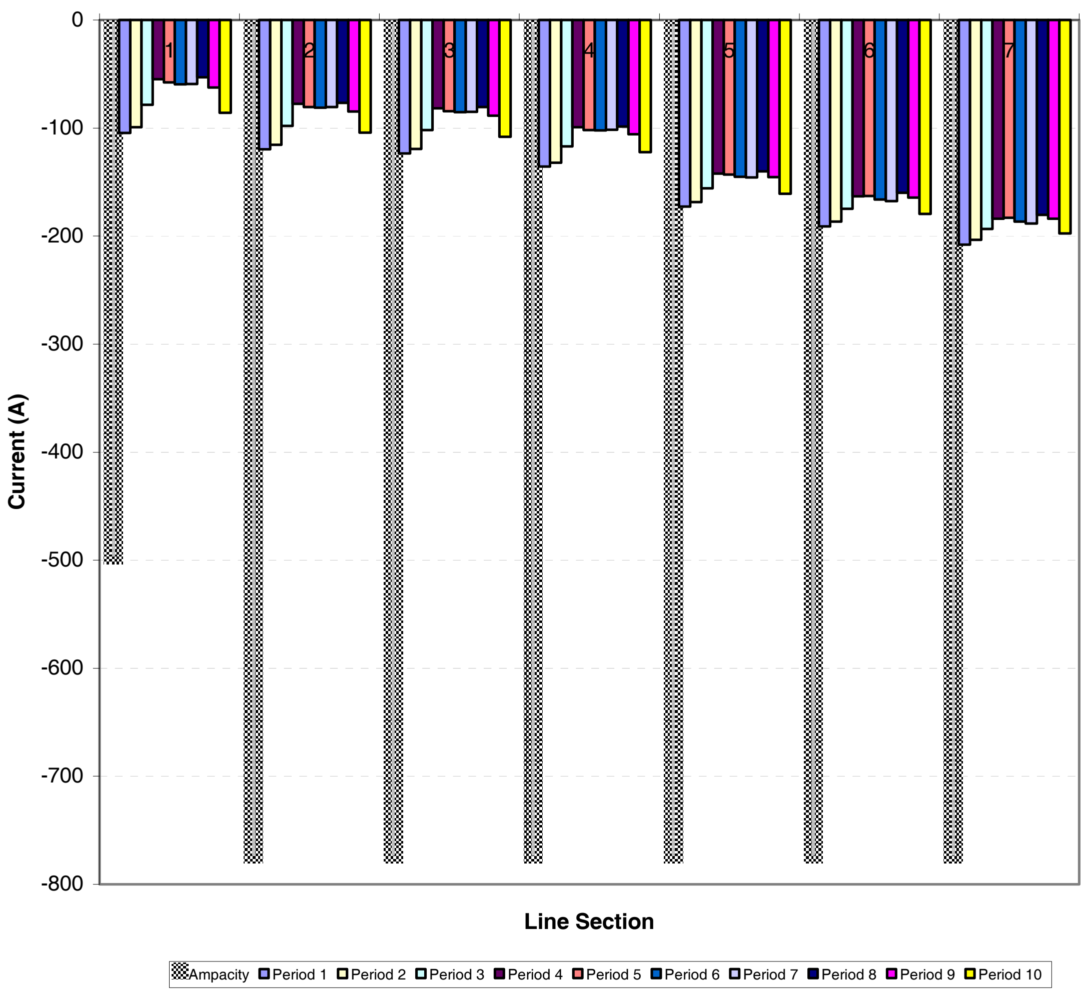

Figure 2.35 Feeder loading per section when 12.3 MW DG is installed after Section B7 and no DS is connected to the feeder

The results of Figure 2.35 show that when 12.3 MW produced by the DG unit, under normal daily load condition, the maximum power export is 5 MW, as specified by the utility. The critical time period when the maximum power export limit is reached is at night (period #1, between midnight and 5:00).

Maximum power export

A normal daily loading is assumed for the feeder of Figure 2.31. The typical daily load diagram is given in Table 2.8. One DG unit is connected to the feeder at the end of section B7. The maximum allowed DG capacity is determined such that the power export from the feeder is less than the cable ampacity of the 1000 kcmil cable of section B1. The study results for this test case are presented on Figure 2.36.

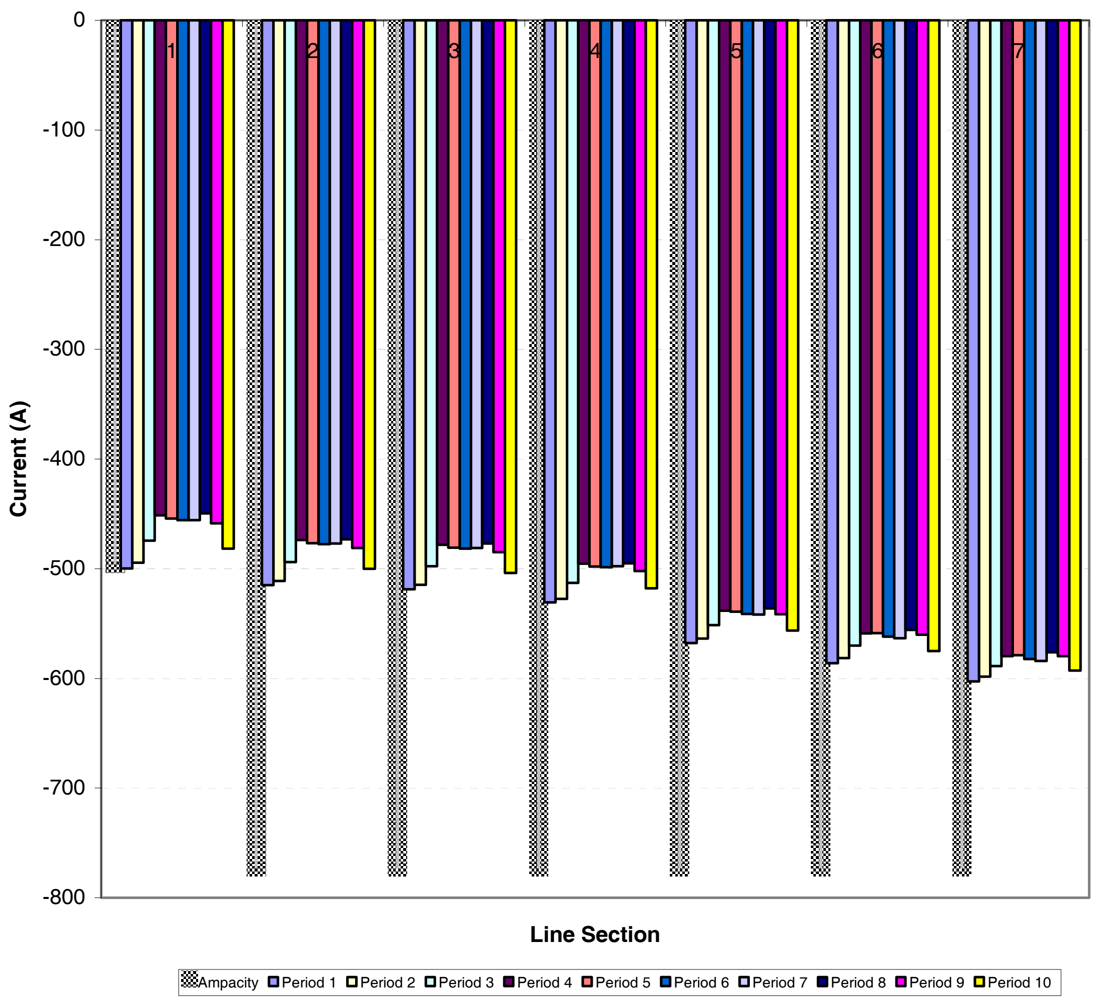

Figure 2.36 Feeder loading per section when 31.9 MW DG is installed after Section B7 and no DS is connected to the feeder

The results of Figure 2.36 show that when 31.9 MW produced by the DG unit, under normal daily load condition, the maximum power export is 23.9 MW which is equal to the cable ampacity of the section B1 feeder (Table 2.7). The critical time period when the maximum power export limit is reached is at night (period #1, between midnight and 5:00).

2.2.2 Battery Option 2 – Generic case with no power or energy limits

The second set of studies is performed under the assumption that one large DS unit is used and the power and energy constrains have not been imposed. An AC efficiency of 70% is assumed for this generic case.

Conventional operation

Based on the feeder cable ampacity (Table 2.7), the maximum permissible power in section B1 is 23.9 MW. In the case study of Figure 2.34, without storage, the daily peak (including the distribution system losses) is equal to the maximum permissible power in section B1 (23.9 MW). By placing the DS unit on the feeder, the maximum load can be increased. Figure 2.37 shows the impact of storage charge/discharge control strategy based on the procedure of Section 1.2.1.

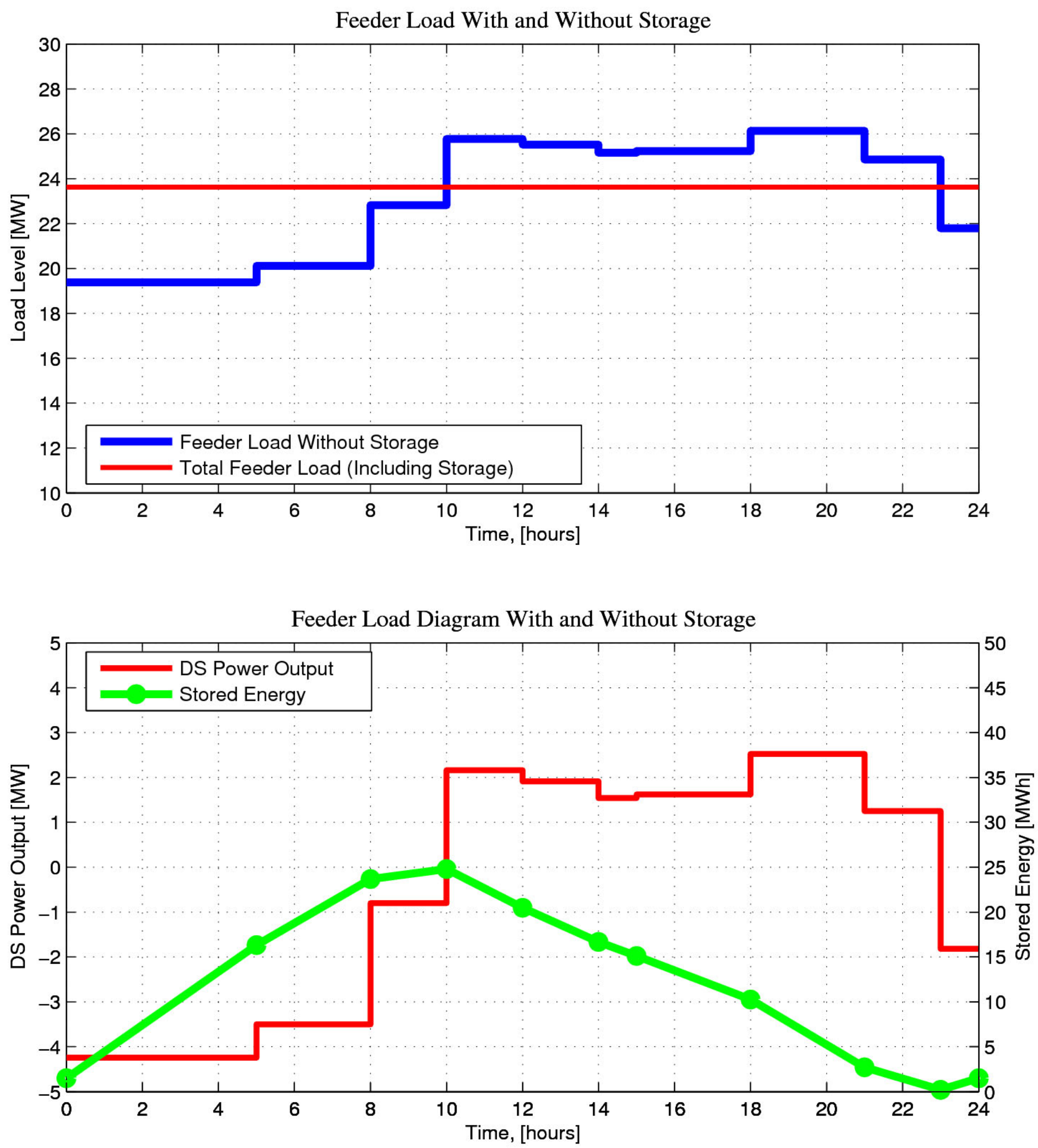

Figure 2.37 DS charge/discharge strategy and the effect of DS unit on feeder loading

On Figure 2.37 the permissible daily peak load in the presence of the DS unit can be increased to 26.4 MW, compared to 23.6 MW for the case without storage. The total energy produced by the DS unit during the battery discharge period is 70% of the consumed energy during the battery charge period. To achieve the storage charge/discharge performance characteristic from Figure 2.37, the DS unit rating should be:

- the maximum charging power of 4.24 MW,
- the maximum discharging power of 2.52 MW,
- the storage capacity of 24.79 MWh.

As explained before, three locations are considered for the DS unit:

- end of section B7, where the major industrial load with a DG is located (Figure 2.8),
- end of section B4, where the large cluster of residential loads is located (Figure 2.9),
- end of section B1, since it has the lowest cable ampacity limit (Figure 2.10).

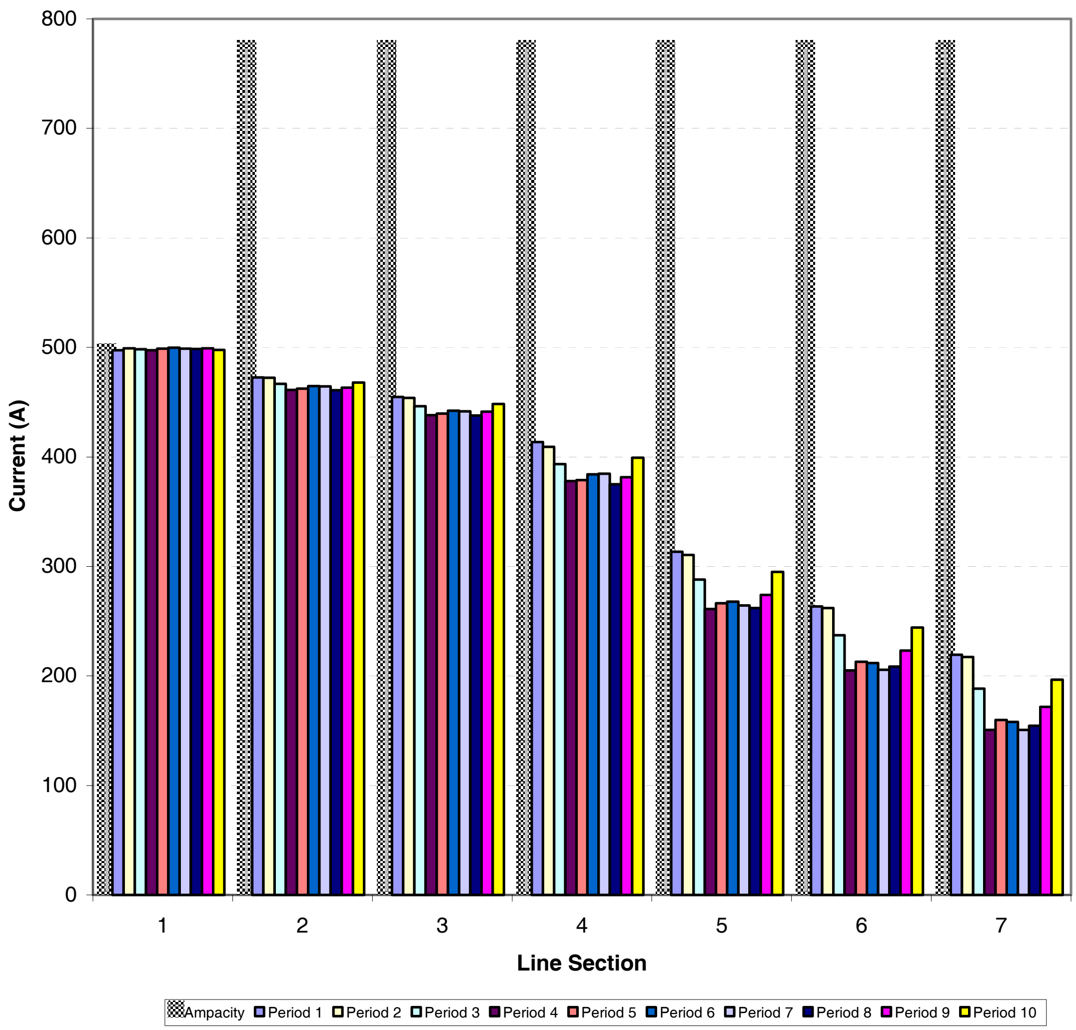

Figure 2.38 Feeder loading per section for cable ampacity loading with one DS unit (70% efficiency and no power/energy limits), located after section B7 and no DG in the system

Figure 2.38 shows that locating the DS unit at the end of the feeder (after section B7) reduces the feeder loading on all feeder sections during the mid-day period. This results in a higher total load limit (26.4 MW), compared to the case without the storage (23.6 MW). The feeder loading at night is increased on all sections (due to the DS charging).

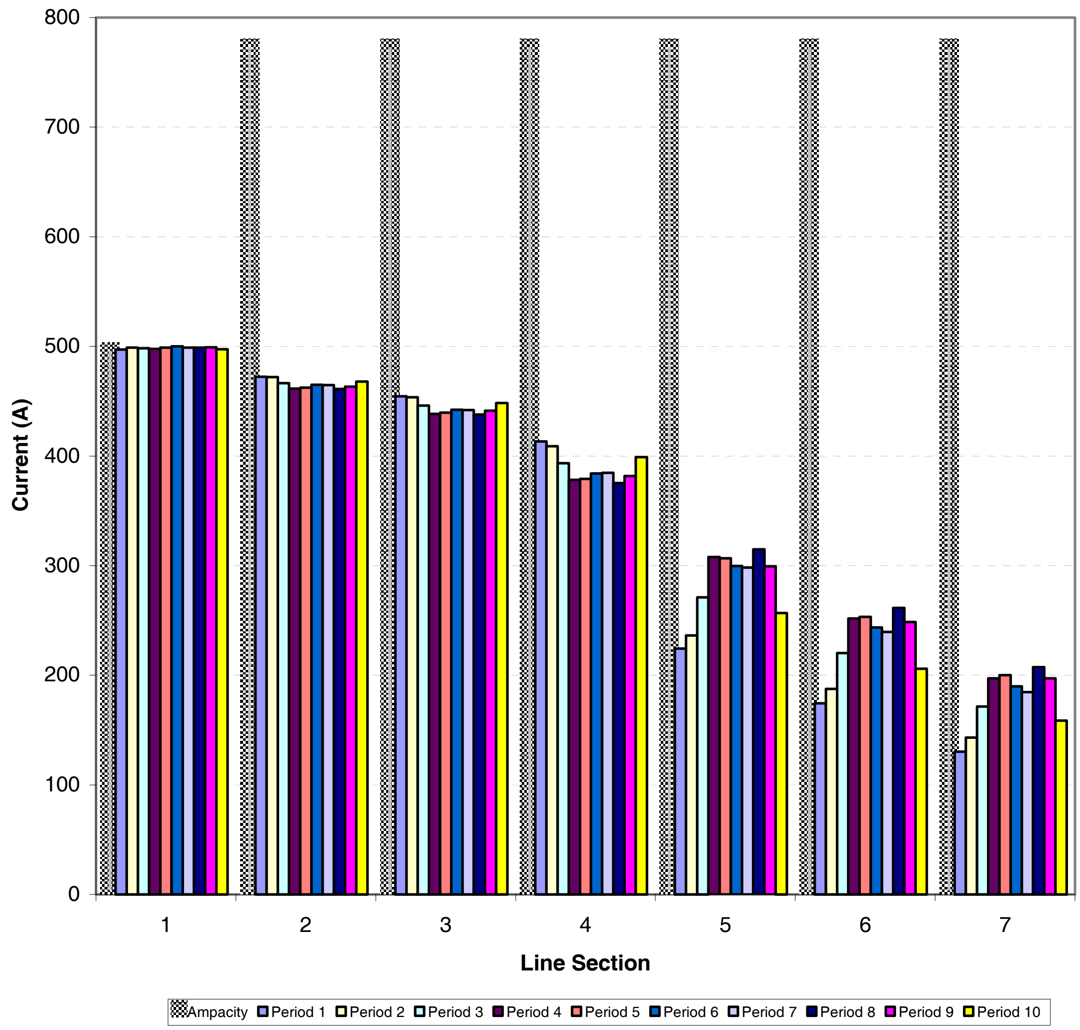

Figure 2.39 Feeder loading per section for cable ampacity loading with one DS unit (70% efficiency and no power/energy limits), located after section B4 and no DG in the system

Figure 2.39 shows that locating the DS unit after section B4 reduces the loadings of feeder sections B1, B2, B3, and B4 during the mid-day. Sections B1, B2, B3, and B4 experience higher loadings at night (due to the DS charging) a similar way to the previous case. Loadings of section B5, B6 and B7 are not affected by the presence of the DS unit. The loadings of those sections do not affect the maximum permissible load because of their high ampacity limits (777 A).

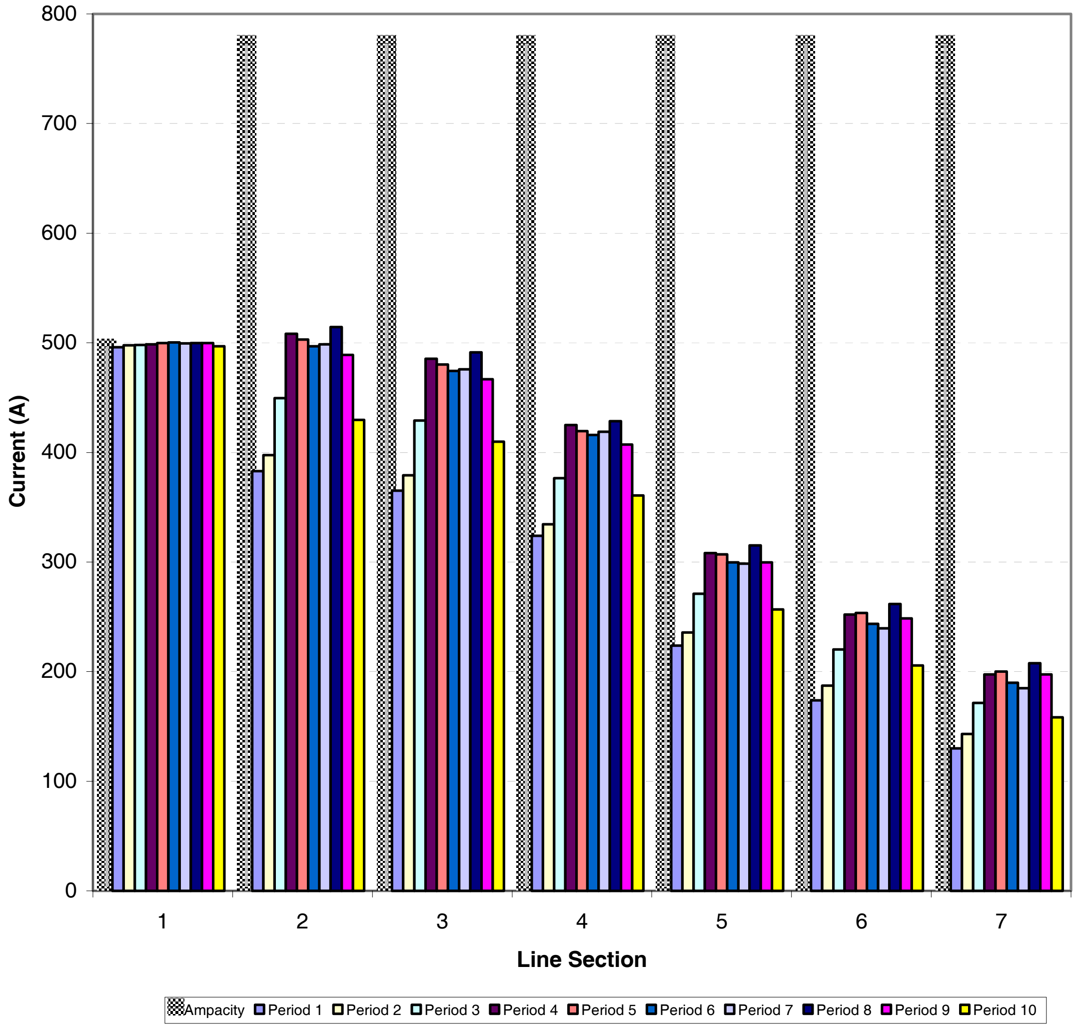

Figure 2.40 Feeder loading per section for cable ampacity loading with one DS unit (70% efficiency and no power/energy limits), located after section B1 and no DG in the system

Figure 2.40 shows that locating the DS unit after section B1 reduces the feeder loading on feeder section B1 only. The loadings of the downstream sections (B2, B3, B4, B5, B6 and B7) are not affected by the presence of the DS unit. The feeder loading of section B1 at night is increased (due to the DS charging) similar to the previous case.

The study results from Figures 2.38 to 2.40 show that in all case studies the presence of the DS unit allows for higher load levels (26.4 MW vs. 23.6 MW) without overloading the critical feeder section (B1).

To evaluate the effect of the DS unit location, the detailed analysis of system losses for all three scenarios has been performed. The system losses for the three scenarios corresponding to various DS unit locations and all ten time periods are presented in Table 2.9. Distribution of power losses throughout the day for the three DS unit location scenarios is given on Figure 2.41.

Table 2.9 System losses for all three DS unit location scenarios

Time Period	Hours	Power loss (kW)			Energy loss per day (kWh)		
		DS after B1	DS after B4	DS after B7	DS after B1	DS after B4	DS after B7
1	5	192	248	262	959	1241	1310
2	3	207	255	267	622	765	800
3	2	256	267	270	511	534	539
4	2	313	267	274	627	533	547
5	2	312	284	278	625	569	556
6	1	300	278	273	300	278	273
7	3	297	273	268	891	820	804
8	3	327	267	281	980	800	844
9	2	301	267	279	602	533	558
10	1	234	267	266	234	267	266
				Total	6350	6339	6498

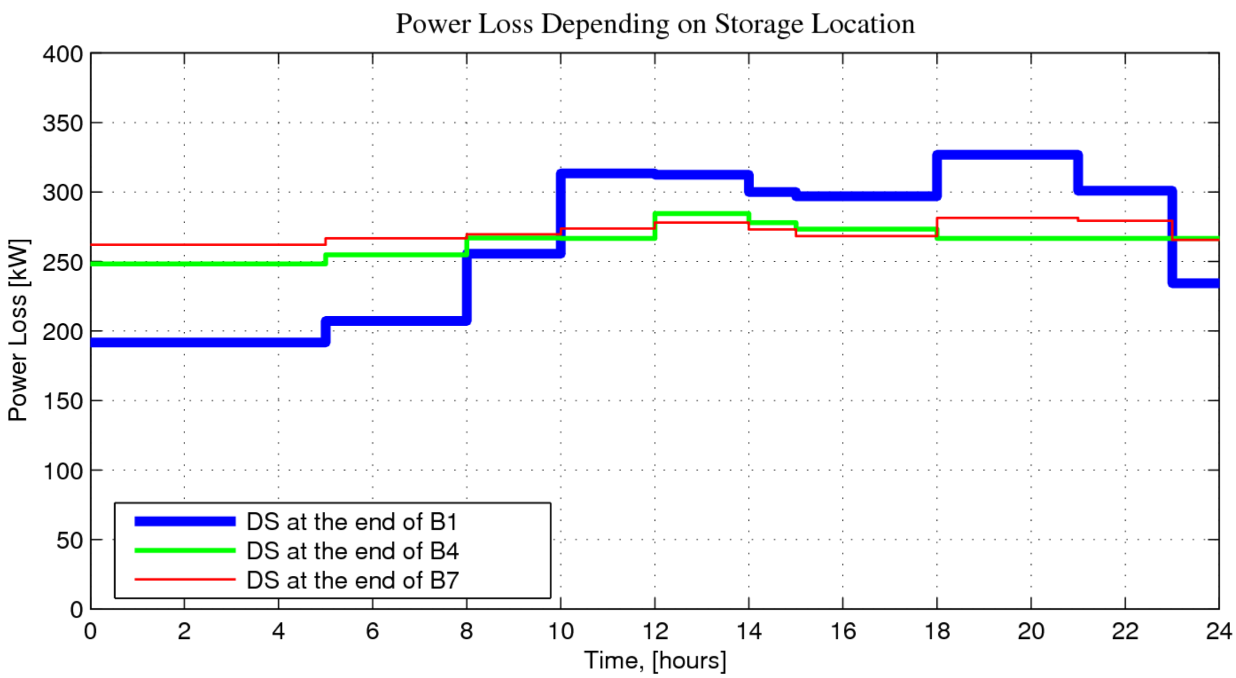

Figure 2.41 Distribution of system losses for all three DS unit location scenarios

Table 2.9 and Figure 2.41 show that the most efficient operation is when the DS unit is located just after the feeder section with the highest section resistance (B4 in this case). The difference between the lowest (after section B4) and the highest loss values (after section B7) is 2.5%. This indicates that from the point of view of the maximum allowable feeder loading, the DS unit should be located just after the feeder section with the highest section resistance.

Permissible power export

A typical daily load diagram based on Table 2.8 is assumed. One DG unit and one DS unit are connected to the feeder. The criterion for the DS charge/discharge strategy is to enable the DG unit to export maximum constant power throughout the day. Figure 2.42 shows the loading of the feeder section B1, the required DS charging/discharging power, and the energy stored in the DS (so that the combined power of the load and the DS is constant).

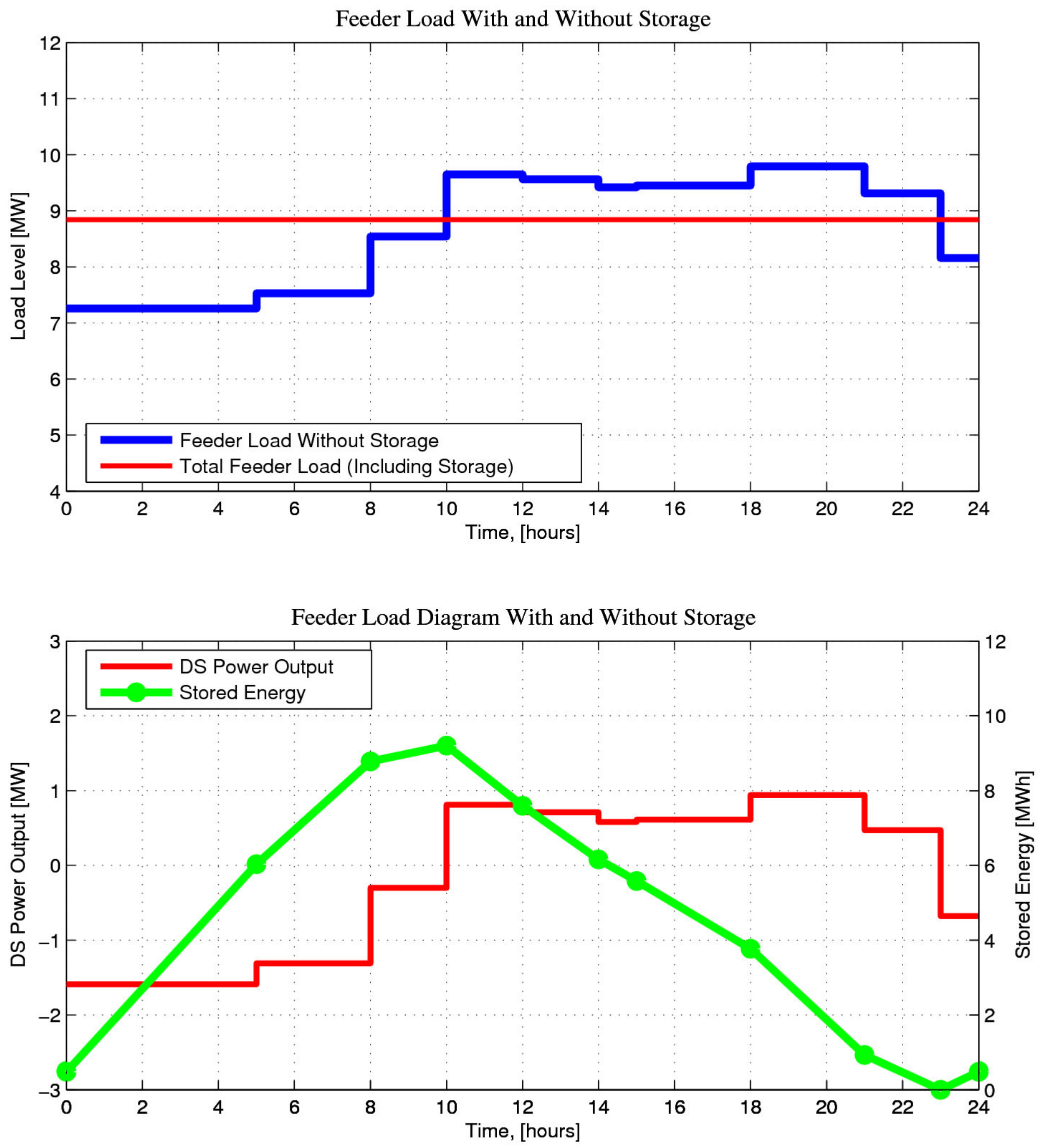

Figure 2.42 DS charge/discharge strategy and the effect of DS unit on feeder loading

Figure 2.42 shows that a constant power of 8.84 MW can be achieved for the mixture of the load and the DS unit. The parameters of the DS unit that satisfies charge/discharge strategy shown on Figure 2.42 are:

- the maximum charging power of 1.59 MW,
- the maximum discharging power of 0.94 MW,
- the storage capacity of 9.2 MWh.

The total power export from the feeder is the difference between the exported power from the DG unit and the combined power of the load and the DS unit. From Figure 2.42, to keep the maximum power export at the utility at the permissible value of 5 MW, the exported power from the DG should be 13.8 MW. This is an approximate value, as it does not take into consideration that the DG reverses the power flow in all feeder sections and, thus losses in the system are different with and without the DG unit in service. The practical DG power limit is determined from the power flow studies and is slightly larger, 13.9 MW. This is 1.6 MW more than it would be allowed if the DS is not in the system.

In power flow studies, three locations are considered for the DS unit:

- end of section B7, where the major industrial load with a DG is located (Figure 2.43),
- end of section B4, where the large cluster of residential loads is located (Figure 2.44),
- end of section B1, since section B1 has the lowest cable ampacity limit (Figure 2.45).

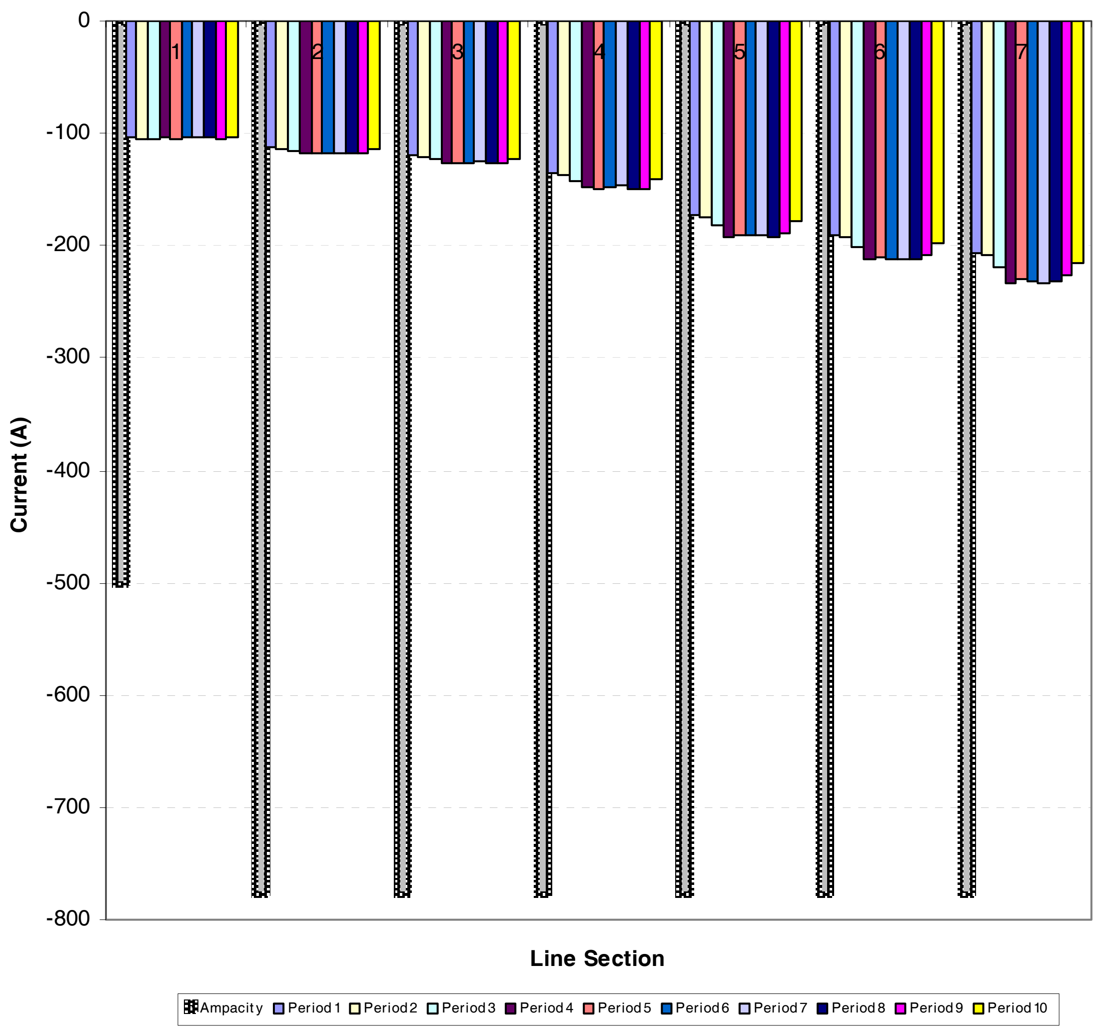

Figure 2.43 Feeder loading per section when 13.9 MW DG is installed after Section B7 and DS is connected of the feeder (after Section B7)

In the case of Figure 2.43, the DS unit is located at the end of the feeder (after section B7), at the same location as the DG unit. The DS unit utilizes excess power from the DG unit at night, thus reducing the loading of all feeder sections during the critical time period for power export (from Figure 2.35, without the DS unit, the feeder loading is highest on all sections during period #1, from midnight to 5 am). The feeder loadings are at all times are much lighter than the cable ampacity limits.

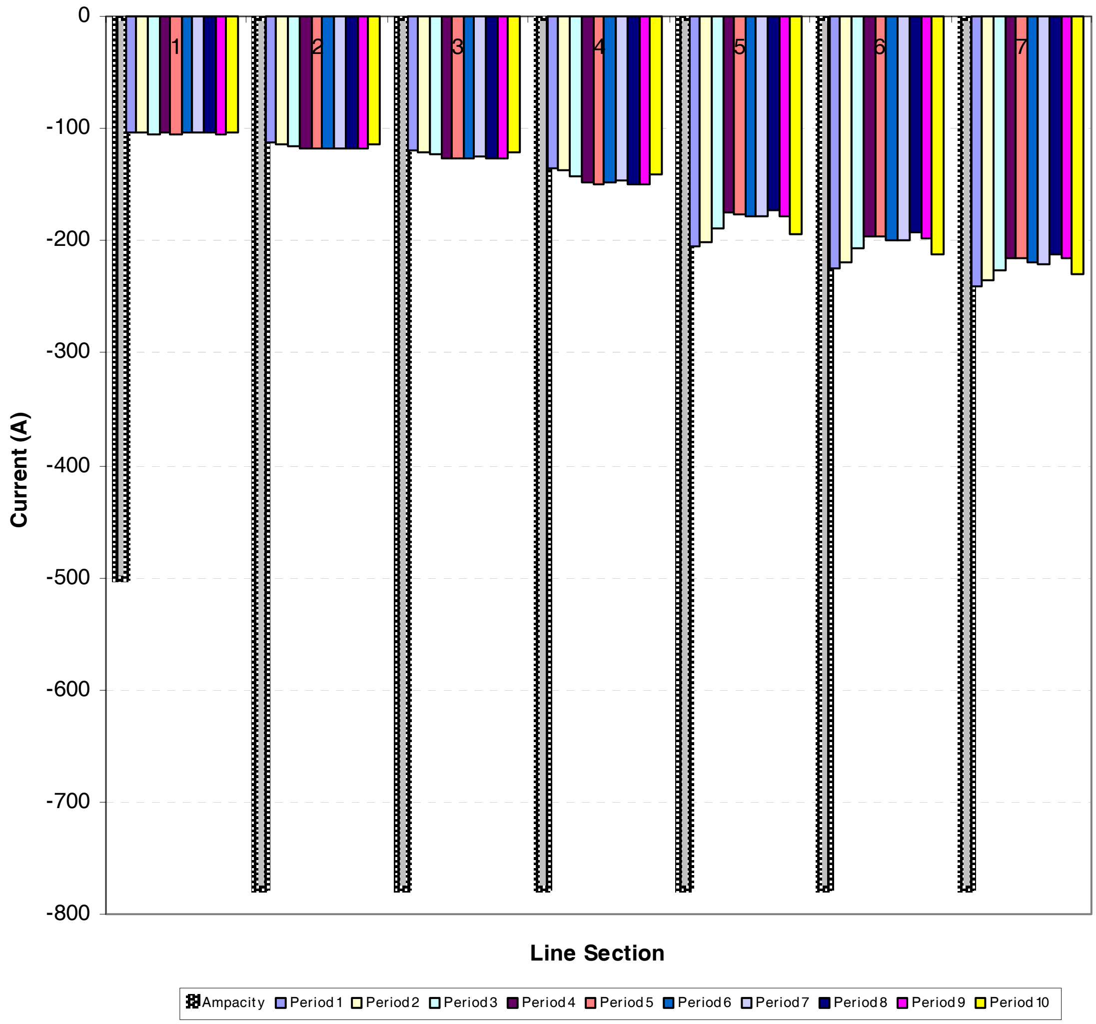

Figure 2.44 Feeder loading per section when 13.9 MW DG is installed after Section B7 and DS is connected of the feeder (after Section B4)

In the case of Figure 2.44, the DS unit is located after section B4 and during the period of light load the DS unit absorbs a portion of power generated by the DG unit. This allows for a higher power export at night (13.9 MW vs. 12.3 MW) and reduces the loadings of the feeder sections B1, B2, B3, and B4. The loadings of feeder sections B5, B6 and B7, for the same DG power, are not affected by the presence of the DS unit. The feeder loadings at all times are much less than the corresponding cable ampacity limits.

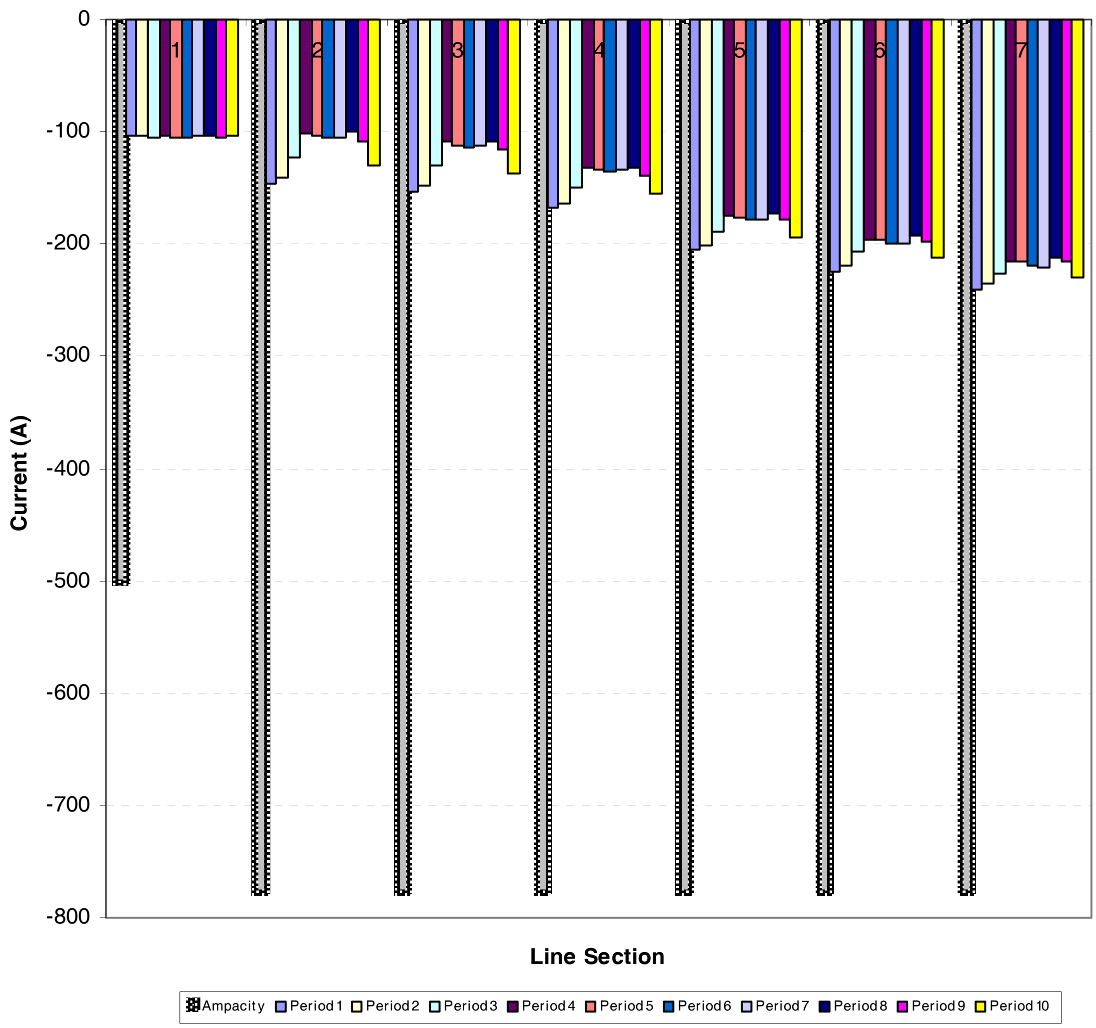

Figure 2.45 Feeder loading per section when 13.9 MW DG is installed after Section B7 and DS is connected of the feeder (after Section B1)

In the case of Figure 2.45, the DS unit is located immediately after feeder section B1 and during the period of the light load the DS unit absorbs a portion of the power generated by the DG unit. Similar to the previous two study cases, this reduces the feeder power export to the permissible limit of 5 MVA. The loadings of sections B2, B3, B4, B5, B6 and B7 are not affected by the presence of the DS unit (for the same DG power export). The feeder loadings at all times are much less than the cables ampacity limits.

The study results show that in all cases the presence of the DS unit allows for a larger DG unit to be installed at the industrial customer's site (13.9 MW vs. 12.3 MW) without violating the prescribed power export limit of 5 MW.

To evaluate the effect of the DS unit location, a detailed loss analysis for all three scenarios has been performed. The system losses for the three DS unit location scenarios and the ten time periods are presented in Table 2.10. Distribution of power losses throughout the day for the three DS unit location scenarios is given on Figure 2.46.

Table 2.10 System losses for all three DS unit location scenarios

Time Period	Hours	Power loss (kW)			Energy loss per day (kWh)		
		DS after B1	DS after B4	DS after B7	DS after B1	DS after B4	DS after B7
1	5	120	111	106	599	554	530
2	3	116	109	105	348	326	314
3	2	105	104	103	211	208	206
4	2	96	100	102	192	200	205
5	2	96	100	102	192	199	203
6	1	98	101	103	98	101	103
7	3	99	102	104	296	306	311
8	3	94	98	101	281	295	303
9	2	97	100	102	195	200	203
10	1	110	106	104	110	106	104
				Total	2521	2495	2483

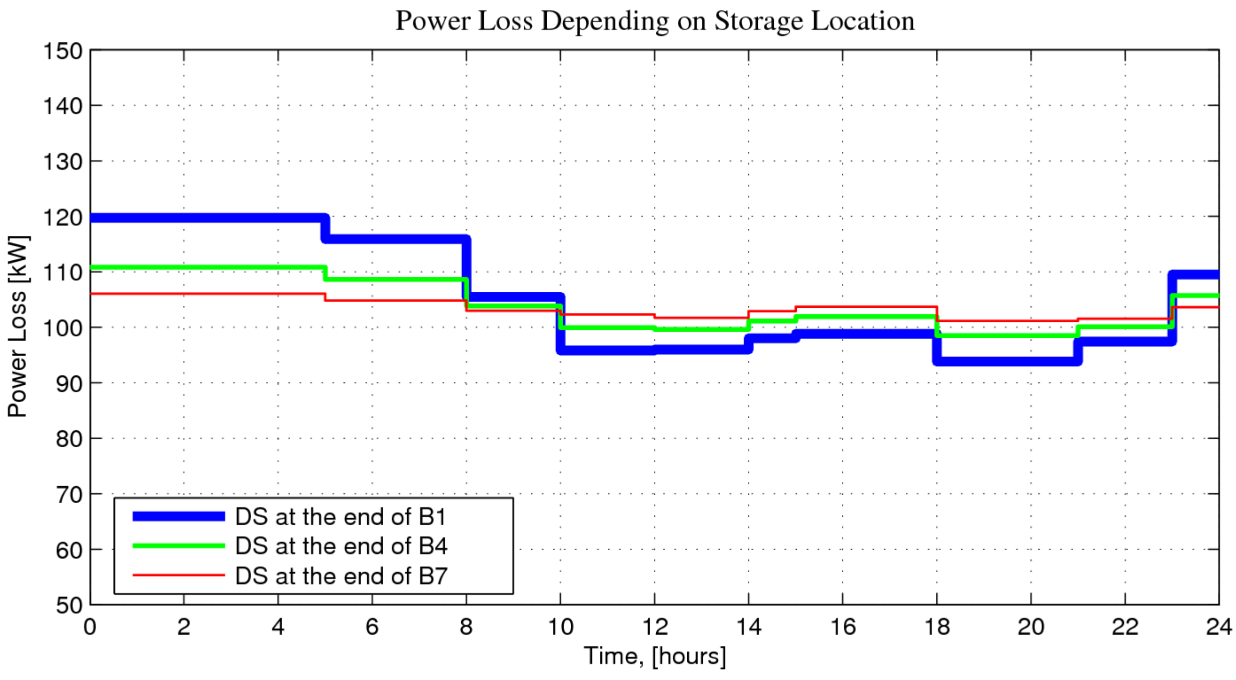

Figure 2.46 Distribution of system losses for all three DS unit location scenarios

Table 2.10 and Figure 2.46 show that the most efficient operation is when the DS unit is located after section B7. The reason is that the charging current is higher than the discharging current. Furthermore locating the DS unit at the same location as the DG unit exists minimizes losses during charging. The difference between the lowest and the highest loss values is 1.5%. This indicates that in this case the DS location is not a significant factor in the system energy loss.

Maximum power export

A typical daily load diagram based on Table 2.8 is assumed. One DG unit and one DS unit are connected to the feeder. The same DS unit charge/discharge strategy as shown on Figure 2.42 is adopted to keep the combined power of the load and the DS constant. It is assumed that the DG export power is limited so that the feeder current is less than or equal to the feeder ampacity limit. To keep the critical feeder section (B1 in this case) from overloading, the DG power limit is determined from the power flow studies and is 33.3 MW. This is 1.4 MW more than it would be allowed if the DS does not exist in the system.

In power flow studies, three locations are considered for the DS unit:

- end of section B7, where the major industrial load with a DG is located (Figure 2.47),
- end of section B4, where the large cluster of residential loads is located (Figure 2.48),
- end of section B1, since section B1 has the lowest cable ampacity limit (Figure 2.49).

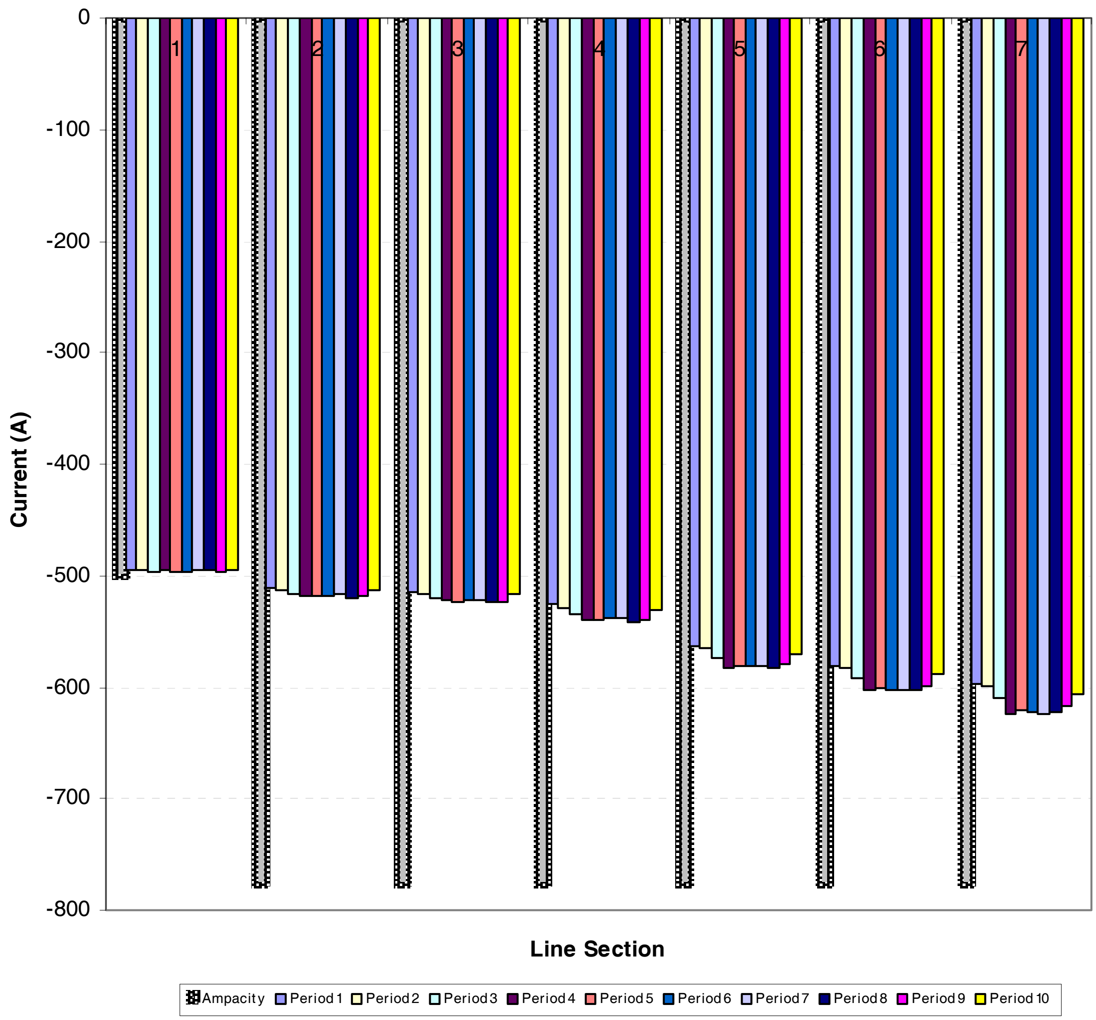

Figure 2.47 Feeder loading per section when 33.3 MW DG is installed after Section B7 and DS is connected of the feeder (after Section B7)

In the case of Figure 2.47, the DS unit is located at the end of the feeder (after section B7), and during the period of light load the DS unit absorbs a portion of the power generated by the DG unit. With this higher DG power export, the feeder loading on all feeder sections is reduced during period of light load so the higher export power from DG can be achieved (33.3 MW vs. 31,9 MW).

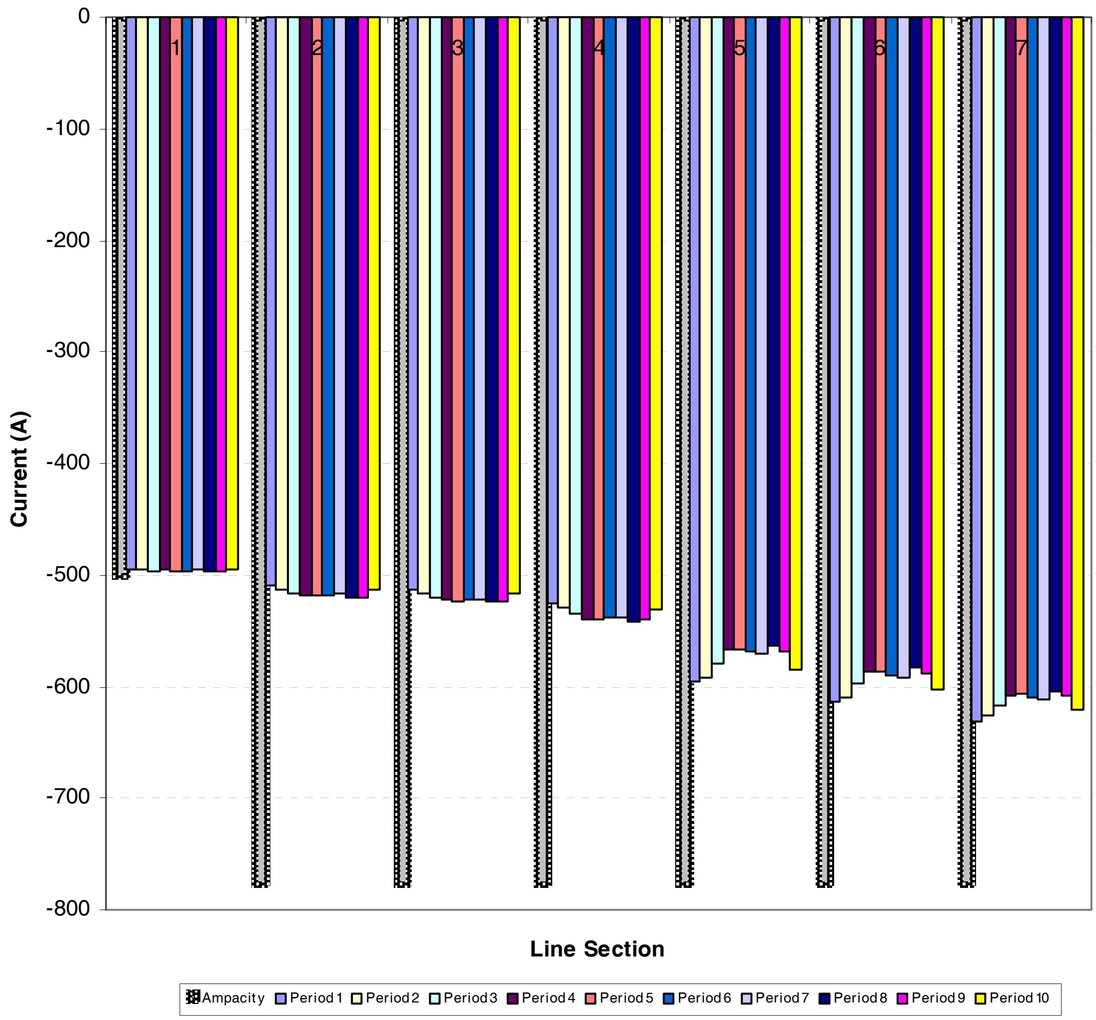

Figure 2.48 Feeder loading per section when 33.3 MW DG is installed after Section B7 and DS is connected of the feeder (after Section B4)

In the case of Figure 2.48, the DS unit is located after section B4 and during the period of light load the DS unit absorbs a portion of power generated by the DG unit. This allows for a higher power export at night (33.3 MW vs. 31.9 MW) and reduces the loadings of feeder sections B1, B2, B3, and B4. The loadings of feeder sections B5, B6 and B7 are not affected by the presence of the DS unit (for the same DG power export). The feeder loadings at all times are much less than the cable ampacity limits on all sections, except section B1.

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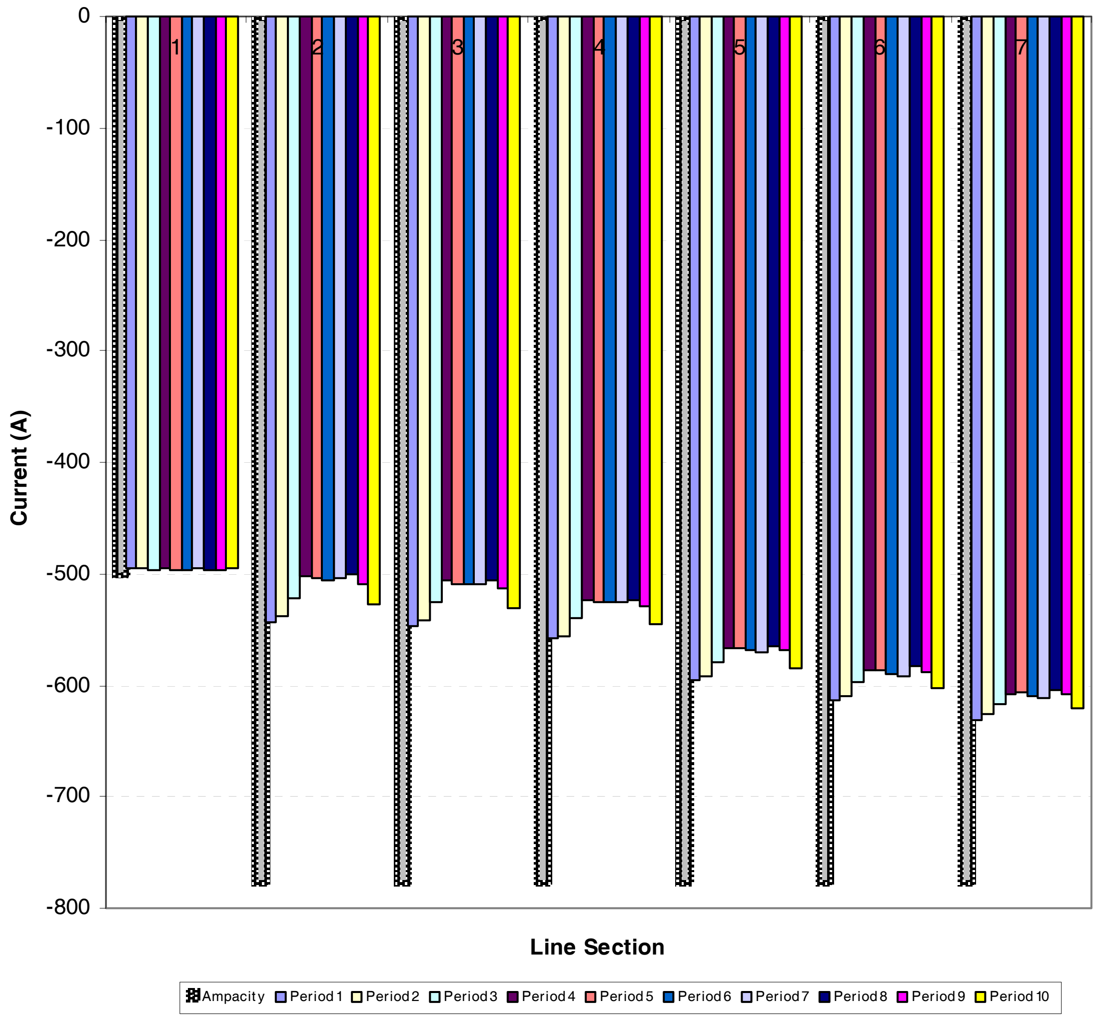


Figure 2.49 Feeder loading per section when 33.3 MW DG is installed after Section B7 and DS is connected of the feeder (after Section B1)

In the case of Figure 2.49, the DS unit is located after section B1 and during the period of light load the DS unit absorbs a portion of the power generated by the DG unit. This reduces section B1 current to the cable ampacity limit of 500 A. The loadings of sections B2, B3, B4, B5, B6 and B7 are not affected by the presence of the DS unit (for the same DG power export). The feeder loadings at all times are much less than the cables ampacity limits on all sections, except section B1.

The most efficient operation is when the DS unit is located after section B7. The reason is that the charging current is higher than the discharging current (due to storage efficiency), and locating DS in the same place as the DG unit exists minimizes losses during charging.

To evaluate the effect of the DS unit location, a detailed analysis of system losses for the three scenarios has been performed. The system losses for the three DS unit locations and the ten time periods are presented in Table 2.11. Distribution of power losses throughout the day for three DS unit location scenarios is given on Figure 2.50.

Table 2.11 System losses for all three DS unit location scenarios

Time Period	Hours	Power loss (kW)			Energy loss per day (kWh)		
		DS after B1	DS after B4	DS after B7	DS after B1	DS after B4	DS after B7
1	5	958	927	914	4790	4637	4570
2	3	947	922	911	2841	2766	2734
3	2	915	909	907	1830	1819	1814
4	2	883	898	905	1766	1796	1809
5	2	884	897	903	1768	1794	1806
6	1	890	902	907	890	902	907
7	3	893	904	909	2678	2712	2727
8	3	877	894	901	2630	2681	2703
9	2	889	899	903	1778	1797	1805
10	1	928	914	908	928	914	908
				Total	21898	21817	21783

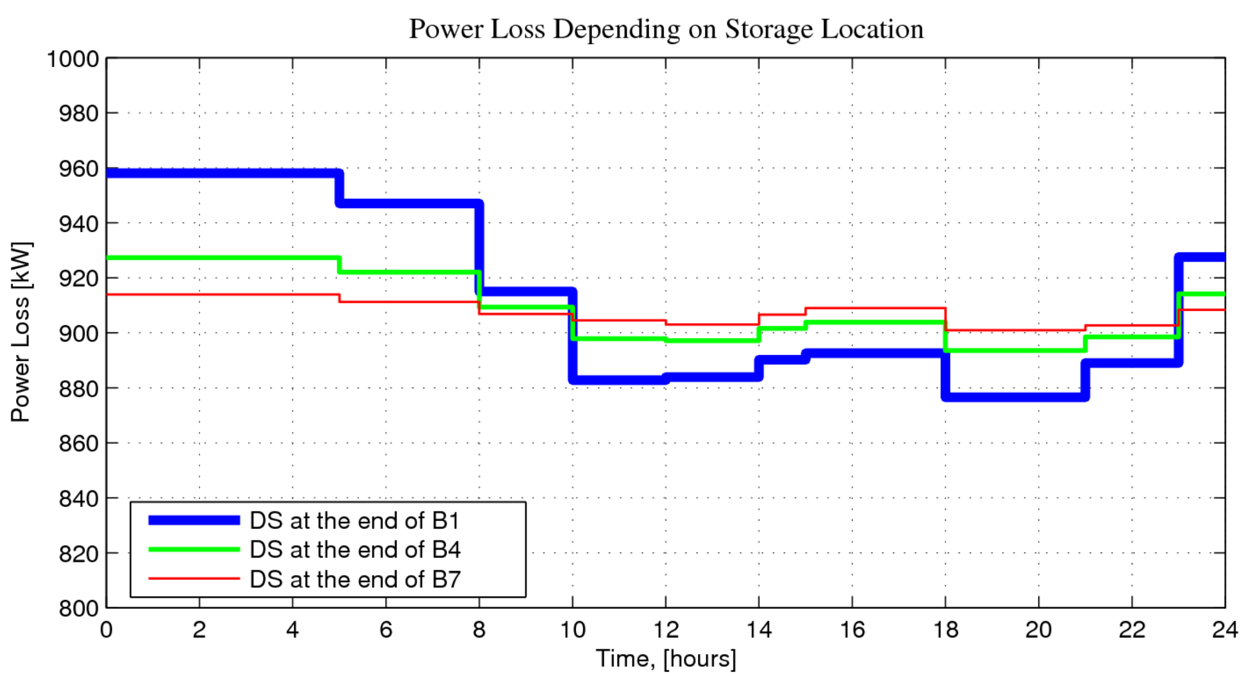


Figure 2.50 Distribution of system losses for all three DS unit location scenarios

Table 2.11 and Figure 2.50 show that the most efficient operation is when the DS unit is located after section B7, however the differences between the three scenarios are insignificant.

2.2.3 Battery Option 3 – 1 MW NaS Battery with 100% DOD

The third set of studies is performed under the assumption that one large 1 MW NaS battery-based on the main technical data from Section 1.2.2 is used. Charging power (on the AC side) is limited to 1.2 MW, while discharging power limit (on the AC side) is 1.2 MW for up to 3 hours and 1 MW perpetually. The available stored energy is up to 7.2 MWh (100% DOD). An AC efficiency of 80% is assumed for this case.

Conventional operation

Based on the feeder cable ampacity (Table 2.7), the maximum permissible power in section B1 is 23.9 MW. In the case study that analyzes the maximum permissible feeder loading without storage (Figure 2.34), the daily peak is equal to the maximum permissible power in section B1 (23.9 MW). By placing the DS unit on the feeder, the maximum load can be increased. Figure 2.51 shows the input of the storage charge/discharge control strategy based on the procedures of Section 1.2.2.

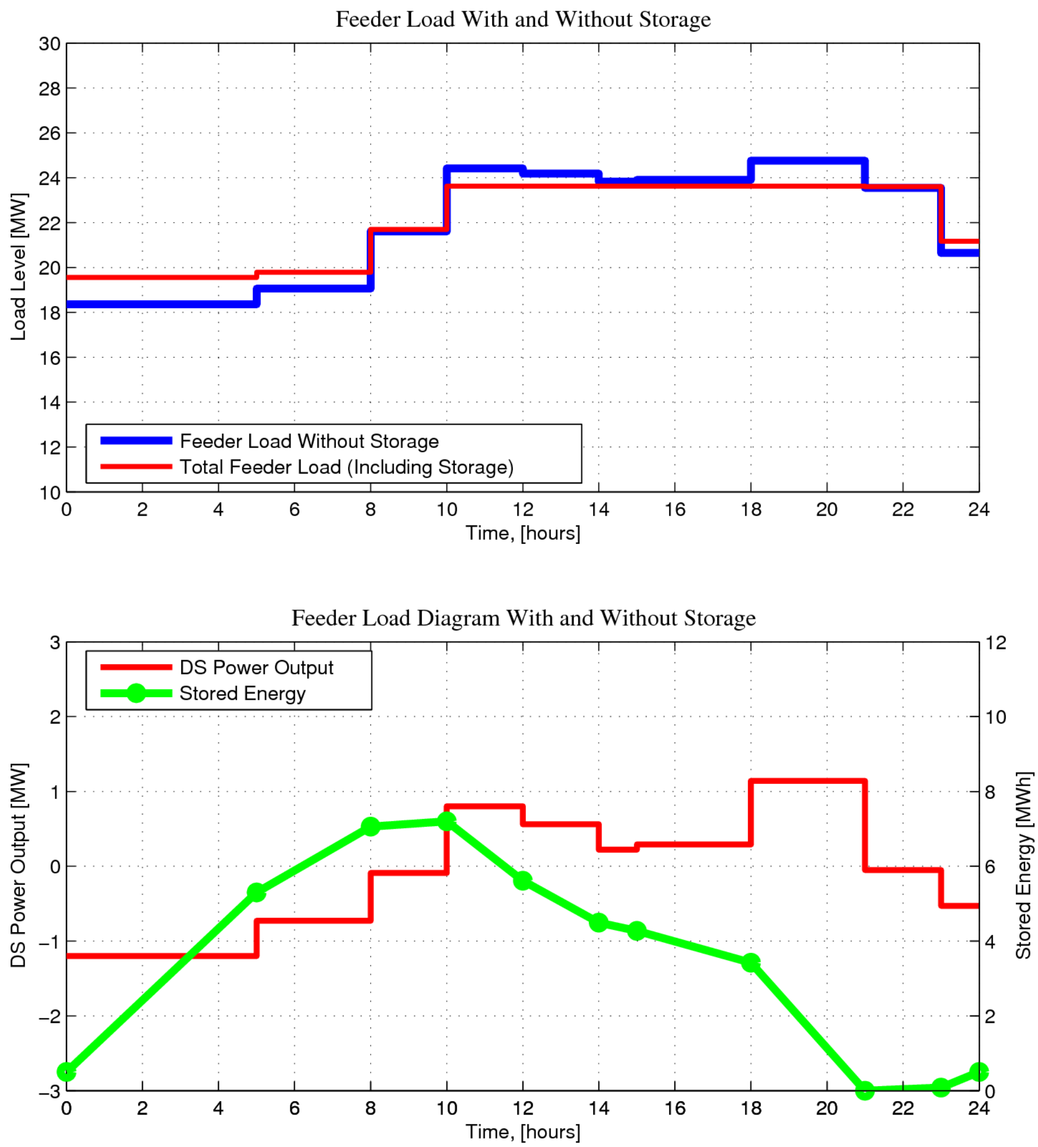


Figure 2.51 DS charge/discharge strategy and the effect of DS unit on feeder loading

On Figure 2.51, the permissible daily peak load in the presence of the 1 MW NaS battery-based DS unit can be increased to 24.8 MW, compared to 23.6 MW for the case without storage. The total energy produced by the DS unit during discharging period is 80% of the consumed energy during charging period.

Based on the analysis from Section 2.2.2, the DS unit location associated with the minimal losses is considered (end of section B4). The loadings and the cable ampacities for all sections are shown on Figure 2.52.

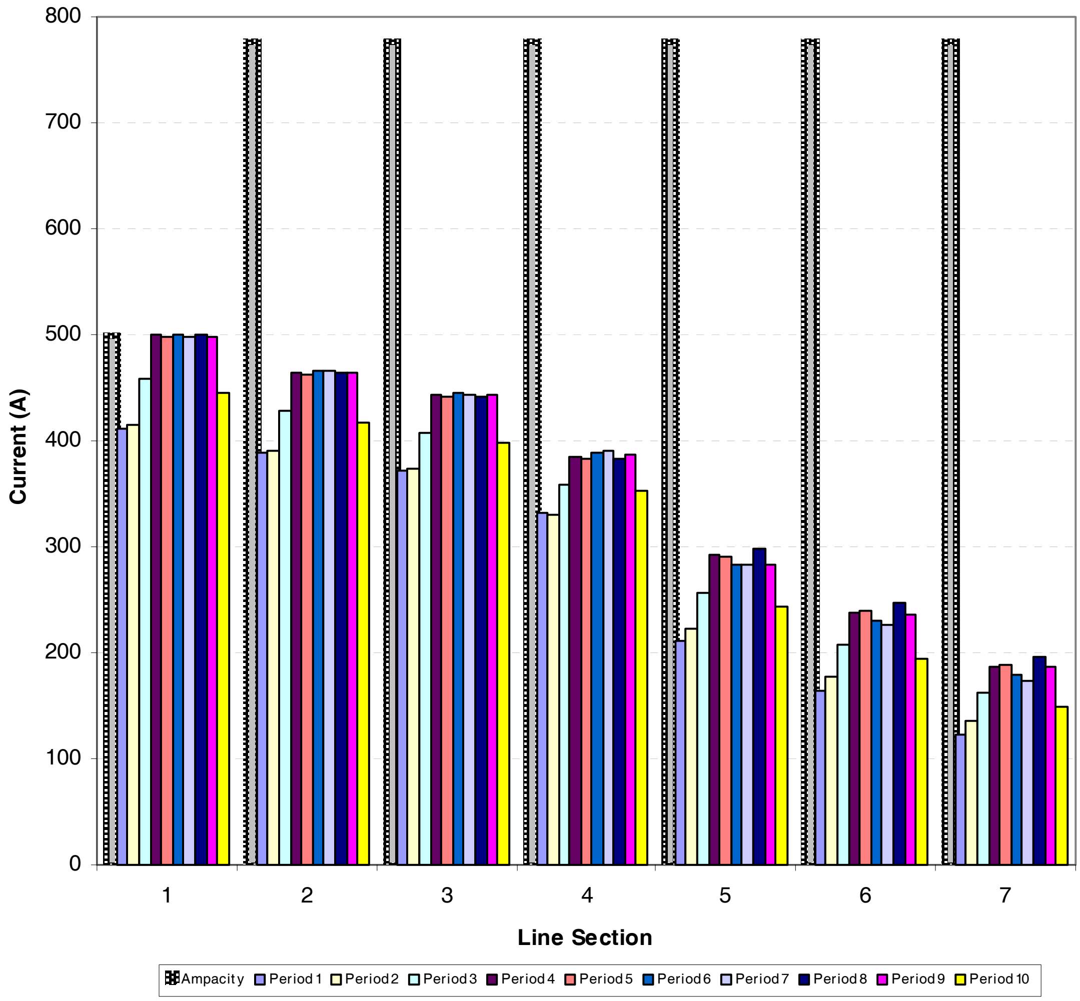


Figure 2.52 Feeder loading per section for cable ampacity loading with one DS unit (1 MW NaS battery with 100% DOD), located after section B4 and no DG in the system

The study results of Figure 2.52 confirm that with the presence of the 1 MW NaS battery-based DS unit, the cable ampacity limits are not violated even if the load peak is as high as 25.1 MW.

Permissible power export

A typical daily load diagram based on Table 2.8 is assumed. One DG unit and one 1 MW NaS battery-based DS unit are connected to the feeder. Without the DG unit, Figure 2.53 shows the loading of section B1 feeder, the DS charging/discharging power, and the energy stored in the DS (so that the combined power of the load and the DS is as level as possible). For exporting power from the feeder, the critical period is during the night when the combined load and the DS unit power is 8.4 MW. The stored energy limit is reached at 8:00 and is 7.2 MWh. On Figure 2.53, the DS output power during charging period is shown as negative value.

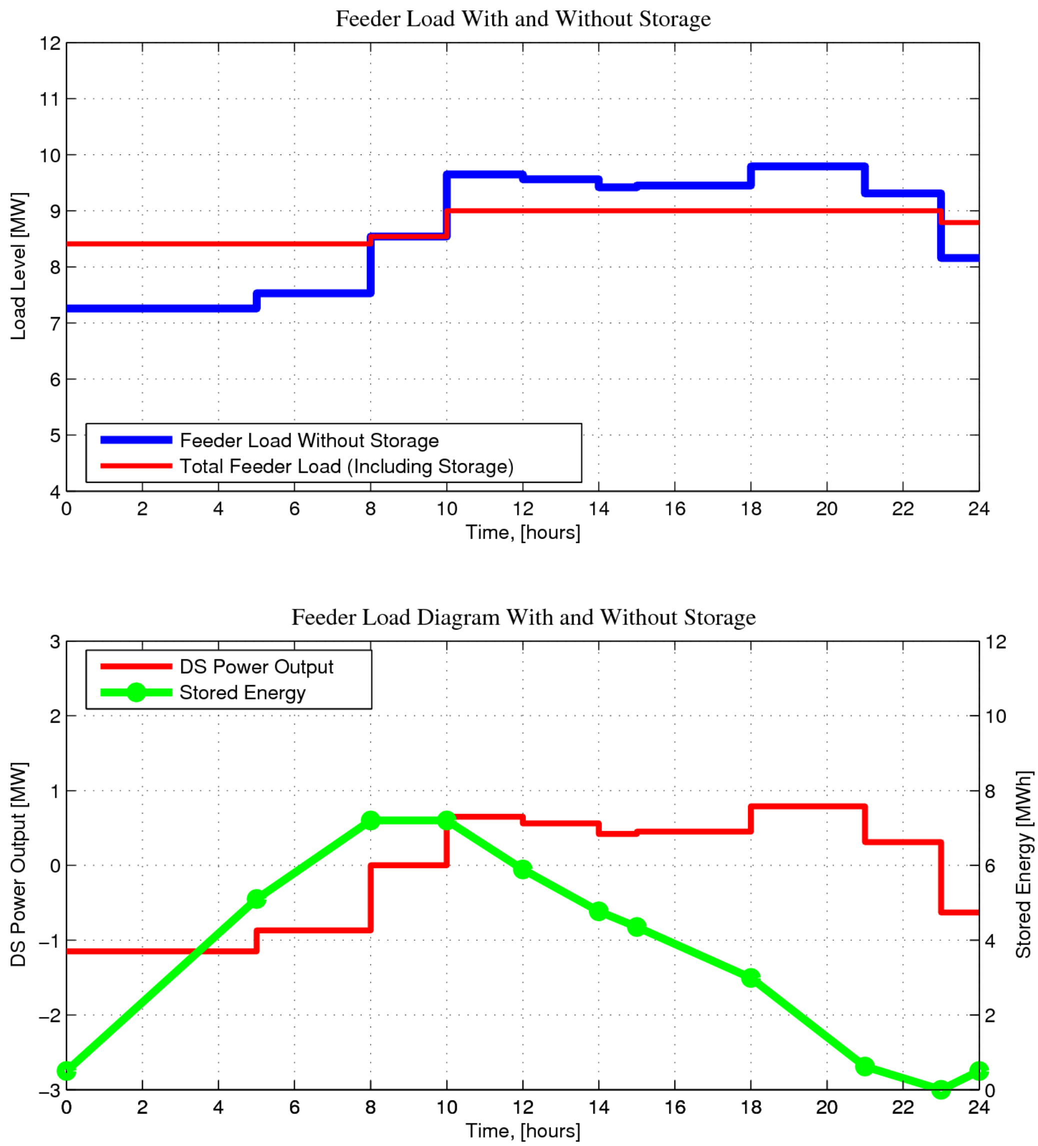


Figure 2.53 DS charge/discharge strategy and the effect of DS unit on feeder loading

The total power export from the feeder is the difference between the exported power from the DG unit and the combined power of the load and the DS during the period of minimal load (8.4 MW). To keep the maximum power export at the prescribed value of 5 MW, the exported power from the DG should be 13.4 MW. This is en approximate value, as it does not take into consideration that due to the reversed power flow, losses in the system are changed. The realistic DG power limit is determined from the power flow studies and is slightly larger, 13.5 MW. This is 1.2 MW more than it would be allowed if the DS unit is not included in the system. The study results, with the DS unit connected to the feeder after section B7, are shown on Figure 2.54.

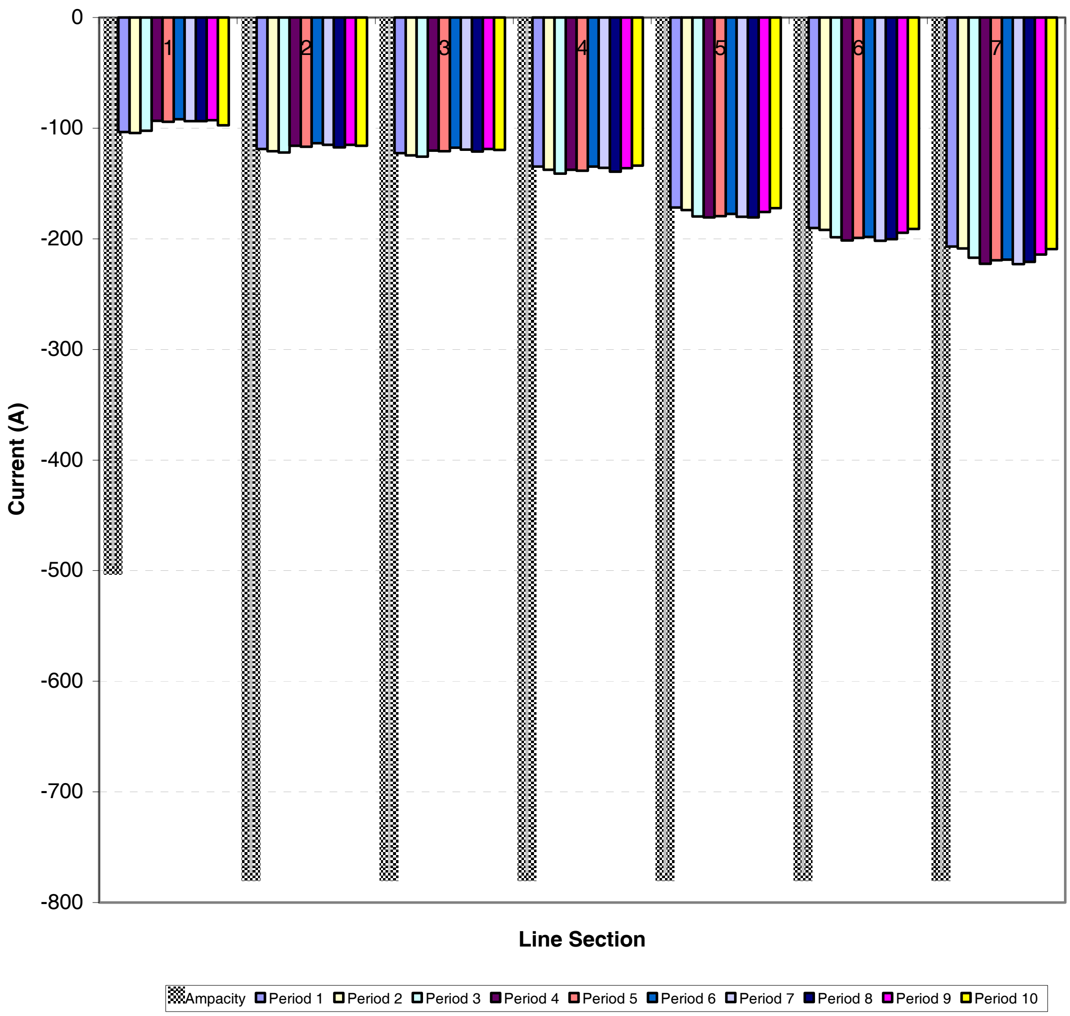


Figure 2.54 Feeder loading per section when 13.35 MW DG is installed after Section B7 and DS is connected of the feeder (after Section B7)

The study results from Figure 2.54 show that the presence of the DS unit allows for a larger DG unit to be installed at the industrial customer's site (13.5 MW vs. 12.3 MW), without violating the prescribed power export limit of 5 MW.

Maximum power export

A typical daily load diagram based on Table 2.8 is assumed. One DG unit and one 1 MW NaS battery-based DS unit are connected to the feeder. The same charge/discharge strategy, shown on Figure 2.53, is assumed for the DS unit. It is assumed that the DG export power is limited so that the feeder current is less than or equal to the feeder ampacity limit. The study results for the case when the DS unit is in the same location as the DG unit (at the end of section B7) are shown on Figure 2.55.

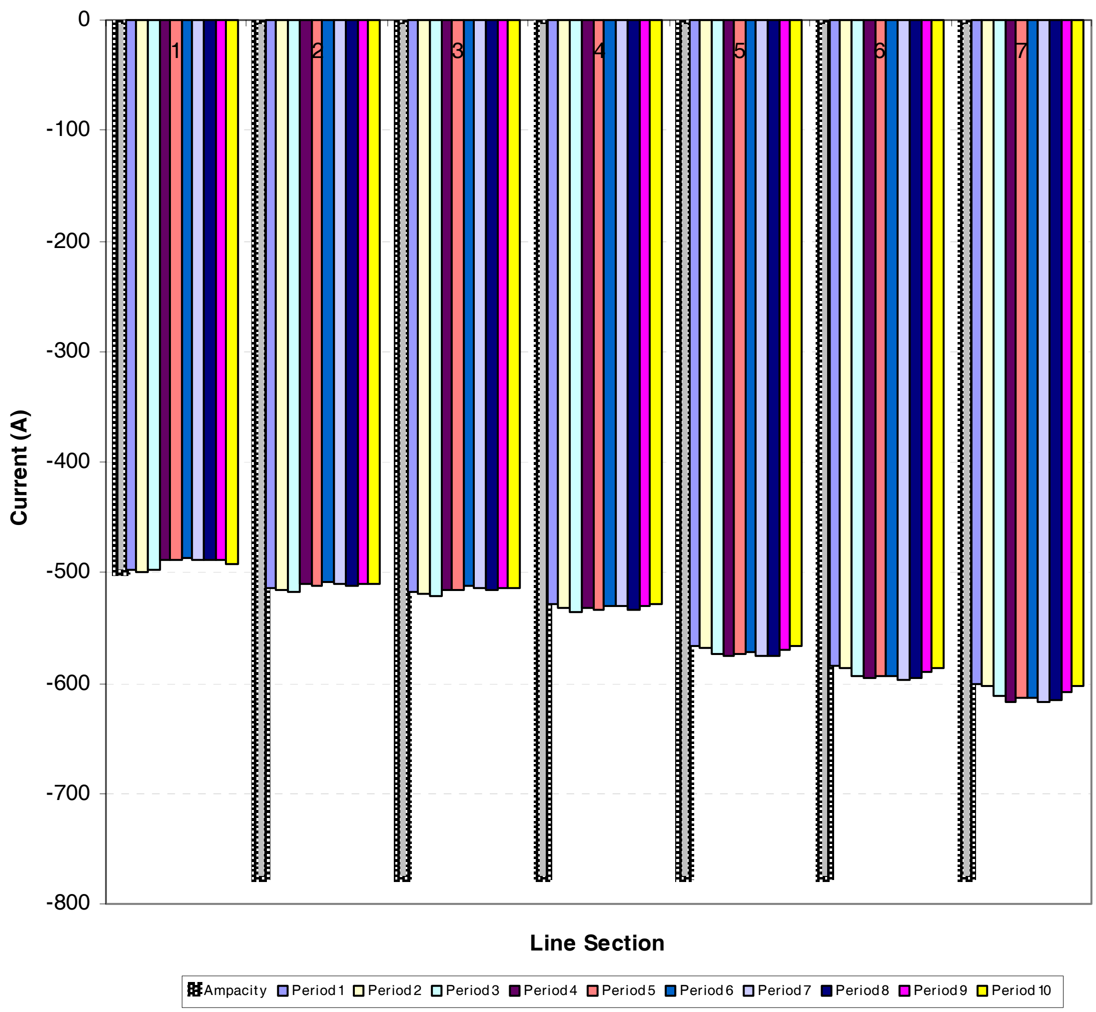


Figure 2.55 Feeder loading per section when 32.9 MW DG is installed after Section B7 and DS is connected of the feeder (after Section B7)

In the case of Figure 2.55, the DG power limit that does not overload the critical feeder section (B1 in this case) is 33.3 MW. This is 1.4 MW more than it would be allowed if the DS does not exist in the system.

2.2.4 Battery Option 4 – 1 MW NaS Battery with 90% DOD

The fourth set of simulations is performed under the assumption that the same 1 MW NaS battery of Section 2.2.3 is used. The charging power (on the AC side) is limited to 1.2 MW, while the discharging power limit (on the AC side) is 1.2 MW for up to 3 hours and 1 MW perpetually. The available stored energy is up to 6.48 MWh (battery capacity is 7.2 MWh, but only 90% DOD is allowed to increase the life of the battery). An AC efficiency of 80% is assumed for this case.

Conventional operation

Based on the feeder cable ampacity (Table 2.7), the maximum allowed power in section B1 is 23.9 MW. If we implement a storage charge/discharge control strategy based on the procedure from Section 1.2.3, the peak load in the presence of 1 MW NaS battery (90% DOD) is 24.7 MW. The relative load diagram applicable for Feeder B is scaled up so that the peak load is the same as the maximum allowed peak loading. Figure 2.56 shows the loading of the section B1 feeder, the DS charging/discharging power, and the energy stored in the DS. On Figure 2.56, the DS output power during charging period is shown as a negative value.

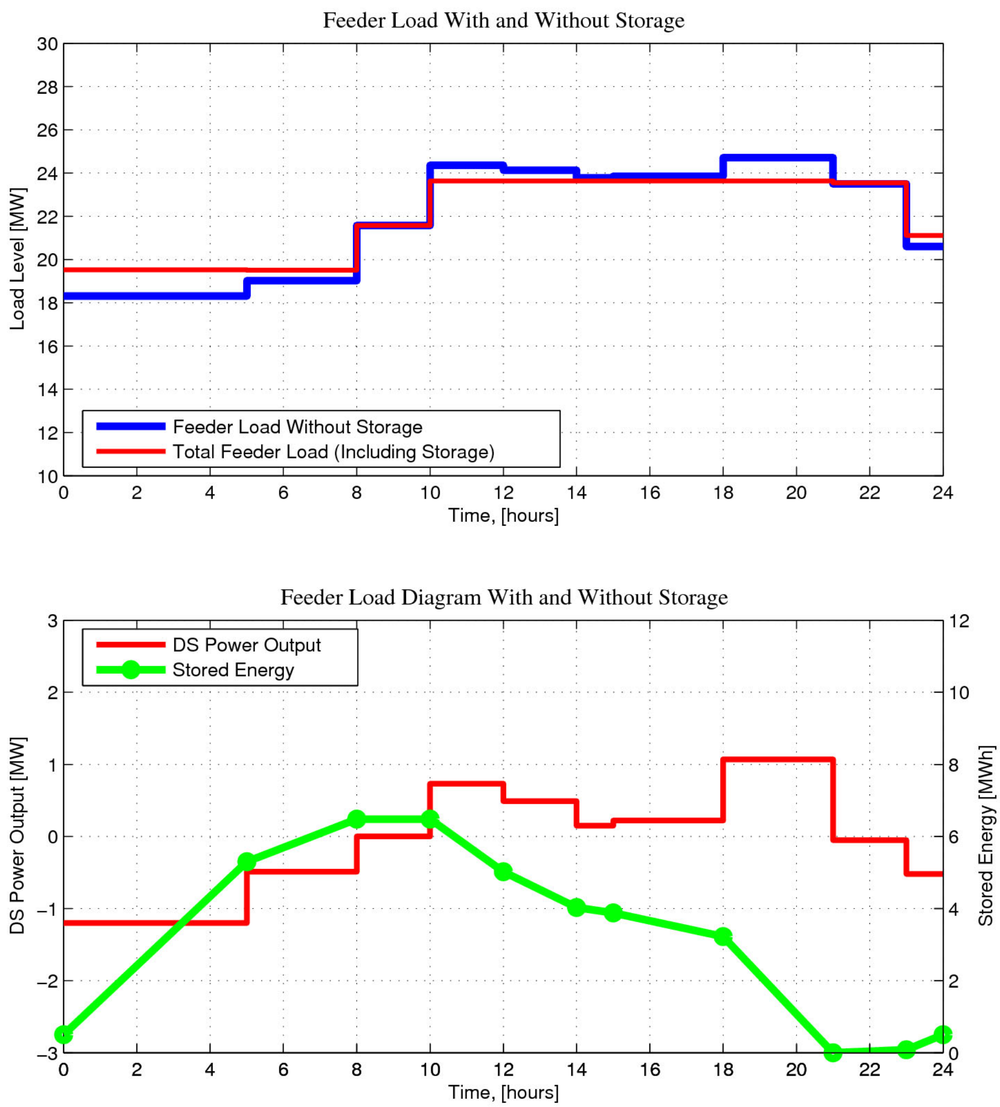


Figure 2.56 DS charge/discharge strategy and the effect of DS unit on feeder loading

Based on the analysis of Section 2.2.2, the DS unit location associated with the minimal losses is considered (after section B4). The loadings of all sections throughout the day are shown on Figure 2.57.

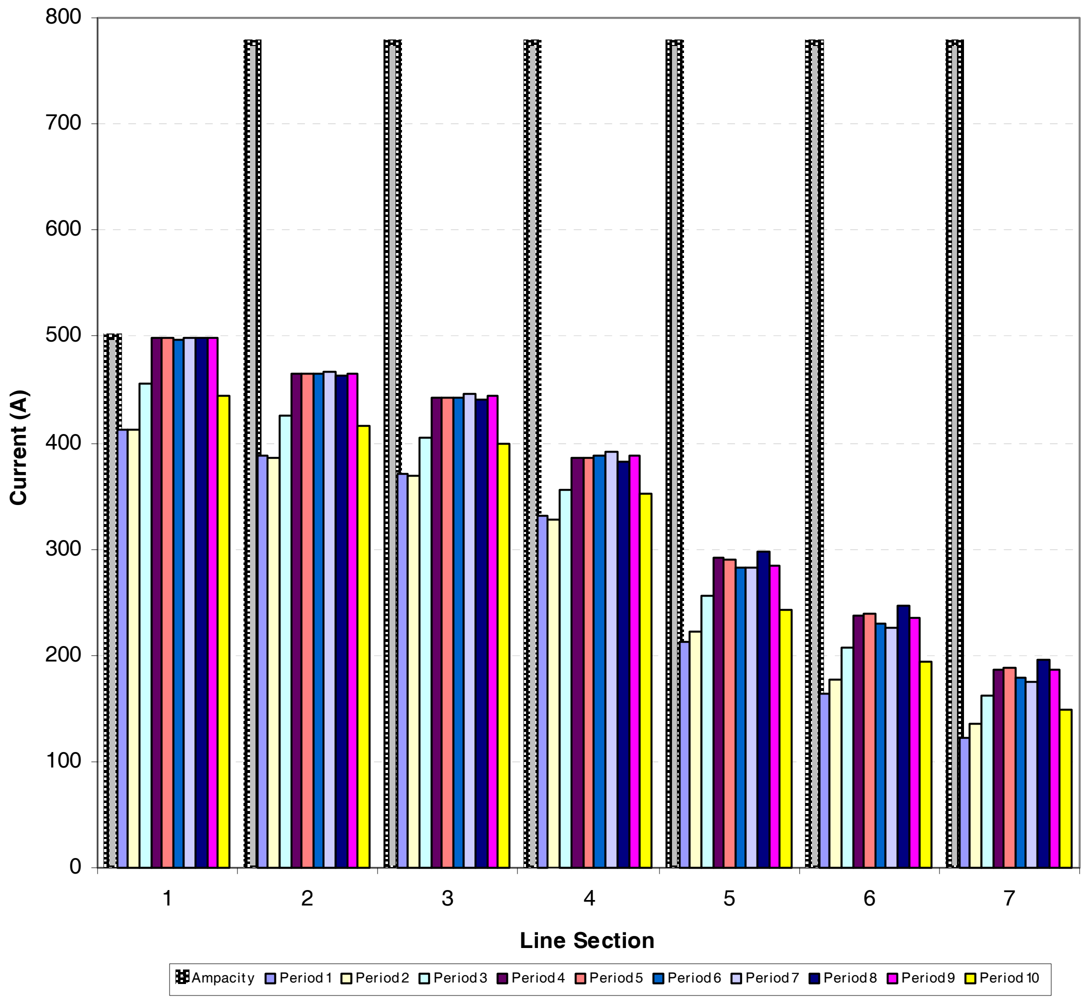


Figure 2.57 Feeder loading per section for cable ampacity loading with one DS unit (1 MW NaS battery with 90% DOD), located after section B4 and no DG in the system

The study results from Figure 2.57 confirm that with the presence of the 1 MW NaS battery-based DS unit, the cable ampacity limits are not violated even if the load peak is as high as 24.7 MW. For the conventional operation of feeder B1, the critical parameter is the maximum stored energy and not the maximum output power. Therefore, the effect of reducing DOD from 100% DOD to 90% reduces the load peak by 0.1 MW.

Permissible power export

A typical daily load diagram based on Table 2.8 is assumed. One DG unit and one 1 MW NaS battery-based DS unit are connected to the feeder. Without the DG unit, Figure 2.58 shows the loading of section B1 feeder, the DS charging/discharging power, and the energy stored in the DS (so that the combined power of the load and the DS is as level as possible). For exporting power from the feeder, the critical period is during the night when the combined load and the DS unit power is 8.4 MW. The stored energy limit is reached at 8:00 and is 6.48 MWh. On Figure 2.58, the DS output power during charging period is shown as a negative value.

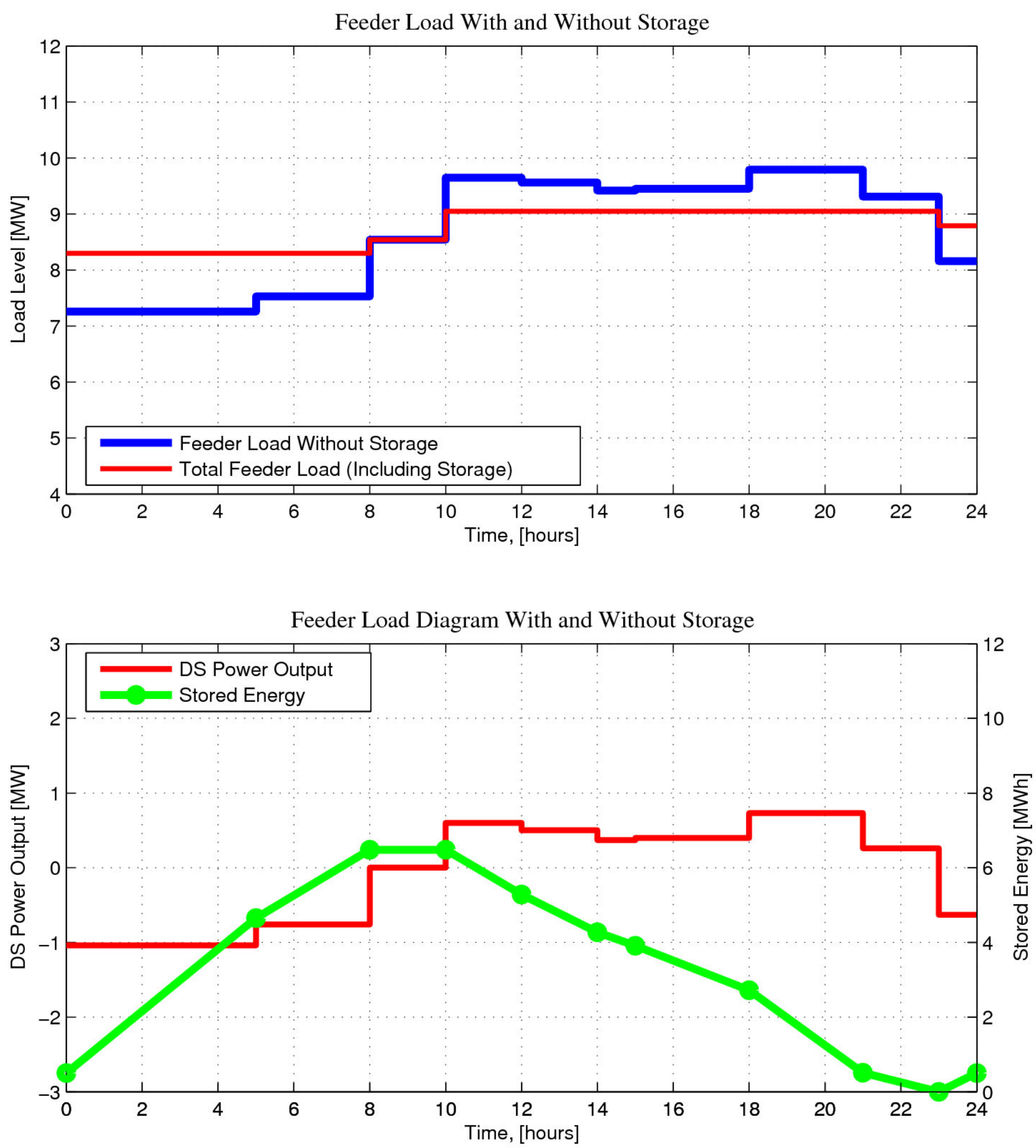


Figure 2.58 DS charge/discharge strategy and the effect of DS unit on feeder loading

The total power export from the feeder is the difference between the exported power from the DG unit and the combined power of the load and the DS during the period of minimal load (8.3 MW). To keep the maximum power export at the prescribed value of 5 MW, the exported power from the DG should be 13.3 MW. This is an approximate value, as it does not take into consideration that due to reversed power flow in the first three sections, losses in the system are changed. The actual DG power limit is determined from the power flow studies and is slightly larger, 13.4 MW. This is 1.1 MW more than it would be allowed if the DS unit is not included in the system. The study results, with the DS unit connected to the feeder after section B7, are shown on Figure 2.59.

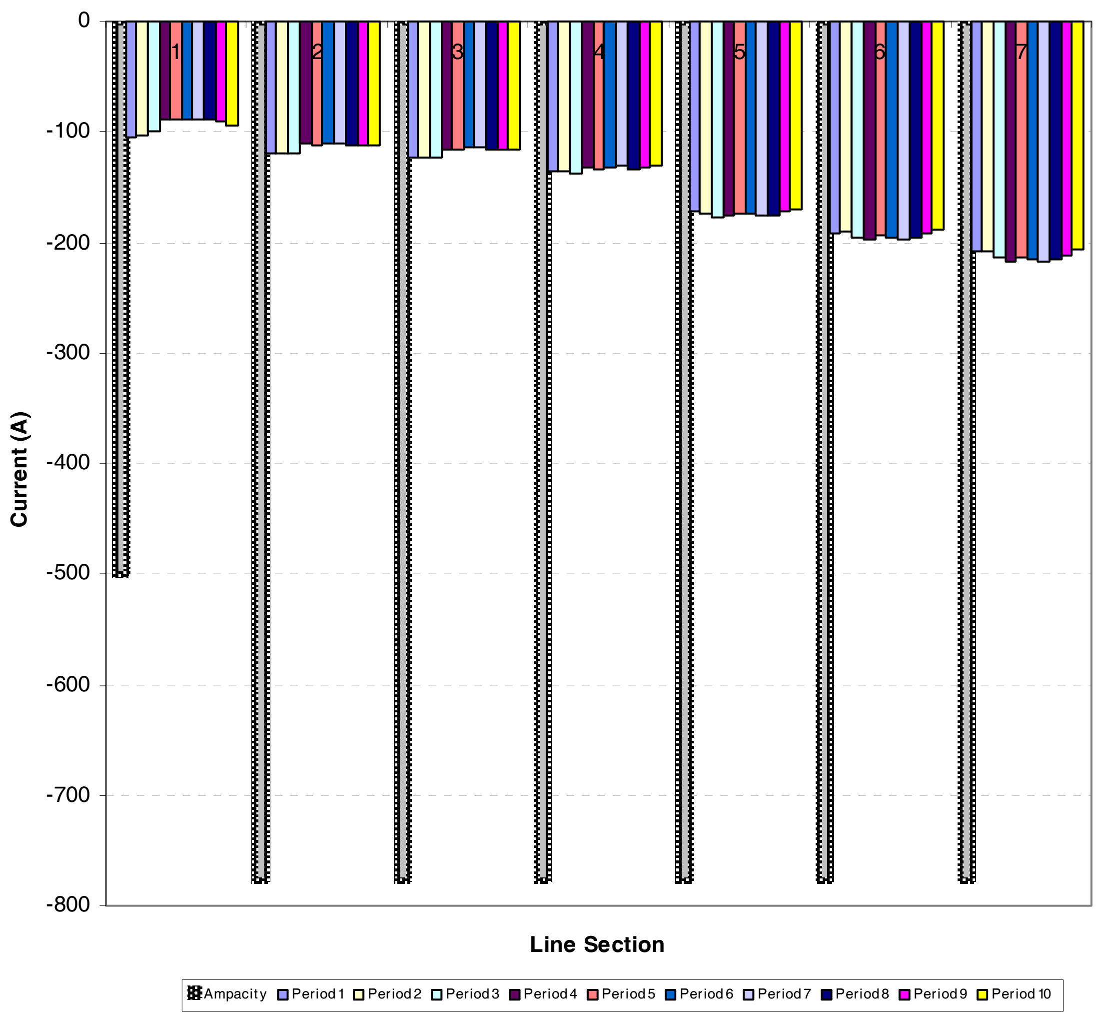


Figure 2.59 Feeder loading per section when 13.4 MW DG is installed after Section B7 and DS is connected of the feeder (after Section B7)

The study results show that the presence of the DS unit allows for a larger DG unit to be installed at the industrial customer's site (13.4 MW vs. 12.3 MW), without violating the prescribed power export limit of 5 MW. This is 0.1 MW less then when the same 1 MW NaS battery operates with 100% DOD.

Maximum power export

A typical daily load diagram based on Table 2.8 is assumed. One DG unit and one 1 MW NaS battery-based DS unit are connected to the feeder. The same charge/discharge strategy, shown on Figure 2.58, is assumed for the DS unit. It is assumed that the DG export power is limited so that the feeder current is less than or equal to the feeder ampacity limit. The study results for the case when the DS unit is in the same location as the DG unit (at the end of section B7) are shown on Figure 2.60.

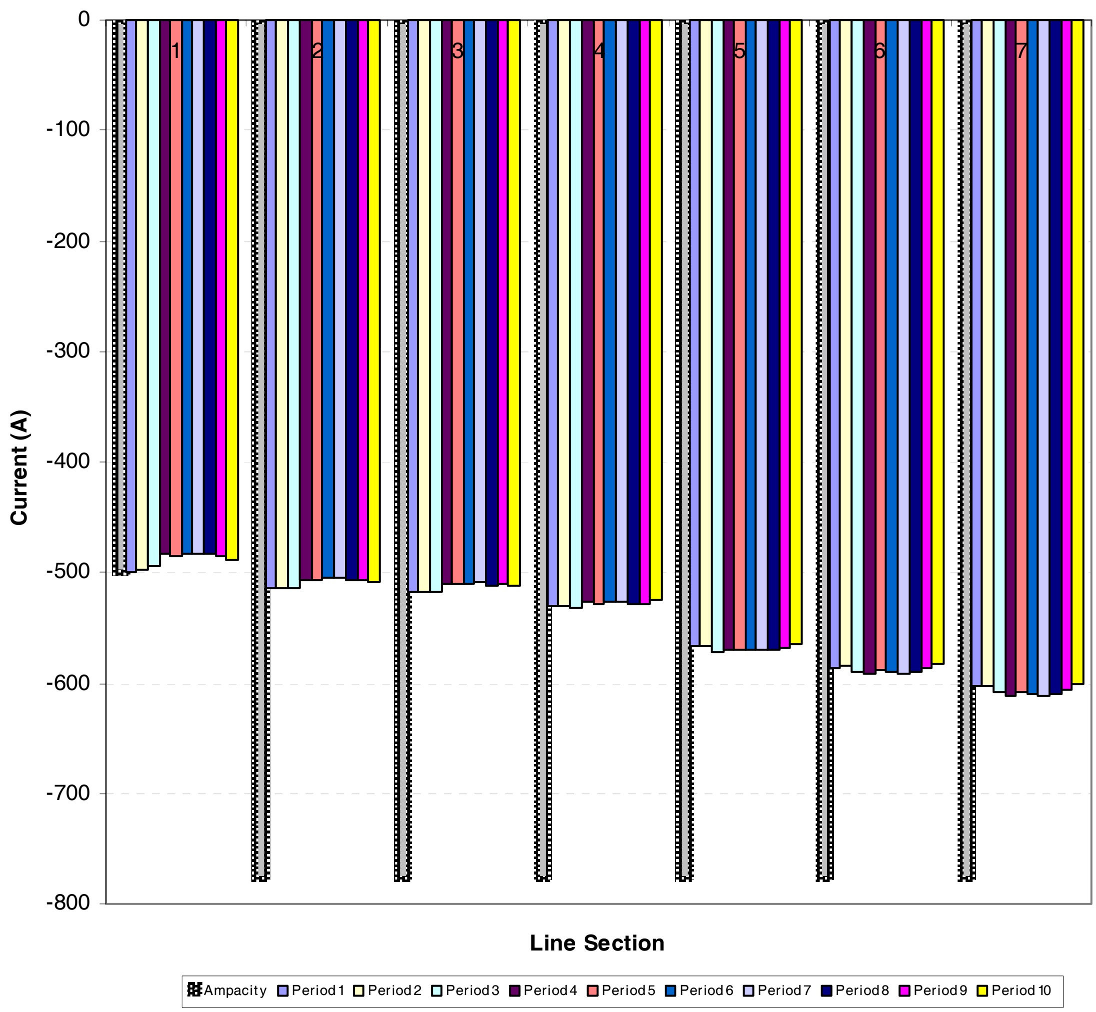


Figure 2.60 Feeder loading per section when 32.9 MW DG is installed after Section B7 and DS is connected of the feeder (after Section B7)

In the case of Figure 2.60, the DG power limit that does not overload the critical feeder section (B1 in this case) is 32.9 MW. This is 1 MW more than it would be allowed if the DS does not exist in the system and 0.1 MW less then when the same 1 MW NaS battery operates with 100% DOD.

2.2.5 Summary

The study results show the effect of integration of distributed storage (DS) on the typical industrial/residential feeder loading. It is demonstrated that the presence of DS can reduce load fluctuation throughout the day, and depending on the DS characteristics/ratings, the maximum feeder loading can be increased:

- When a DS unit with the AC efficiency of 70% and without power and storage capacity constraints is used, the maximum allowed load peak power on the feeder is increased from the 23.6 MW to 26.4 MW. The DS parameters required for this case are: (i) the maximum charging power of 4.24 MW, (ii) the maximum discharging power of 2.52 MW, and (iii) the storage capacity of 24.79 MWh.
- When a DS unit of typical 1 MW NaS battery with 7.2 MWh storage capacity and 100% DOD is used, the maximum allowed load peak power on the feeder is increased from 23.6 MW to 24.8 MW.
- When the DS unit is a typical 1 MW NaS battery with 7.2 MWh storage capacity and 90% DOD, the maximum allowed load peak power on the feeder is increased from the 23.6 MW to 24.7 MW.

When the feeder includes DG units, the DS unit allows for a higher level of DG power export:

- When a DS unit with the AC efficiency of 70% and without power and storage capacity constraints is used, the maximum allowed DG power export is increased by 1.59 MW. The DS unit parameters required for this case are: (i) the maximum charging power of 1.59 MW, (ii) the maximum discharging power of 0.94 MW, and (iii) the storage capacity of 9.2 MWh.
- When the DS unit is a typical 1 MW NaS battery with 7.2 MWh storage capacity and 100% DOD, the maximum allowed DG power export is increased up to 1.4 MW. The actual value is between 1.2 MW and 1.4 MW and depends on the permissible power export from the feeder.
- When the DS unit is a typical 1 MW NaS battery with 7.2 MWh storage capacity and 90% DOD, the maximum allowed DG power export is increased by 1.0 MW.

The study results show that the location of the DS unit can change the overall system losses but in all cases this effect is less than 2.4%. The most efficient location is a location as close as possible to the source for DS unit charging.

2.3 Feeder Type C - Residential/Commercial/Industrial feeder

The third feeder type analyzed in this study is a mixed Residential/Commercial/Industrial feeder, Figure 2.61. The feeder consists of a large number of residential and commercial loads distributed along the feeder and one large industrial near the end of the feeder. The industrial load can include one large DG unit.

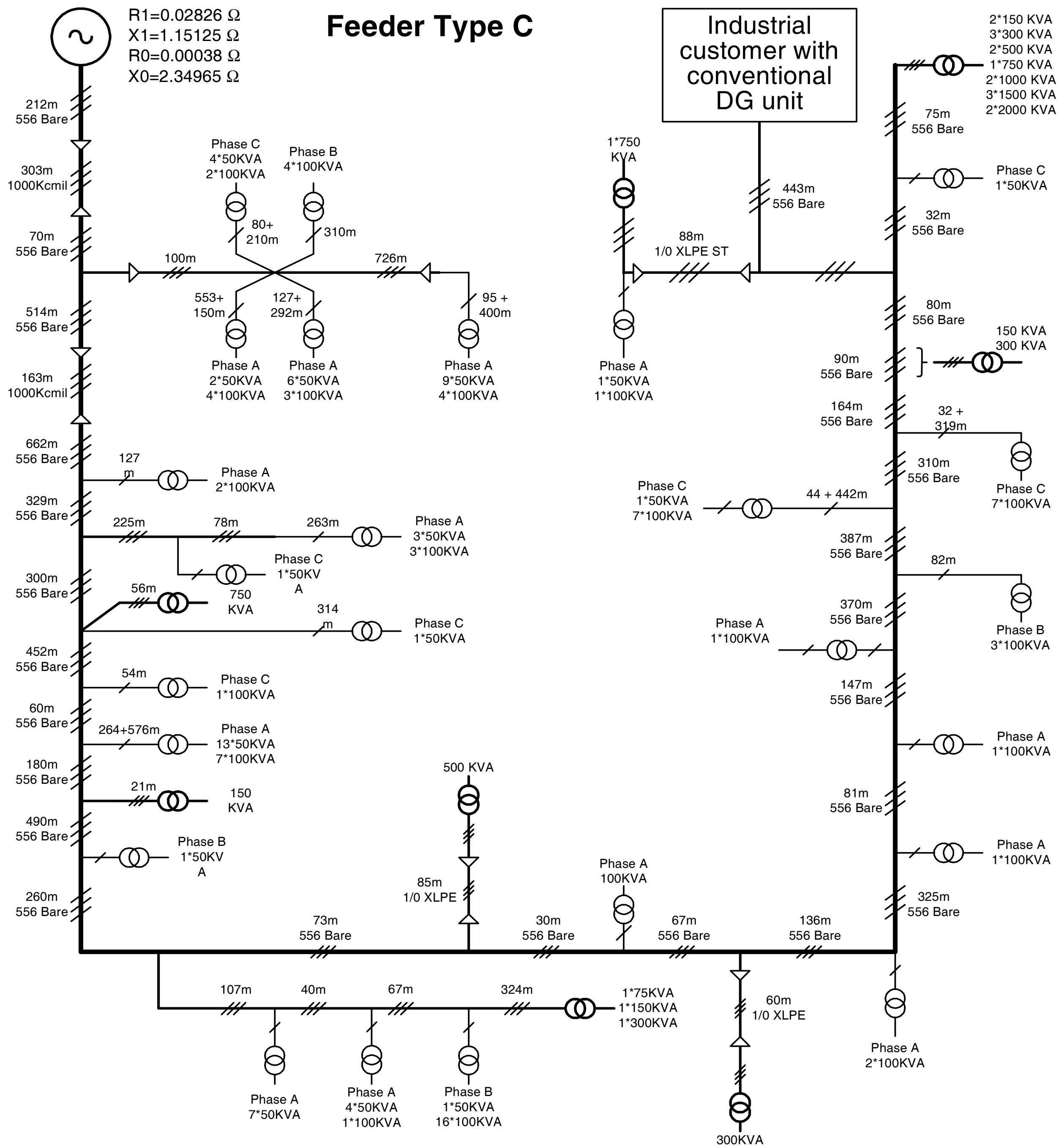


Figure 2.61 One-line diagram of Feeder Type C - Residential/Commercial/Industrial feeder

To identify the cable ampacity limits and to specify potential DS unit locations, the feeder of Figure 2.61 is divided in multiple sections, as shown in Figure 2.62. The feeder is sectionized so that there is at least one feeder section between any two major loads or a group of loads. Seven sections are used for feeder type C. The maximum feeder loading for each section is based on the cable ampacity as shown in Table 2.12. Feeder sections C1 and C2 include the 1000 kcmil cable with the maximum current of 500 A. The minimal currents for all other sections are higher (777 A), therefore sections C1 and C2 are critical for all cable ampacity studies.

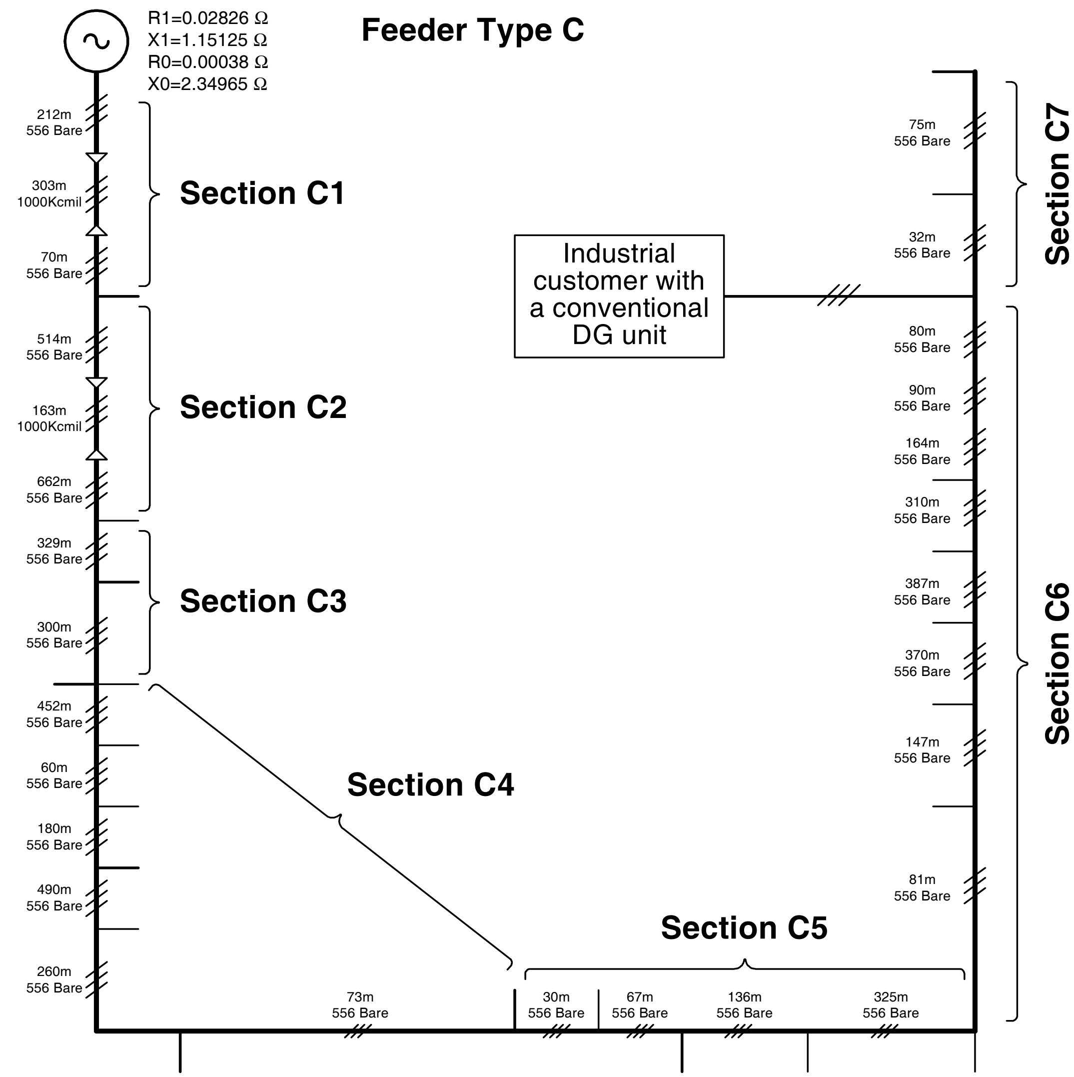


Figure 2.62 Sections of Feeder Type C - Residential/Commercial/Industrial feeder

The industrial customer that includes a conventional DG unit is located between feeder sections C6 and C7, as indicated on Figure 2.62. Three potential locations for placing a DS unit are analyzed:

- end of section C6, where the major industrial load with a DG is located,
- end of section C2, since section C2 is one of the sections with the lowest cable ampacity limit (500 A).
- end of section C1, since the section C1 it the other section with the lowest cable ampacity limit (500 A).

Typical daily peak load for this feeder is 14.08 MW and the normal daily load diagram, based on the typical load data from Tables 1.1 and 2.1, is given in Table 2.13.

Table 2.12 Feeder cable ampacity per section

Section number	Cable Type	Cable Ampacity (A)	Maximum Power (MW)	Section Resistance (mΩ)
C1	1000kcmil	500	23.9	64.3
C2	1000kcmil	500	23.9	139.1
C3	556 Bare	777	37.1	64.2
C4	556 Bare	777	37.1	154.5
C5	556 Bare	777	37.1	56.9
C6	556 Bare	777	37.1	166.2
C7	556 Bare	777	37.1	10.9

Table 2.13 Normal daily load diagram for Feeder Type C

Time Period (hours)			Industrial Load, MW	Commercial Load, MW	Residential Load, MW	Total Feeder Load, MW
Period #	From	To				
1	0	5	3.82	2.89	2.96	9.66
2	5	8	3.70	4.06	3.25	11.01
3	8	10	3.89	4.92	3.88	12.69
4	10	12	4.28	5.34	4.46	14.08
5	12	14	4.08	5.24	4.52	13.84
6	14	15	4.28	5.34	4.29	13.91
7	15	18	4.48	5.34	4.17	14.00
8	18	21	4.08	4.06	4.69	12.84
9	21	23	3.89	3.85	4.46	12.20
10	23	24	3.89	3.42	3.59	10.90

2.3.1 Battery Option 1 – No energy storage is available

The first set of simulations is performed under the assumption that there is no storage unit in the system. The results from this case study are used as the benchmark to evaluate the study results when the system includes DS.

Conventional operation

a) ***A normal daily loading*** **-** The total feeder loading is equal to the normal daily loading from Table 2.13. Both Industrial and Commercial loads are distributed among three-phase transformers, while the residential load is distributed among three-phase and single-phase transformers. No DG units are connected to the feeder.

   The study results provide the feeder loading (in Amperes) for each of the seven sections of Feeder Type A (as defined in Figure 2.62), and for all 10 time periods (as specified in Table 2.13). The simulation results are presented in Figure 2.63.

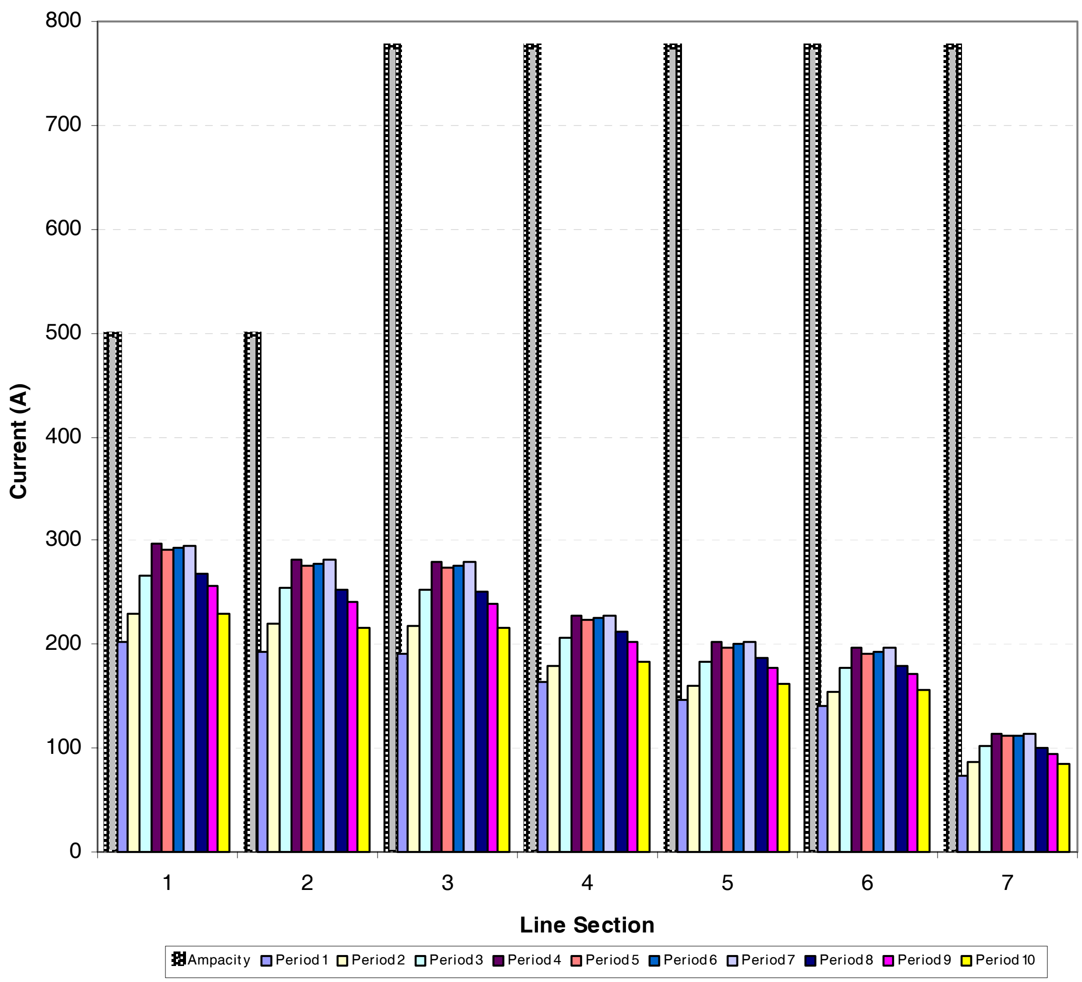


Figure 2.63 Feeder loading per section for normal loading (no DS or DG in the system)

Figure 2.63 compares the current associated with the normal daily loading with the cable ampacity in each feeder section. All cable sections are loaded with less than 30% of the ampacity limit.

b) ***The maximum allowable feeder loading*** – The load for this case study is obtained by scaling up all individual loads of case (a) until one of the cable ampacity limits is reached. The study results for this test case are presented on Figure 2.64.

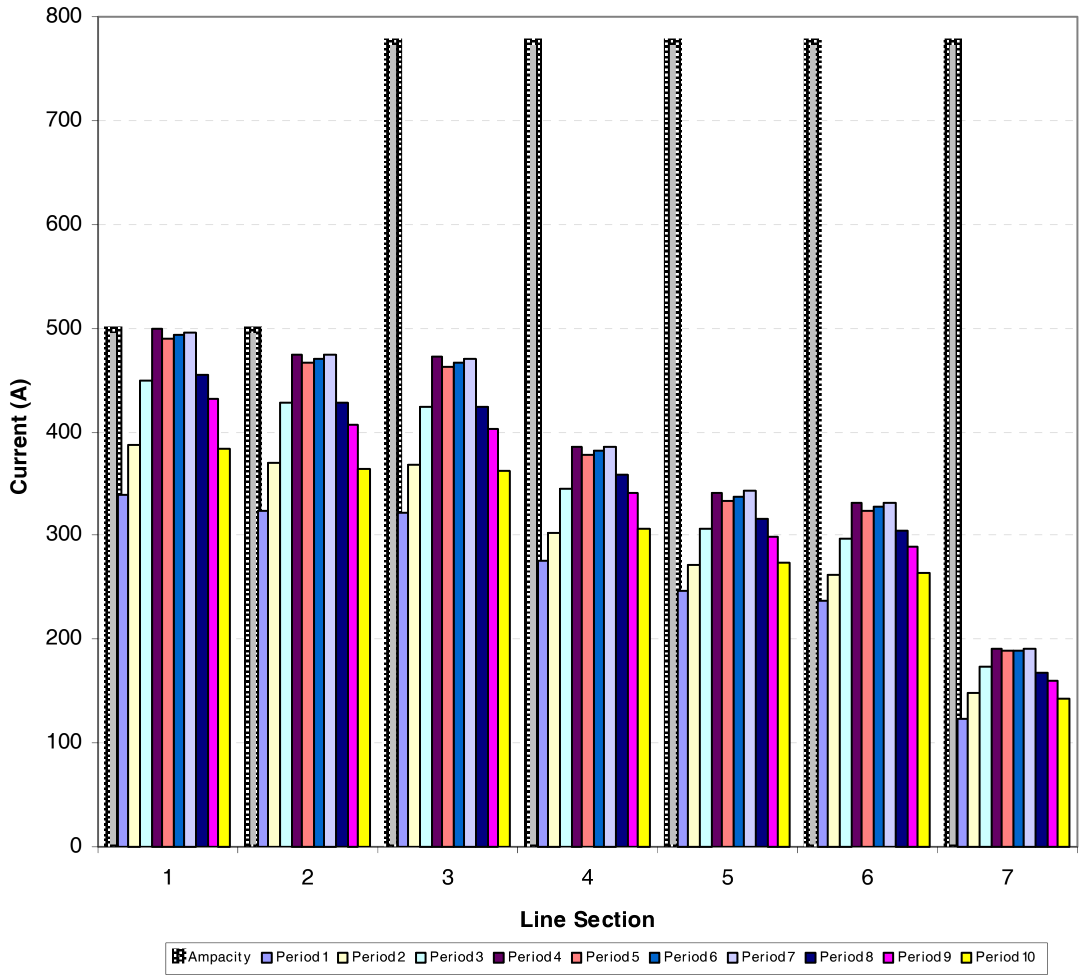


Figure 2.64 Feeder loading per section for cable ampacity loading and no DS or DG in the system

The results of Figure 2.64 show that the maximum cable loading in this case occurs on feeder section C1, during the peak power period (period #4, between 10:00 and 12:00). The total load peak power that brings the cable ampacity of the feeder section C1 to the limit is 23.6 MW, as specified in Table 2.12. The maximum voltage drop for this case is 1.8%. It is calculated at the end of Section 7, during time period #4, between 10:00 and 12:00. This scenario is associated with the highest possible voltage drop for this feeder. Since 1.8% is significantly less than the maximum allowed 6% voltage drop, we conclude that voltage drop is not a factor in any of the case studies for this feeder.

Permissible power export

A normal daily loading is assumed for feeder of Figure 2.61. The typical daily load diagram is given in Table 2.13. One DG unit is connected to the feeder. The maximum allowed DG capacity is determined, such that the power export from the feeder is either less than or equal to the value specified by the utility (e.g. 5 MW) at all times. The simulation results for this test case are presented on Figure 2.65.

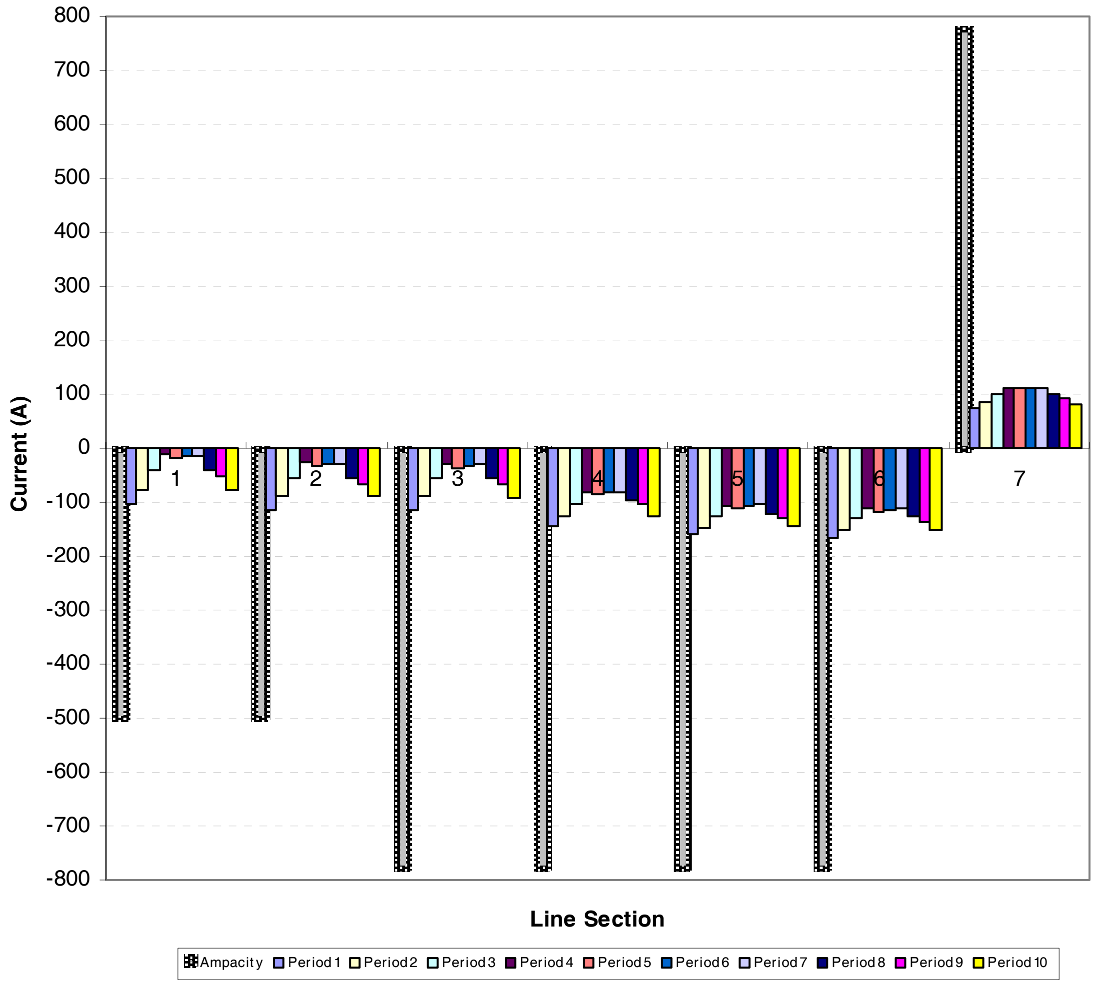


Figure 2.65 Feeder loading per section when 14.6 MW DG is installed after Section C6 and no DS is connected to the feeder

The results of Figure 2.65 show that when 14.6 MW is produced by the DG unit, under normal daily load condition, the maximum power export is 5 MW, as specified by the utility. The critical time period when the maximum power export limit is reached is at night (period #1, between midnight and 5:00).

Maximum power export

A normal daily loading is assumed for feeder of Figure 2.61. The typical daily load diagram is given in Table 2.13. One DG unit is connected to the feeder at the end of the feeder section C6. The maximum allowed DG capacity is determined such that the power export from the feeder is less than the cable ampacity of the 1000 kcmil cables of feeder sections C1 and C2. The study results for this test case are presented on Figure 2.66.

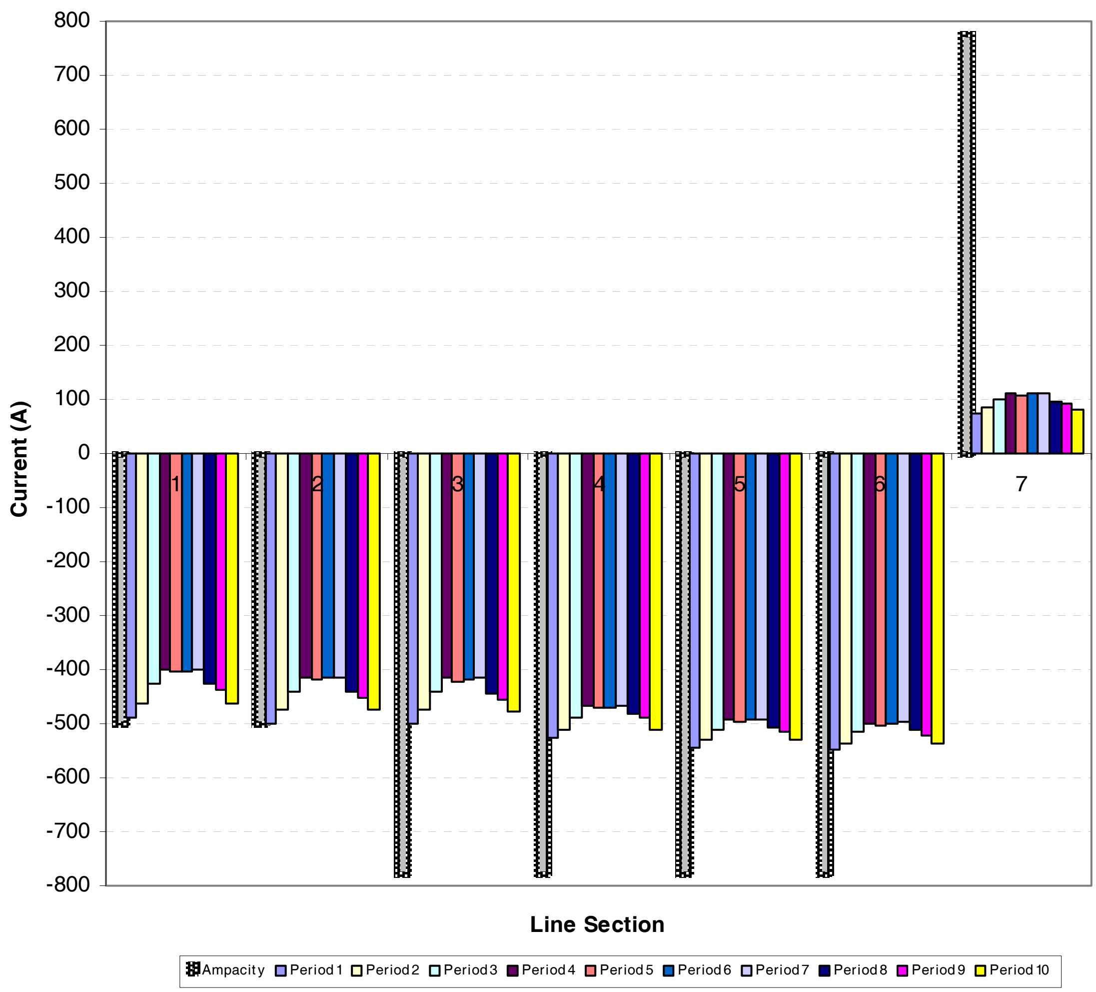


Figure 2.66 Feeder loading per section when 33.4 MW DG is installed after Section C6 and no DS is connected to the feeder

The results of Figure 2.66 show that when 33.4 MW produced by the DG unit, under normal daily load condition, the maximum power export is 23.4 MW, which is less then the cable ampacity of the section C2 (23.9 MW, as per Table 2.12). This is due to the load connected between sections C1 and C2. The critical time period when the maximum power export limit is reached is at night (period #1, between midnight and 5:00).

2.3.2 Battery Option 2 – Generic case with no power or energy limits

The second set of studies is performed under the assumption that one large DS unit is used and power and energy constrains have not been imposed. An AC efficiency of 70% is assumed for this generic case.

Conventional operation

Based on the feeder cable ampacity (Table 2.12), the maximum permissible power in section C1 is 23.9 MW. In the case study of Figure 2.61, without the storage the daily peak is approximately 23.6 MW. By placing the DS unit on the feeder, the maximum load can be increased. Figure 2.67 shows the impact of the storage charge/discharge control strategy based on the procedure from Section 1.2.1.

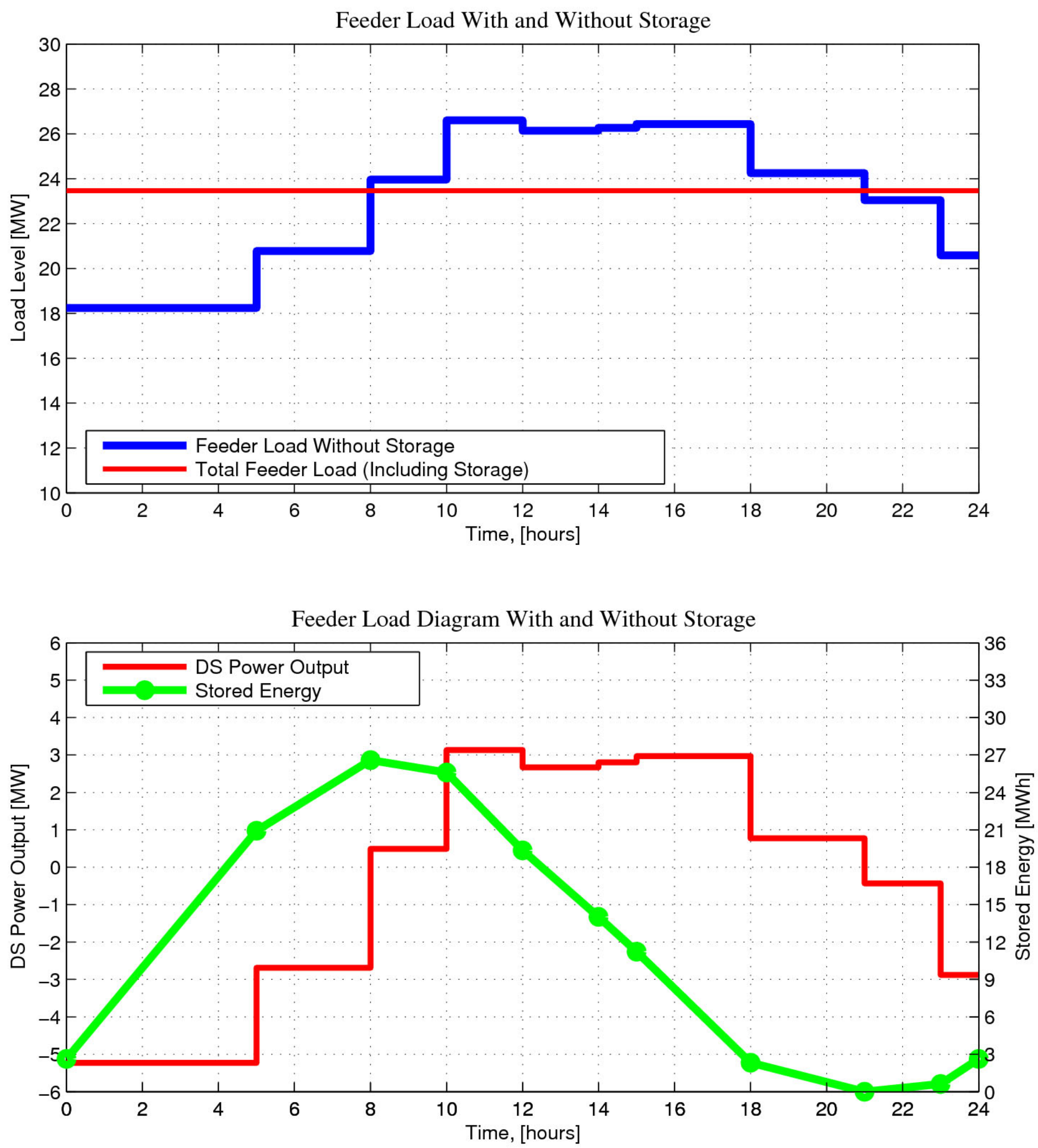


Figure 2.67 DS charge/discharge strategy and the effect of DS unit on feeder loading

On Figure 2.67, the permissible daily peak load in the presence of the DS unit can be increased to 26.6 MW, compared to 23.6 MW for the case without the storage. The total energy produced by the DS unit during battery discharge period is 70% of the consumed energy during the battery charge period. To achieve the storage charge/discharge performance characteristic from Figure 2.67, the DS unit rating should be:

- maximum charging power 5.23 MW,
- maximum discharging power 2.97 MW,
- storage capacity 26.58 MWh.

As explained before, three locations are considered for the DS unit:

- end of section C6, where the major industrial load with a DG is located (Figure 2.68),
- end of section C2, since it has the critical cable ampacity limit (Figure 2.69),
- end of section C1, since it has the critical cable ampacity limit (Figure 2.70).

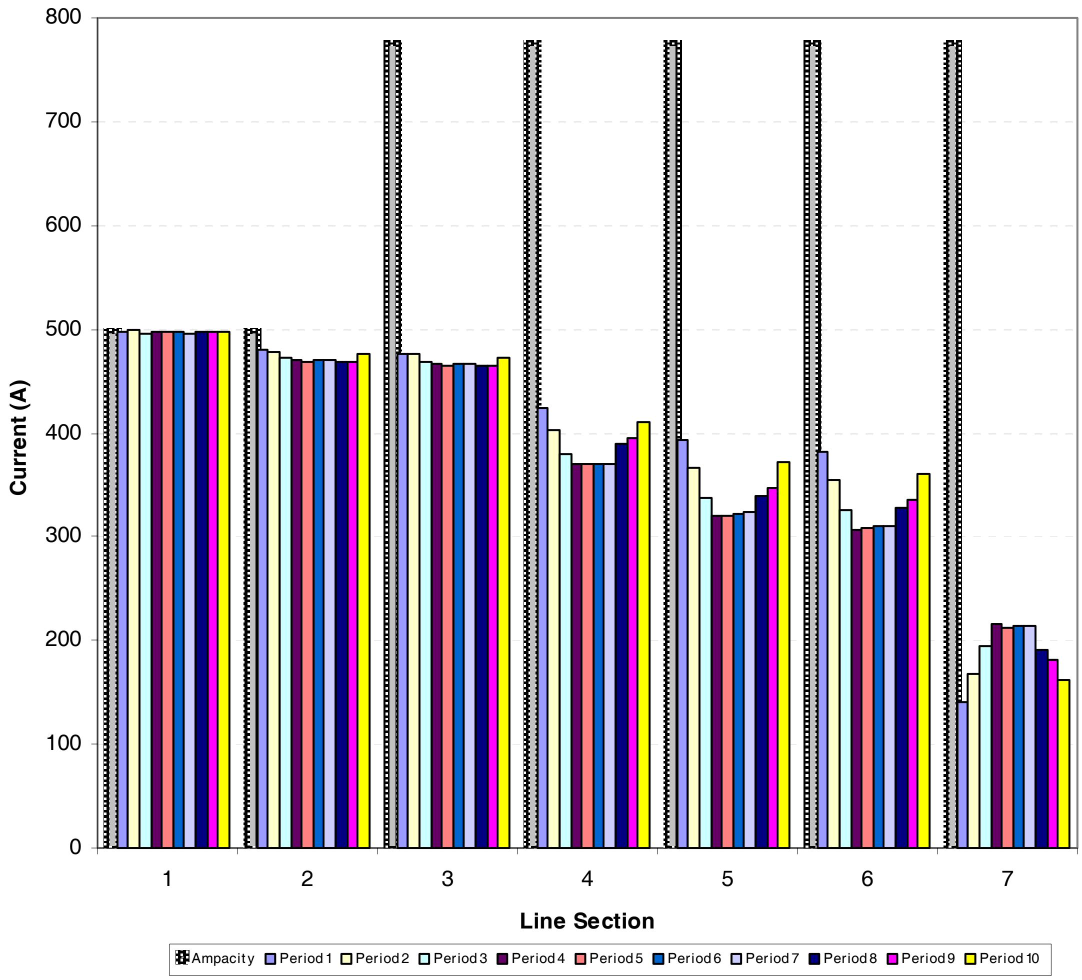


Figure 2.68 Feeder loading per section for cable ampacity loading with one DS unit (70% efficiency and no power/energy limits), located after section C6 and no DG in the system

Figure 2.68 shows that locating the DS unit at the end of the feeder (after section C6) reduces the feeder loading on all feeder sections during the mid-day period. This results in a higher total load limit (26.6 MW), compared to the case without the storage (23.6 MW). The feeder loading at night is increased in sections C1 to C6 (due to DS charging).

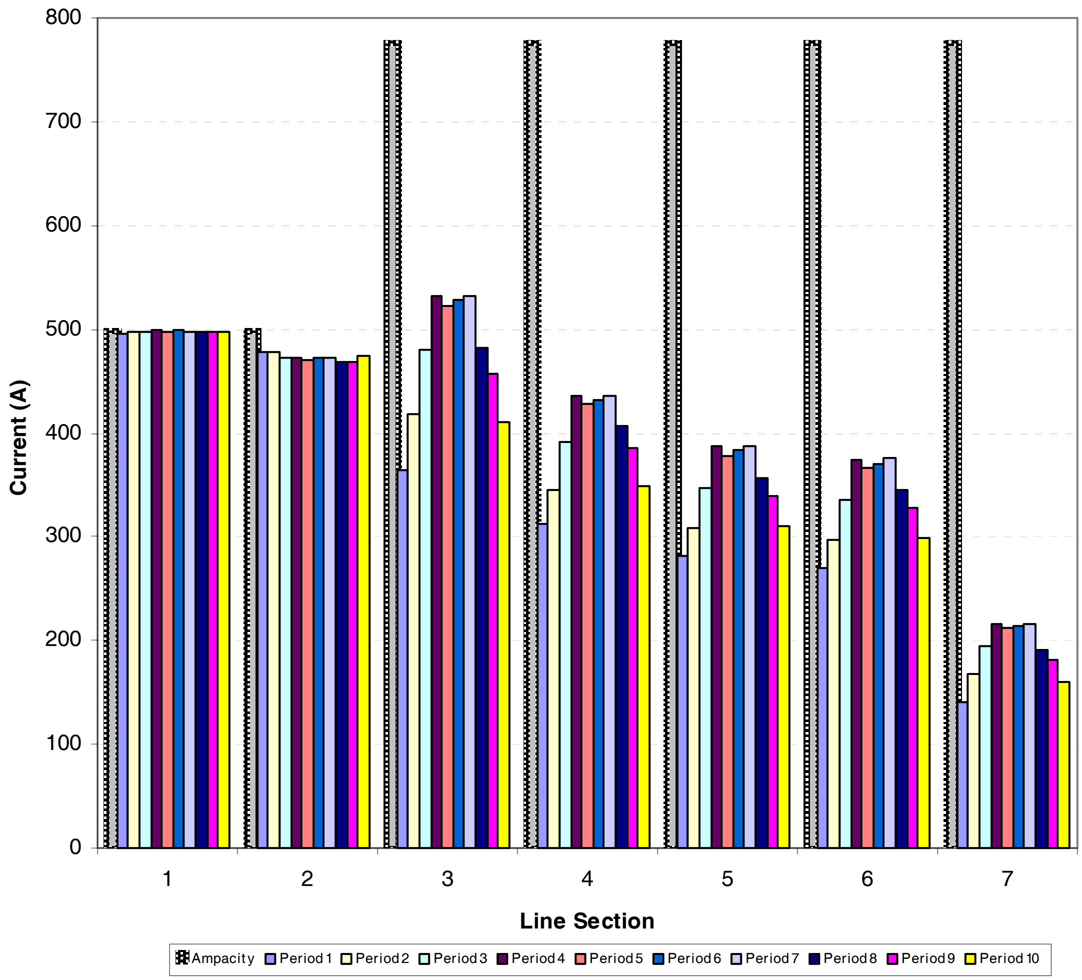


Figure 2.69 Feeder loading per section for cable ampacity loading with one DS unit (70% efficiency and no power/energy limits), located after section C2 and no DG in the system

Figure 2.69 shows that locating the DS unit after section C2 reduces the loading of feeder sections C1 and C2 during the mid-day. Both sections C1 and C2 experience higher loading at night (due to the DS charging), similar to the previous case. Loadings of feeder section C3, C4, C5, C6 and C7 is not affected by the presence of the DS unit.

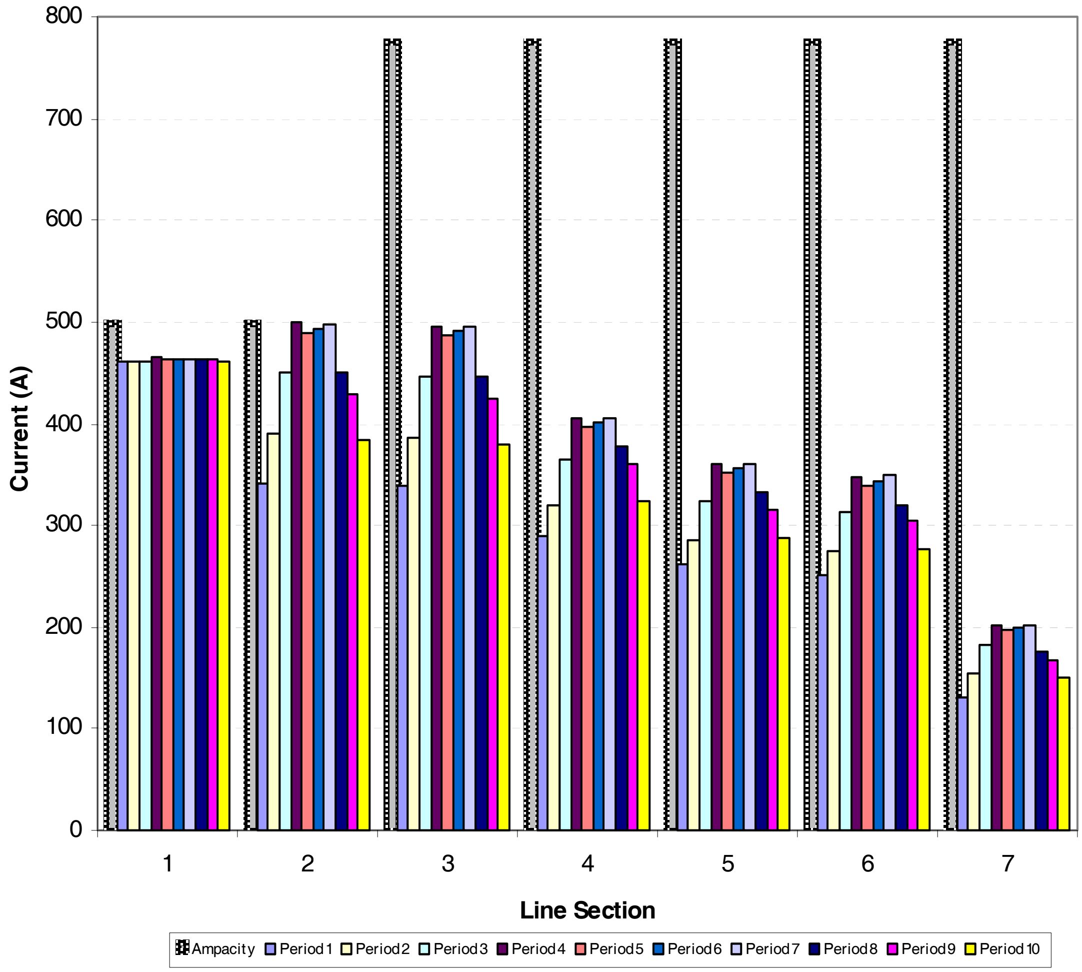


Figure 2.70 Feeder loading per section for cable ampacity loading with one DS unit (70% efficiency and no power/energy limits), located after section C1 and no DG in the system

Figure 2.70 shows that locating the DS unit after section C1 reduces the feeder loading on feeder section C1 only. The loadings of the downstream sections (C2, C3, C4, C5, C6 and C7) are not affected by the presence of the DS unit. The ampacity limit of feeder section C2 reduces the maximum permissible load by 2 MW, from 26.6 MW to 24.6 MW.

The study results from Figures 2.68 to 2.70 show that in all the case studies the presence of the DS unit after sections C2 or C6 allows for higher load levels (26.6 MW vs. 23.9 MW) without overloading the critical feeder sections C1 and C2. When the DS unit is located between feeder sections C1 and C2, the maximum allowed load (24.6 MW) is less than 26.6 MW due to ampacity limit of section C2. Therefore, this is not the optimal DS unit location for the conventional feeder operation with unidirectional power flow.

To further evaluate the effect of the DS unit location, the detailed analysis of system losses for the other two scenarios that result in higher load levels (26.6 MW) has been performed. The system losses for the two scenarios corresponding to DS unit locations (after section C2 and after section C6) and all ten time periods are presented in Table 2.14. Distribution of power losses throughout the day for the two DS unit location scenarios (after section C2 and after section C6) is given on Figure 2.71.

Table 2.14 System losses for all three DS unit location scenarios

Time Period	Hours	Power loss (kW)		Energy loss per day (kWh)	
		DS after C2	DS after C6	DS after C2	DS after C6
1	5	317	384	1584	1921
2	3	289	367	867	1101
3	2	360	351	719	702
4	2	409	349	818	699
5	2	400	349	800	697
6	1	402	349	402	349
7	3	405	347	1214	1040
8	3	379	364	1136	1093
9	2	357	365	714	730
10	1	320	374	320	374
			Total	8574	8707

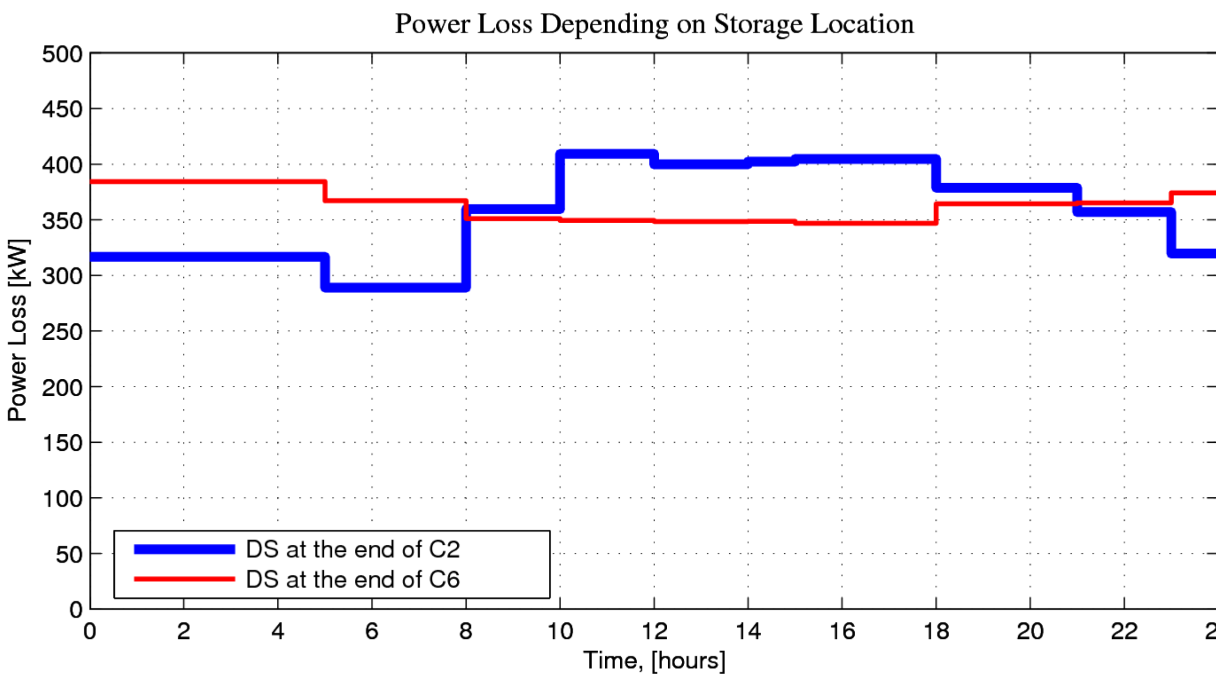


Figure 2.71 Distribution of system losses for all two DS unit location scenarios

Table 2.14 and Figure 2.71 show that the more efficient operation is when the DS unit is located just after the critical section (C2 in this case). The reason is that the charging current is higher than the discharging current (due to the DS unit efficiency). The difference between the lowest and the highest loss values is 1.5%. This indicates that from the point of view of the maximum allowable feeder loading, the DS unit should be located just after section C2. If this is not possible due to other constraints, placing the DS unit after section C6 is another option.

Permissible power export

A typical daily load diagram based on Table 2.13 is assumed. One DG unit and one DS unit are connected to the feeder. The criterion for the DS charge/discharge strategy is to enable the DG unit to export maximum constant power throughout the day. Figure 2.72 shows the loading of section C1, the required DS charging/discharging power, and the energy stored in the DS (so that the combined power of the load and the DS is constant).

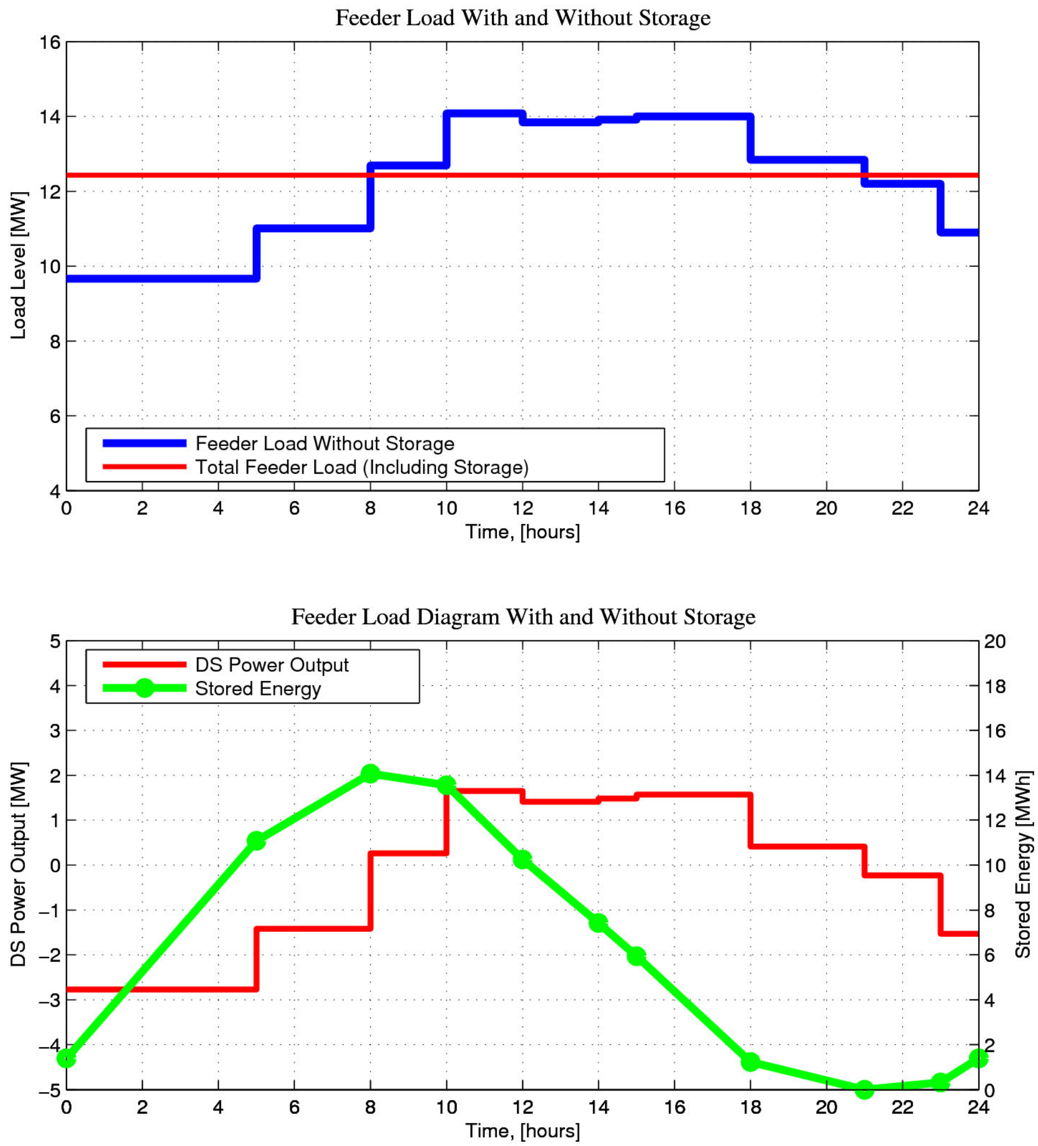


Figure 2.72 DS charge/discharge strategy and the effect of DS unit on feeder loading

Figure 2.72 shows that a constant power of 12.4 MW can be achieved for the mixture of the load and the DS unit. The parameters of the DS unit that satisfies charge/discharge strategy shown on Figure 2.72 are:

- maximum charging power 2.77 MW,
- maximum discharging power 1.65 MW,
- storage capacity 14.07 MWh.

The total power export from the feeder is the difference between the exported power from the DG unit and the combined power of the load and the DS unit. From Figure 2.72, to keep the maximum power export at the utility TS at the permissible value of 5 MW, the exported power from the DG should be 17.4 MW. This is an approximate value, as it does not take into consideration that the DG reverses the power flow in sections C1 to C6, thus the losses in the system are different with and without the DG unit in service. The actual DG power limit is determined from the power flow studies and is confirmed to be 17.4 MW for the permissible power export. This is 2.8 MW more than it would be allowed if the DS does not exist in the system.

In power flow studies, three locations are considered for the DS unit:

- end of section C6, where the major industrial load with a DG is located (Figure 2.73),
- end of section C2, since it has the critical cable ampacity limit (Figure 2.74),
- end of section C1, since it has the critical cable ampacity limit (Figure 2.75).

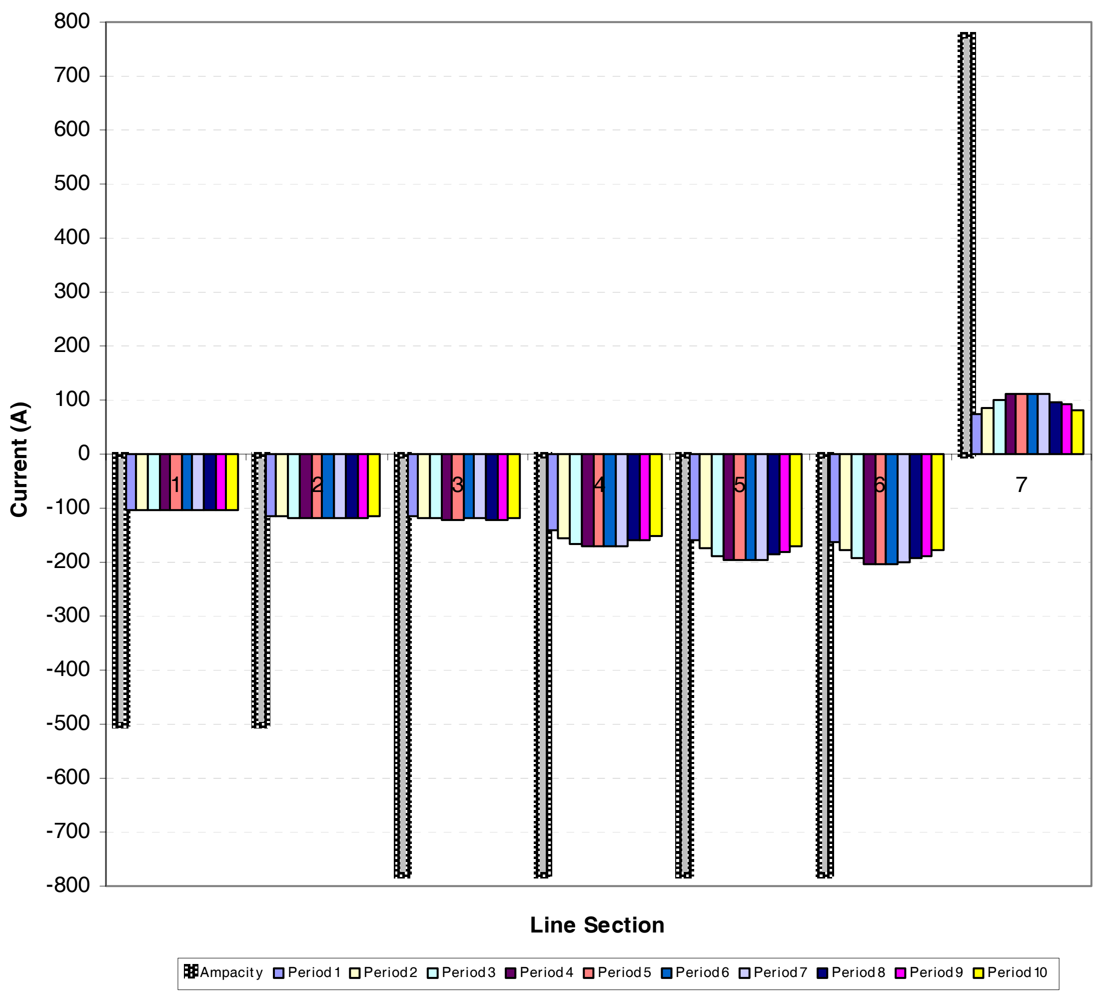


Figure 2.73 Feeder loading per section when 17.4 MW DG is installed after Section C6 and DS is connected of the feeder (after Section C6)

In the case of Figure 2.73, the DS unit is located after feeder section C6, where the DG unit is located. During the period of light load the DS unit absorbs a portion of the power generated by the DG unit. This reduces the loadings of the sections C1 to C6. The loading of section C7 is not affected by the presence of the DS or the DG unit. The Feeder loadings at all times are much less than the cable ampacity limits.

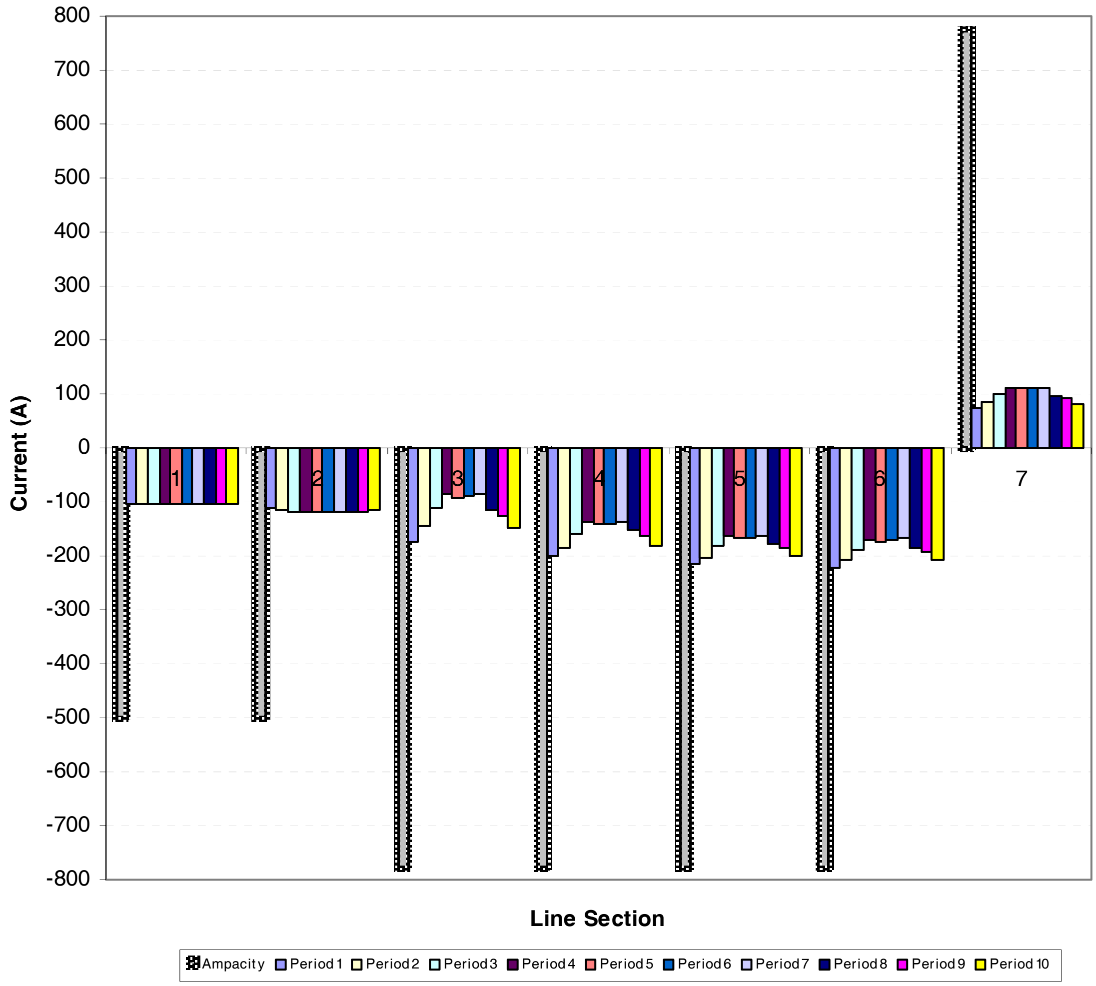


Figure 2.74 Feeder loading per section when 17.4 MW DG is installed after Section C6 and DS is connected of the feeder (after Section C2)

In the case of Figure 2.74, the DS unit is located after section C2 and during the period of light load the DS unit absorbs a portion of the power generated by the DG unit. This reduces the loadings of sections C1 and C2. Loadings of all other feeder sections are not affected by the presence of the DS unit. The feeder loadings at all times are much less than the cable ampacity limits.

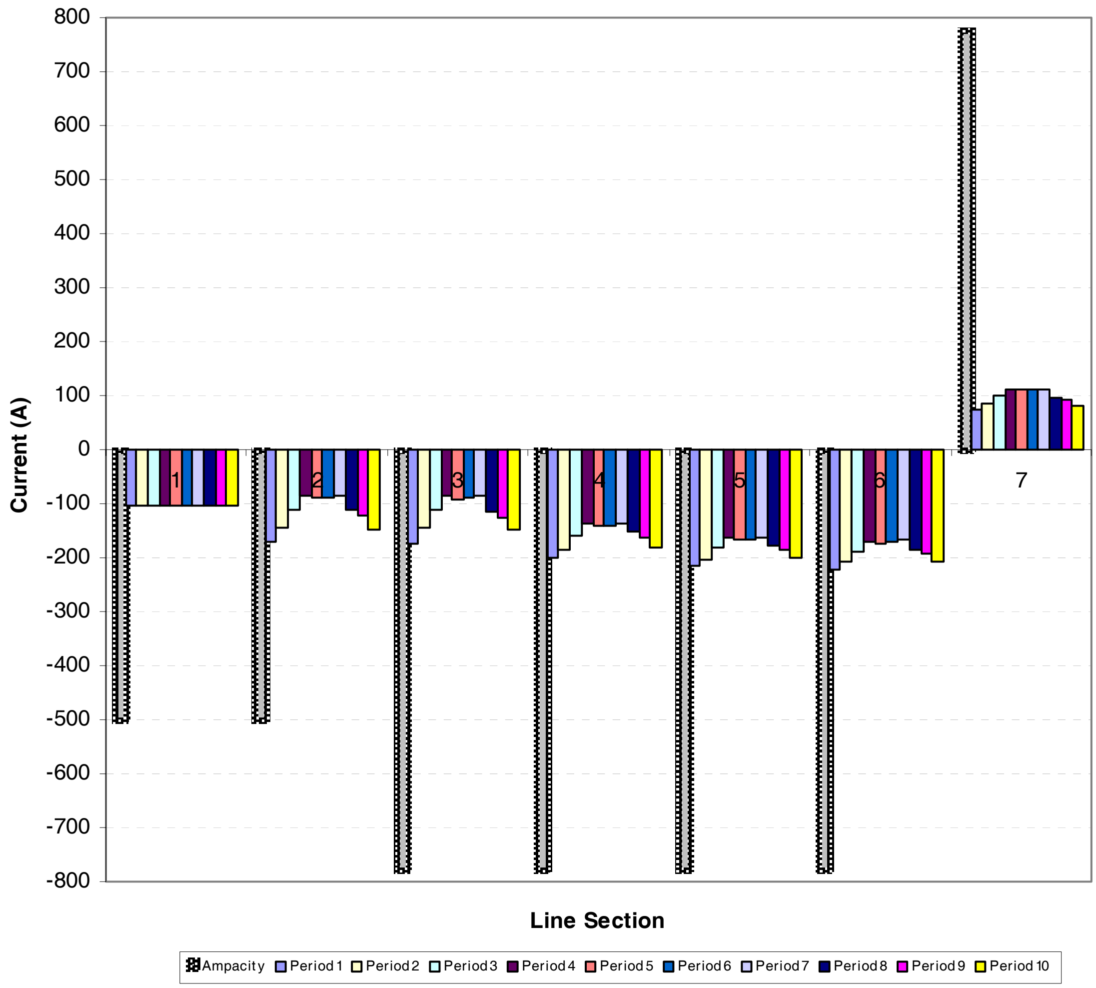


Figure 2.75 Feeder loading per section when 17.4 MW DG is installed after Section C6 and DS is connected of the feeder (after Section C1)

In the case of Figure 2.75, the DS unit is located immediately after section C1 and during the period of the light load the DS unit absorbs a portion of the power generated by the DG unit. Similar to the previous two study cases, this reduces the feeder power export to the permissible limit of 5 MVA. The loadings of all other feeder sections are not affected by the presence of the DS unit. The feeder loadings at all times are much less than the cable ampacity limits.

The study results show that in all cases the presence of the DS unit allows for a larger DG unit to be installed at the industrial customer's site (17.4 MW vs. 14.6 MW) without violating the prescribed power export limit of 5 MW.

To evaluate the effect of the DS unit location, a detailed loss analysis for all three scenarios has been performed. The system losses for all three DS unit location scenarios and all ten time periods are presented in Table 2.15. Distribution of power losses throughout the day for the three DS unit locations is given on Figure 2.76.

Table 2.15 System losses for all three DS unit location scenarios

Time Period	Hours	Power loss (kW)			Energy loss per day (kWh)		
		DS after C1	DS after C2	DS after C6	DS after C1	DS after C2	DS after C6
1	5	96	87	63	480	437	313
2	3	86	82	70	257	246	210
3	2	74	75	78	148	149	156
4	2	66	69	85	131	139	169
5	2	68	72	84	137	143	169
6	1	66	69	83	66	69	83
7	3	64	68	82	192	203	246
8	3	75	76	80	226	229	241
9	2	79	79	78	158	157	155
10	1	86	82	69	86	82	69
				Total	1882	1855	1812

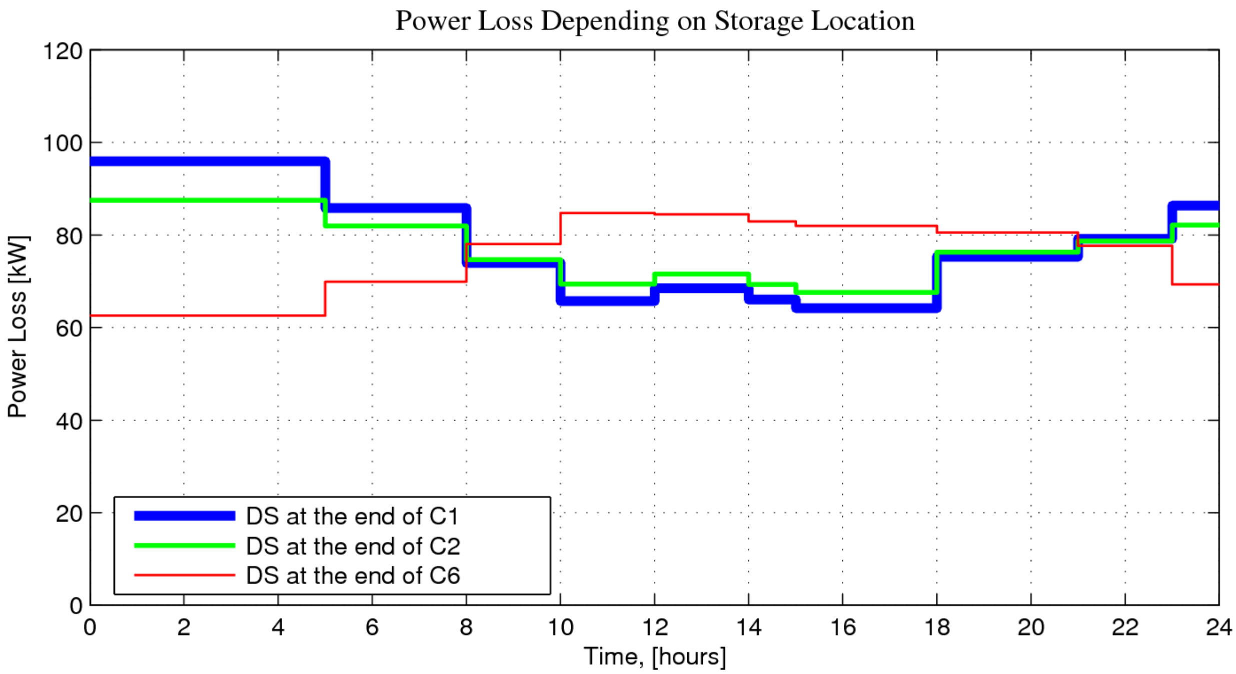


Figure 2.76 Distribution of system losses for all three DS unit location scenarios

Table 2.15 and Figure 2.76 show that the most efficient operation is when the DS unit is located after section C6. The reason is that the charging current is higher than the discharging current and locating the DS unit at the same location as the DG unit exists minimizes losses during charging. The difference between the lowest and the highest loss values is 3.8%. This indicates that in this case the DG location is not a significant factor in system energy loss.

Maximum power export

A typical daily load diagram based on Table 2.13 is assumed. One DG unit and one DS unit are connected to the feeder. The same DS unit charge/discharge strategy as shown on Figure 2.72 is adopted to keep the combined power of the load and the DS constant. It is assumed that the DG export power is limited so that the feeder current is less than or equal to the feeder ampacity limit. To keep the critical feeder sections (C1 and C2 in this case) from overloading, the DG power limit is determined from the power flow studies at 35.9 MW. This is 2.5 MW more than it would be allowed if the DS does not exist in the system.

In power flow studies, three locations are considered for the DS unit:

- end of section C6, where the major industrial load with a DG is located (Figure 2.77),
- end of section C2, since it has the critical cable ampacity limit (Figure 2.78),
- end of section C1, since it has the critical cable ampacity limit (Figure 2.79).

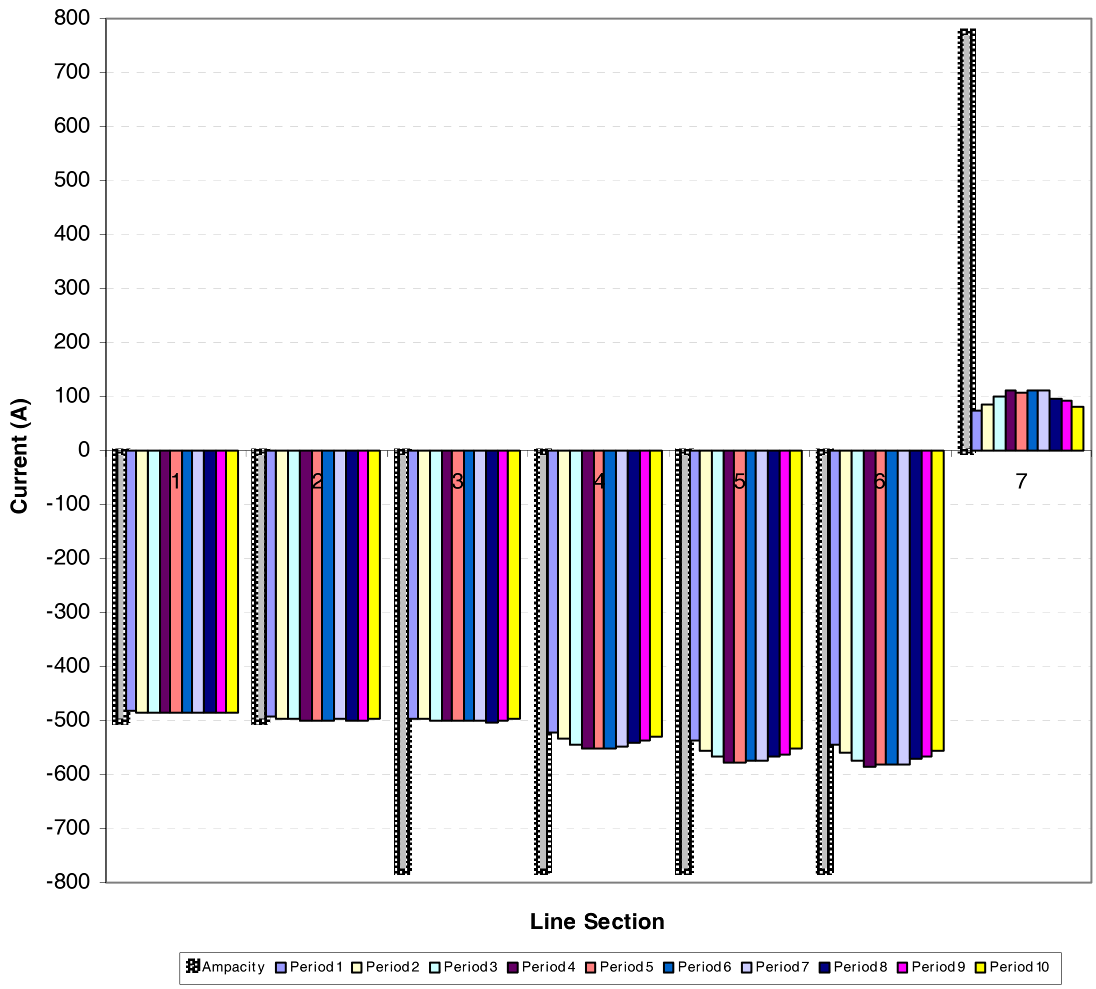


Figure 2.77 Feeder loading per section when 35.9 MW DG is installed after Section C6 and DS is connected of the feeder (after Section C6)

In the case of Figure 2.77, the DS unit is located after feeder section C6, where the DG unit is located. During the period of light load the DS unit absorbs a portion of power generated by the

DG unit. This reduces the loadings of the sections C1 to C6 and allows for larger power export. The loading of feeder section C7 is not affected by the presence of the DS or the DG unit.

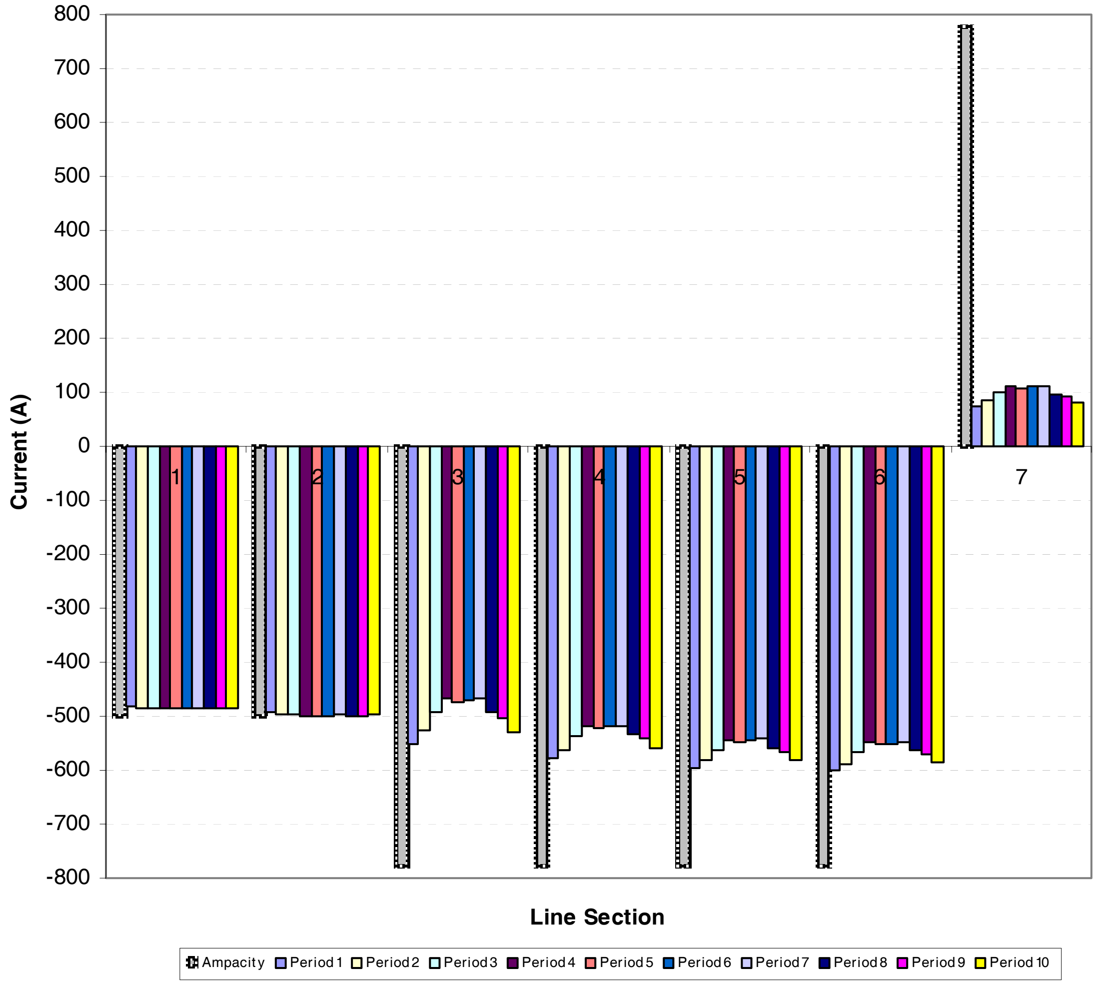
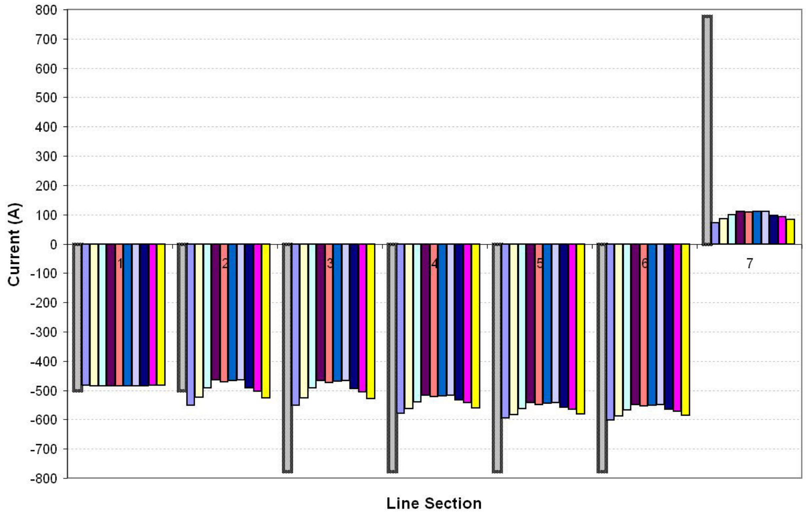
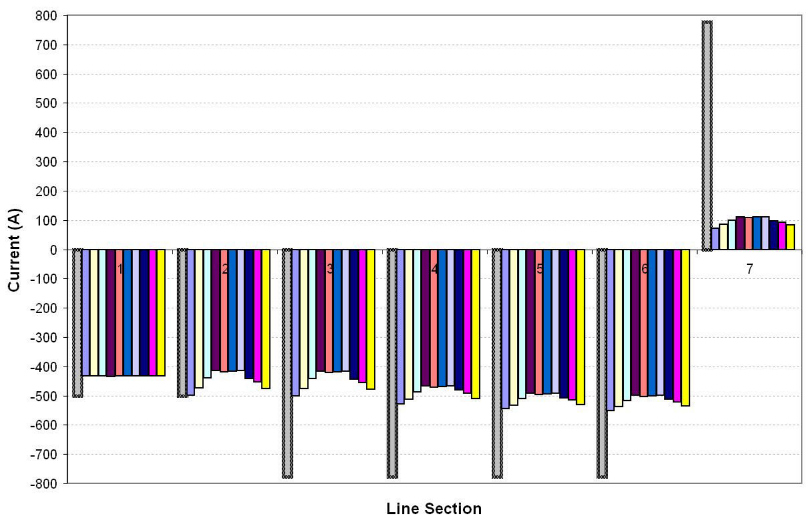


Figure 2.78 Feeder loading per section when 35.9 MW DG is installed after Section C6 and DS is connected of the feeder (after Section C2)

In the case of Figure 2.78, the DS unit is located after section C2 and during the period of light load the DS unit absorbs a portion of power generated by the DG unit. This reduces the loadings of the feeder sections C1 and C2. Loadings of all other feeder sections are not affected by the presence of the DS unit.



(a)



(b)

Figure 2.79 Feeder loading per section when (a) 35.8 MW or (b) 33.4 MW DG is installed after Section C6 and DS is connected of the feeder (after Section C1)

In the case of Figure 2.79 (a), the DS unit is located immediately after feeder section C1 and during the period of the light load the DS unit absorbs a portion of the power generated by the DG unit. The loadings of all other feeder sections are not affected by the presence of the DS unit. This reduces section C1 current to the cable ampacity limit of 500 A (Table 2.12). The maximum current of section C2 exceeds the cable ampacity limit of 500 A by 10%, so the maximum DG power output would have to be reduced by 50 A. Figure 2.79 (b) shows the power flow results when the DG unit power export is reduced to 33.4 MW (same as in the case without the DS unit in service). Loading of feeder section C2 is at the limit. Loadings of all other feeder sections (C3 to C7) are well below cable ampacity limit.

To further evaluate the effect of the DS unit location, the detailed analysis of system losses for two scenarios that result in a higher power export (36.7 MW) has been performed. The system losses for two scenarios corresponding to DS unit locations (after section C2 and after section C6) and all ten time periods are presented in Table 2.16. Distribution of power losses throughout the day for two DS unit locations (after section C2 and after section C6) is given on Figure 2.80.

Table 2.16 System losses for all three DS unit location scenarios

Time Period	Hours	Power loss (kW)		Energy loss per day (kWh)	
		DS after C2	DS after C6	DS after C2	DS after C6
1	5	686	609	3430	3047
2	3	669	631	2006	1892
3	2	641	650	1282	1300
4	2	619	665	1237	1331
5	2	625	664	1250	1328
6	1	620	661	620	661
7	3	615	659	1846	1978
8	3	640	652	1921	1956
9	2	650	645	1300	1291
10	1	667	627	667	627
			Total	15560	15410

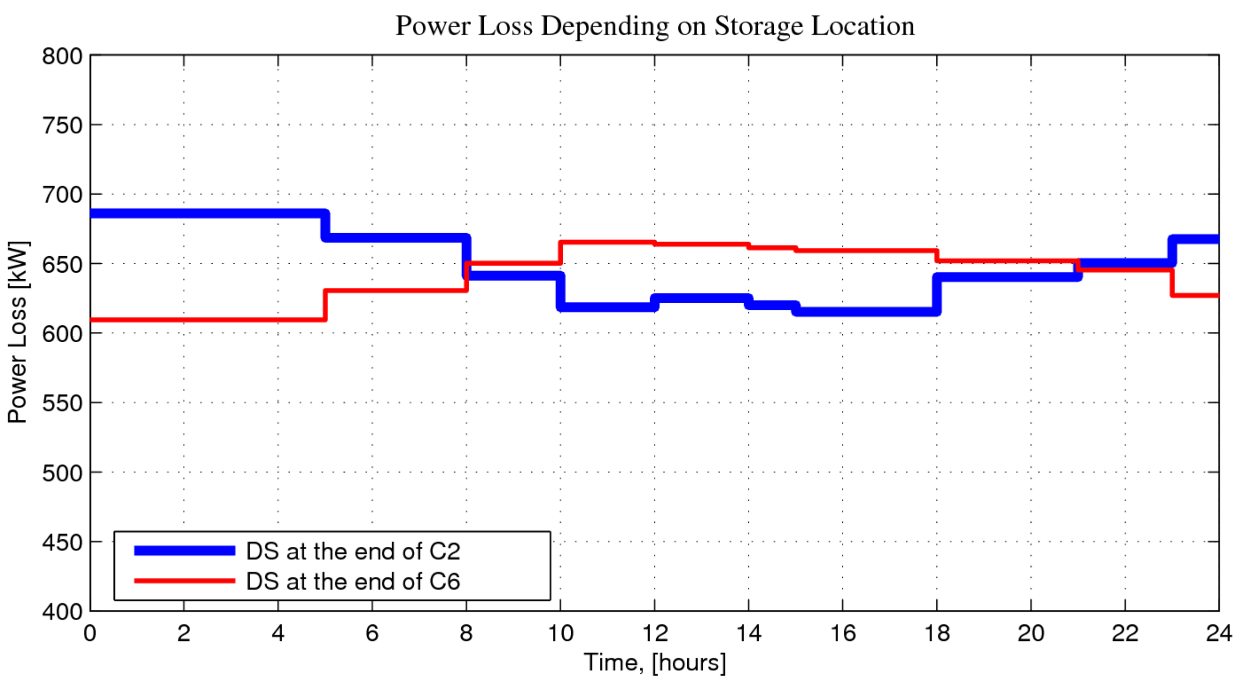


Figure 2.80 Distribution of system losses for all three DS unit location scenarios

Table 2.16 and Figure 2.80 show that the more efficient operation is when the DS unit is located at the same location as the DG unit (after section C6), however the difference between the two scenarios is less than 1%.

2.3.3 Battery Option 3 – 1 MW NaS Battery with 100% DOD

The third set of studies is performed under the assumption that one large 1 MW NaS battery-based on the main technical data from Section 1.2.2 is used. The charging power (on the AC side) is limited to 1.2 MW, while the discharging power limit (on the AC side) is 1.2 MW for up to 3 hours and 1 MW perpetually. The available stored energy is up to 7.2 MWh (100% DOD). An AC efficiency of 80% is assumed for this case.

Conventional operation

Based on the analysis from Section 2.3.1, the maximum allowable loading of feeder type C is 23.6 MW (Figure 2.64). By placing the DS unit on the feeder, the maximum load can be increased. Figure 2.81 shows the input of the storage charge/discharge control strategy based on the procedures of Section 1.2.2.

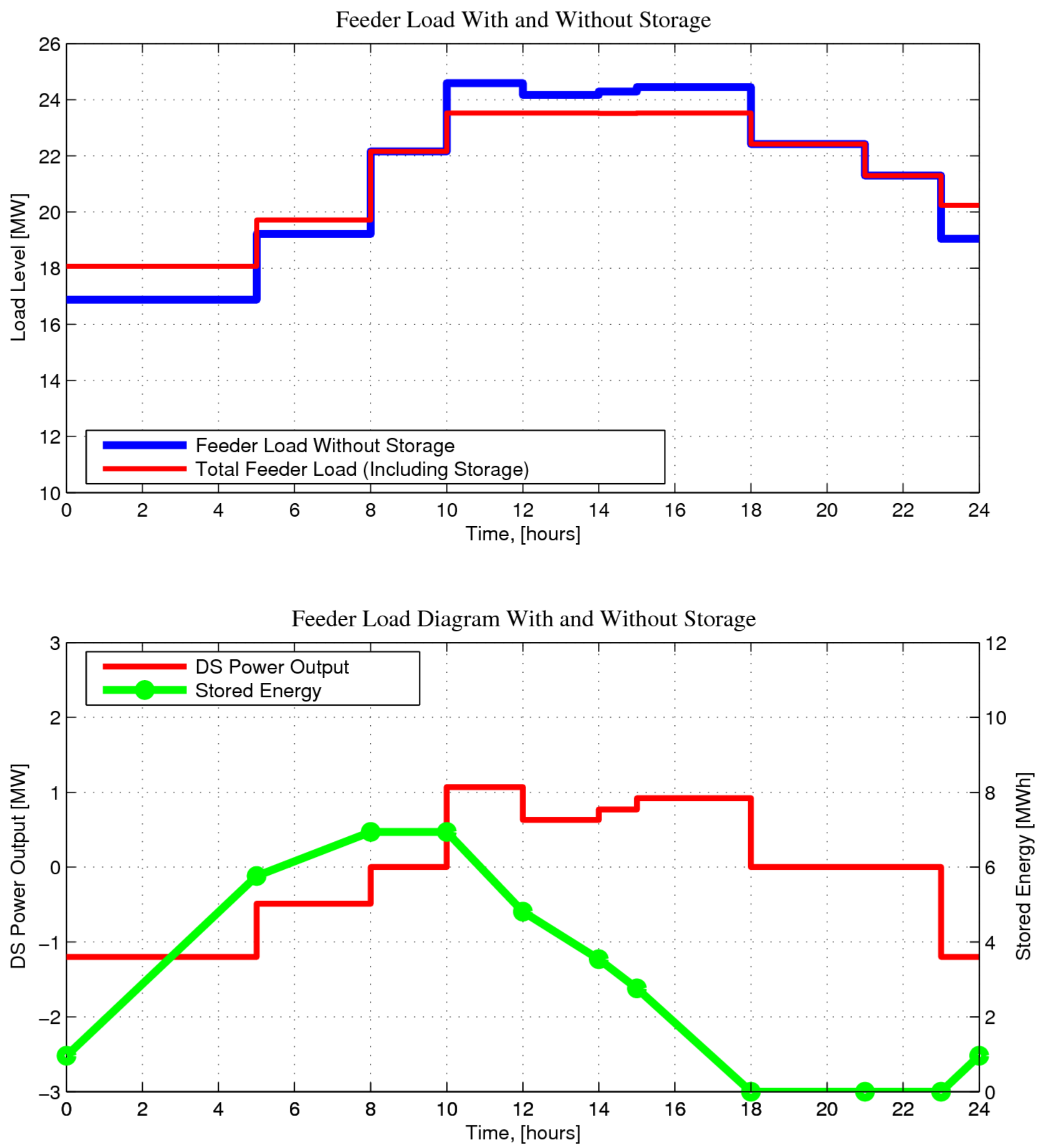


Figure 2.81 DS charge/discharge strategy and the effect of DS unit on feeder loading

On Figure 2.81, the permissible daily peak load in the presence of the 1 MW NaS battery-based DS unit can be increased to 24.6 MW, compared to 23.6 MW for the case without the storage. The total energy produced by the DS unit during discharging period is 80% of the consumed energy during the charging period.

Based on the analysis from Section 2.3.2, the DS unit location associated with the minimal losses is considered (end of section C2). The loadings and the cable ampacities for all sections are shown on Figure 2.82.

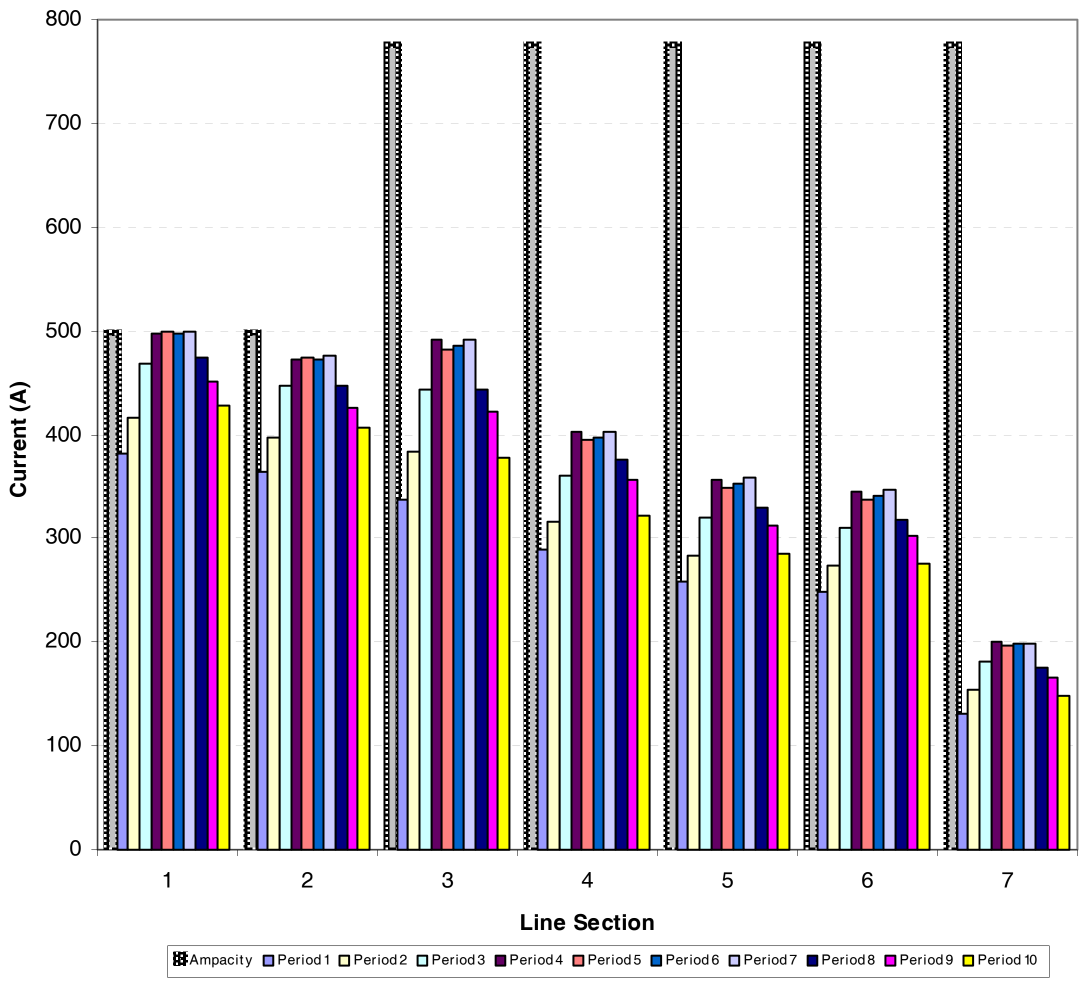
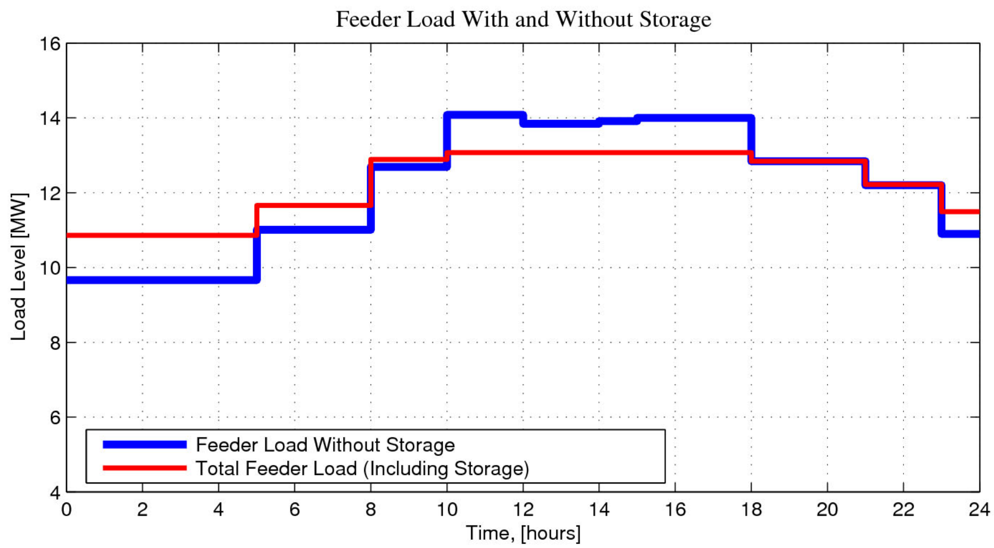


Figure 2.82 Feeder loading per section for cable ampacity loading with one DS unit (1 MW NaS battery with 100% DOD), located after section C2 and no DG in the system

The study results of Figure 2.82 confirm that with the presence of the 1 MW NaS battery-based DS unit, the cable ampacity limits are not violated even if the load peak is as high as 24.6 MW.

Permissible power export

A typical daily load diagram based on Table 2.8 is assumed. One DG unit and one 1 MW NaS battery-based DS unit are connected to the feeder. Without the DG unit, Figure 2.82 shows the loading of section C1, the DS charging/discharging power, and the energy stored in the DS (so that the combined power of the load and the DS is as level as possible). For exporting power from the feeder, the critical period is during the night when the combined load and the DS unit power is 10.86 MW. The stored energy limit is reached at 10:00 and is 7.2 MWh. On Figure 2.83, the DS output power during charging period is shown as a negative value.



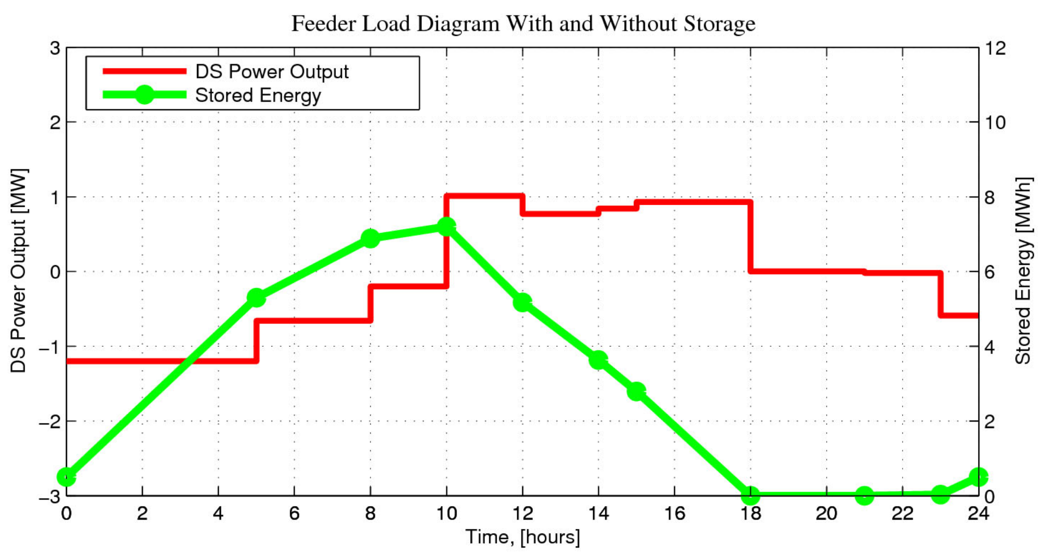


Figure 2.83 DS charge/discharge strategy and the effect of DS unit on feeder loading

The total power export from the feeder is the difference between the exported power from the DG unit and the combined power of the load and the DS during the period of minimal load (10.86 MW). To keep the maximum power export at the prescribed value of 5 MW, the exported power from the DG should be 15.86 MW. This is an approximate value, as it does not take into consideration that due to the reversed power flow in the first three sections, losses in the system are changed.

The actual DG power limit is determined from the power flow studies and is slightly smaller, 15.8 MW. This is 1.2 MW more than it would be allowed if the DS unit is not included in the system. The study results, with the DS unit connected to the feeder after section C6 are shown on Figure 2.84.

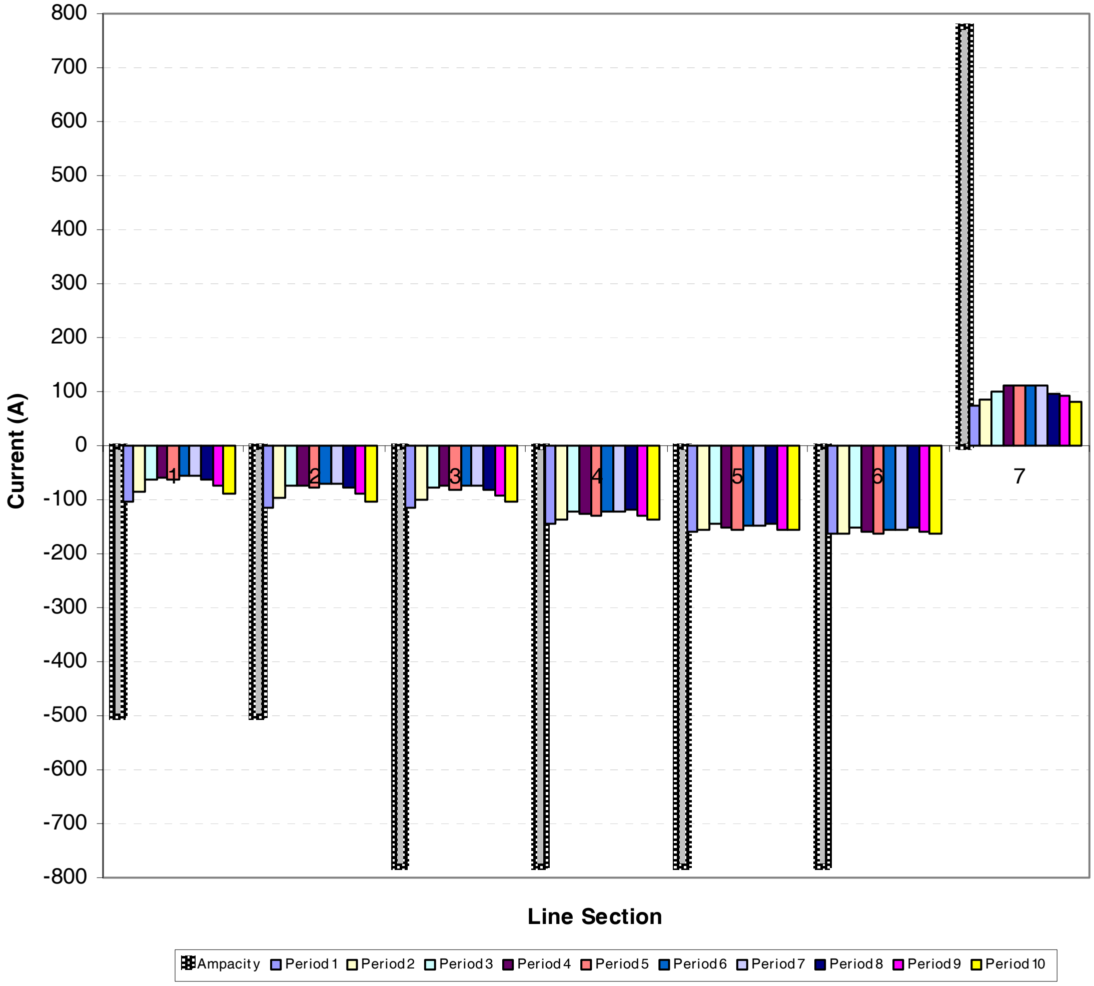


Figure 2.84 Feeder loading per section when 15.8 MW DG is installed after Section C6 and DS is connected of the feeder (after Section C6)

The study results show that the presence of the DS unit allows for a larger DG unit to be installed at the industrial customer's site (15.8 MW vs. 14.6 MW), without violating the prescribed power export limit of 5 MW.

Maximum power export

A typical daily load diagram based on Table 2.8 is assumed. One DG unit and one 1 MW NaS battery-based DS unit are connected to the feeder. The same charge/discharge strategy, shown on Figure 2.83, is assumed for the DS unit. It is assumed that the DG export power is limited so that the feeder current is less than or equal to the feeder ampacity limit. The study results for the case when the DS unit is in the same location as the DG unit (at the end of section C6) are shown on Figure 2.85.

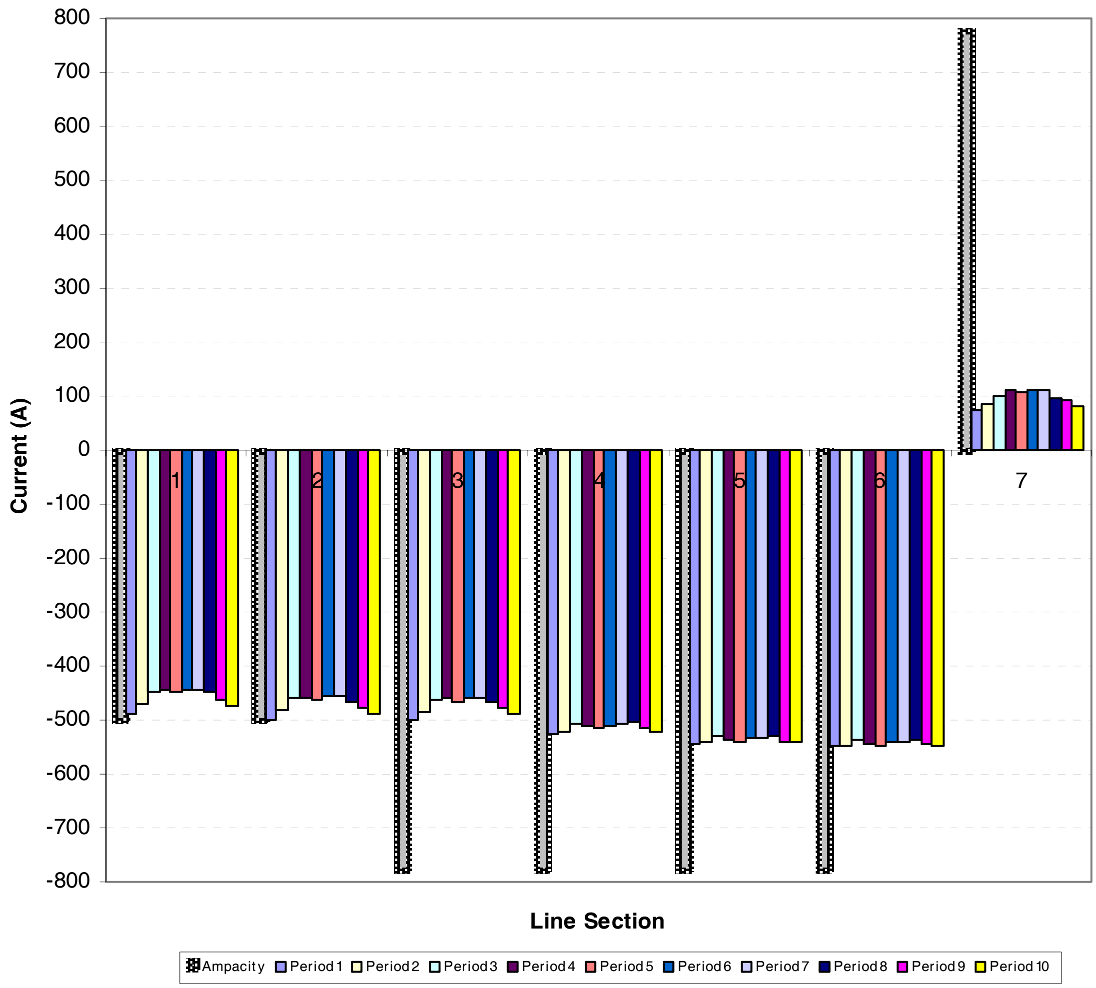


Figure 2.85 Feeder loading per section when 34.6 MW DG is installed after Section C6 and DS is connected of the feeder (after Section C6)

In the case of Figure 2.85, the DG power limit that does not overload the critical feeder section (C2 in this case) is 34.6 MW. This is 1.2 MW more than it would be allowed if the DS does not exist in the system.

2.3.4 Battery Option 4 – 1 MW NaS Battery with 90% DOD

The fourth set of simulations is performed under the assumption that the same 1 MW NaS battery of Section 2.3.3 is used. The charging power (on the AC side) is limited to 1.2 MW, while the discharging power limit (on the AC side) is 1.2 MW for up to 3 hours and 1 MW perpetually. The available stored energy is up to 6.48 MWh (battery capacity is 7.2 MWh, but only 90% DOD is allowed to increase the life of the battery). An AC efficiency of 80% is assumed for this case.

Conventional operation

Based on the analysis from Section 2.3.1, the maximum allowable loading of feeder type C is 23.6 MW (Figure 2.64). If we implement a storage charge/discharge control strategy based on the procedure from Section 1.2.3, the peak load in the presence of 1 MW NaS battery (90% DOD) is increased to 24.5 MW. The relative load diagram applicable for Feeder C is scaled up so that the peak load is the same as the maximum allowed peak loading. Figure 2.86 shows the loading of section C1, the DS charging/discharging power, and the energy stored in the DS. On Figure 2.86, the DS output power during charging period is shown as a negative value.

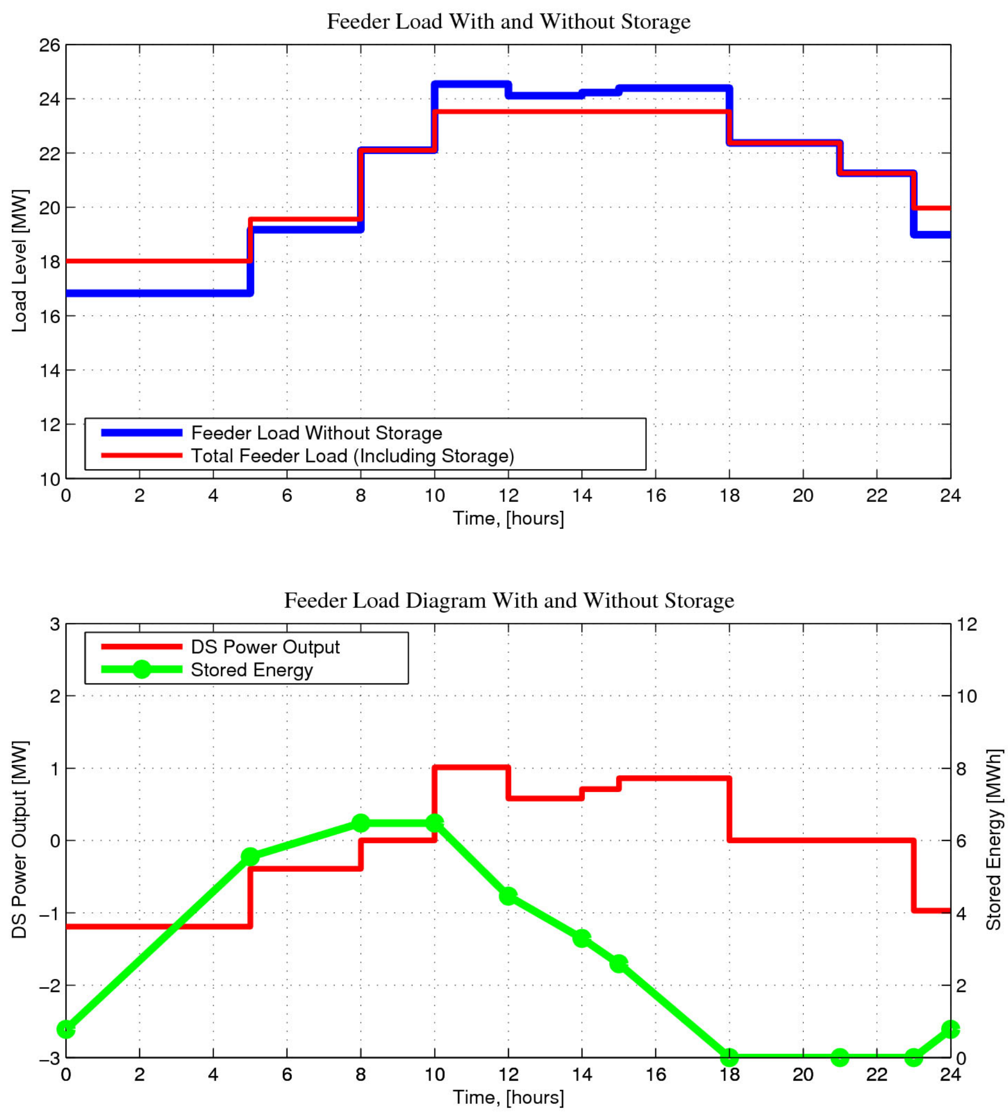


Figure 2.86 DS charge/discharge strategy and the effect of DS unit on feeder loading

Based on the analysis of Section 2.3.2, the DS unit location associated with the minimal losses is considered (after section C2). The loadings of all sections throughout the day are shown on Figure 2.87.

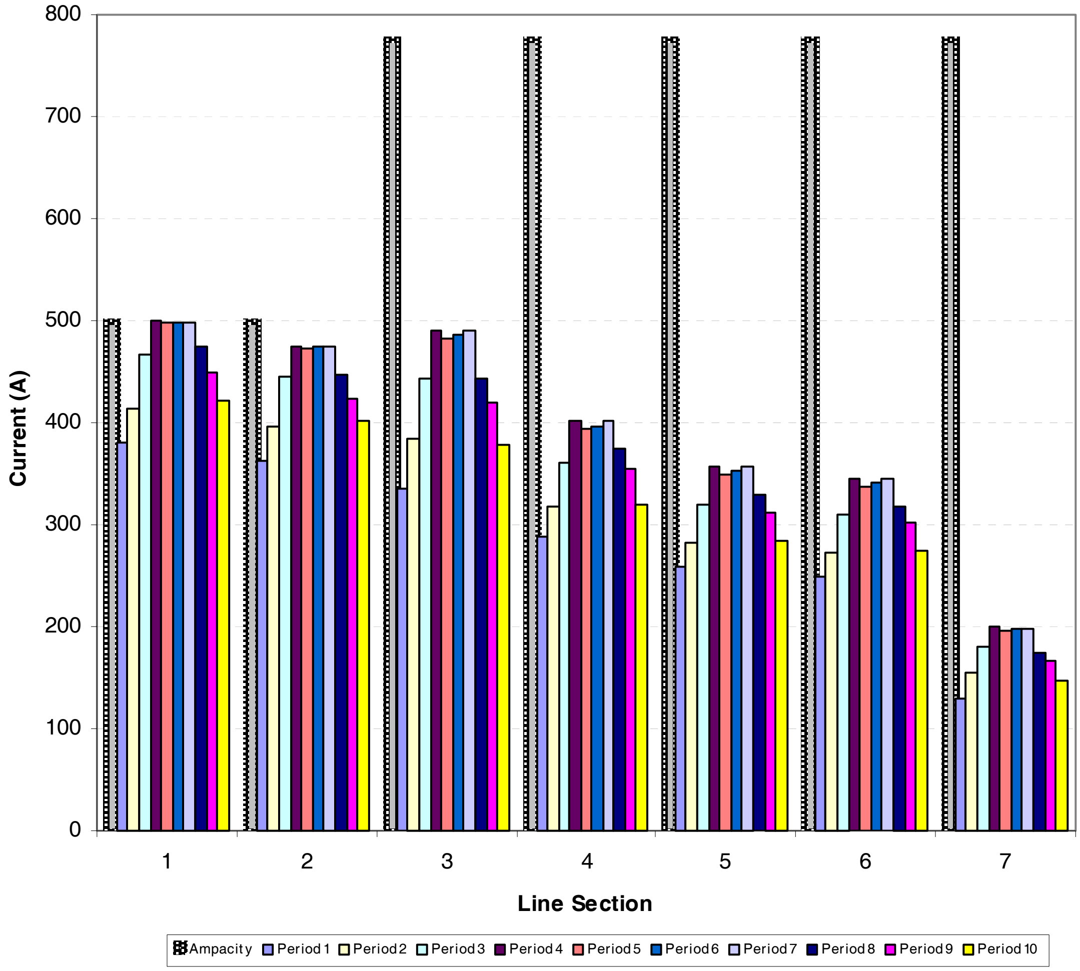
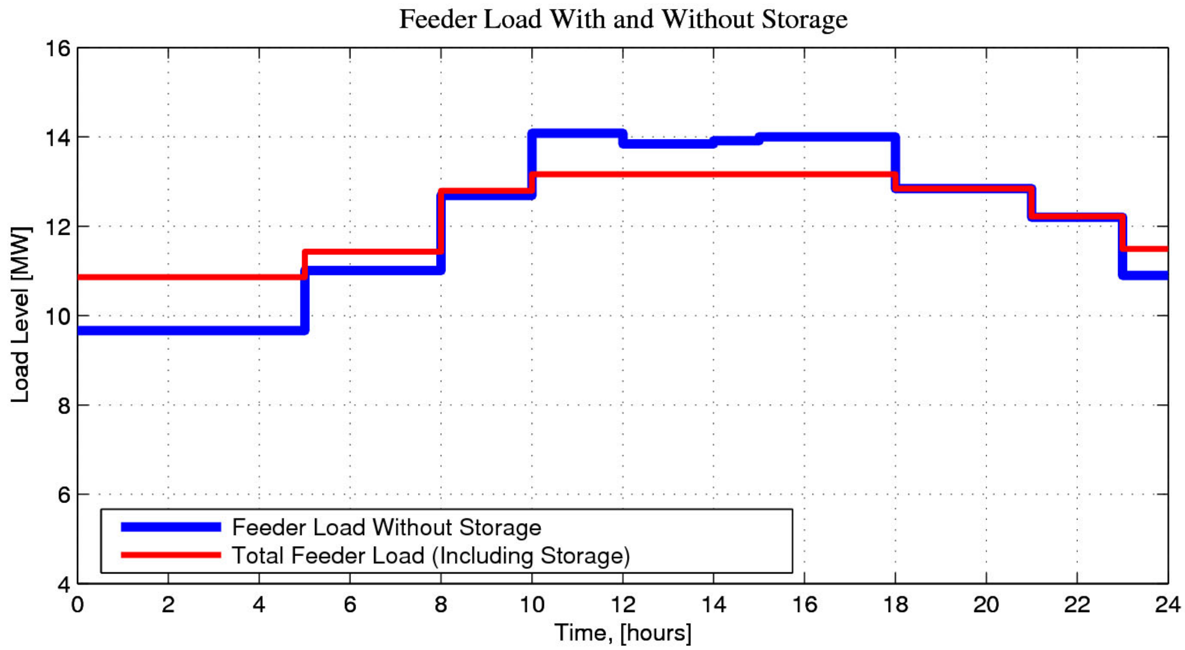


Figure 2.87 Feeder loading per section for cable ampacity loading with one DS unit (1 MW NaS battery with 90% DOD), located after section C2 and no DG in the system

The study results from Figure 2.87 confirm that with the presence of the 1 MW NaS battery-based DS unit, the cable ampacity limits are not violated even if the load peak is as high as 24.5 MW. The effect of reducing DOD from 100% DOD to 90% is less than 100 kW.

Permissible power export

A typical daily load diagram based on Table 2.13 is assumed. One DG unit and one 1 MW NaS battery-based DS unit are connected to the feeder. Without the DG unit, Figure 2.88 shows the loading of section C1 feeder, the DS charging/discharging power, and the energy stored in the DS (so that the combined power of the load and the DS is as level as possible). For exporting power from the feeder, the critical period is during the night when the combined load and the DS unit power is 10.9 MW. The stored energy limit is reached at 10:00 and is 6.48 MWh. On Figure 2.88, the DS output power during charging period is shown as a negative value.



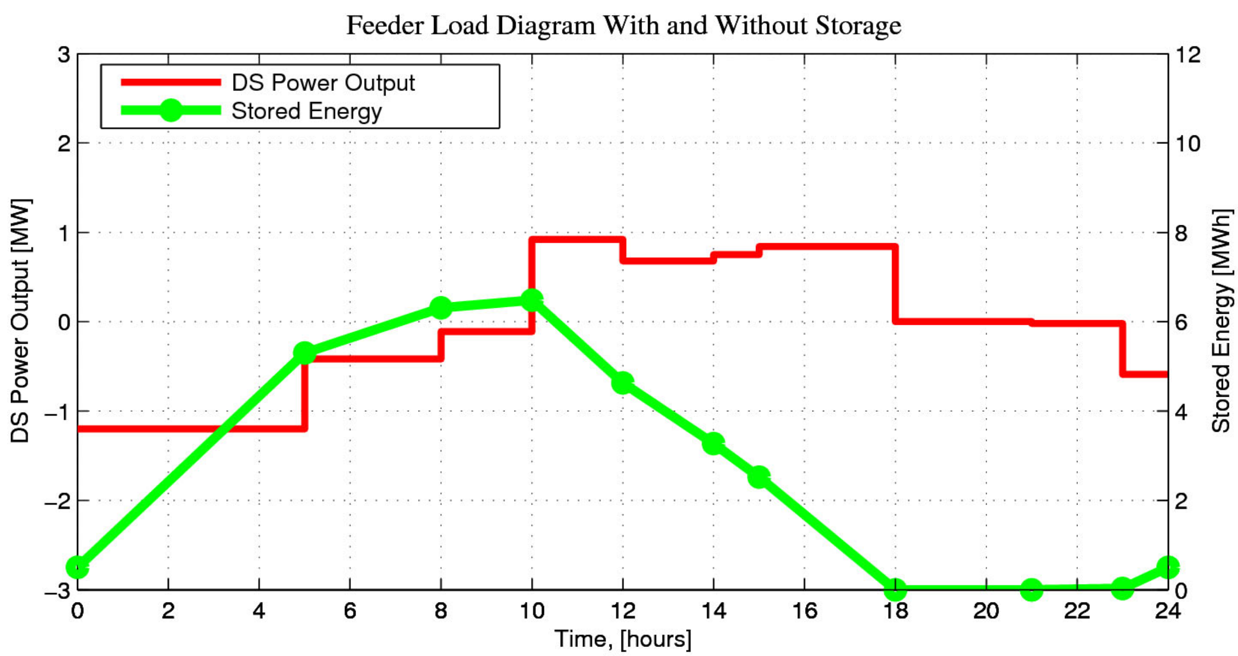


Figure 2.88 DS charge/discharge strategy and the effect of DS unit on feeder loading

The total power export from the feeder is the difference between the exported power from the DG unit and the combined power of the load and the DS during the period of minimal load (10.9 MW). To keep the maximum power export at the prescribed value of 5 MW, the exported power from the DG should be 15.9 MW. This is an approximate value, as it does not take into consideration that due to the reversed power flow in the first three sections, losses in the system are changed. The actual DG power limit is determined from the power flow studies and is slightly smaller, 15.8 MW. This is 1.2 MW more than it would be allowed if the DS unit is not included in the system. The study results, with the DS unit connected to the feeder after section A3, are shown on Figure 2.89.

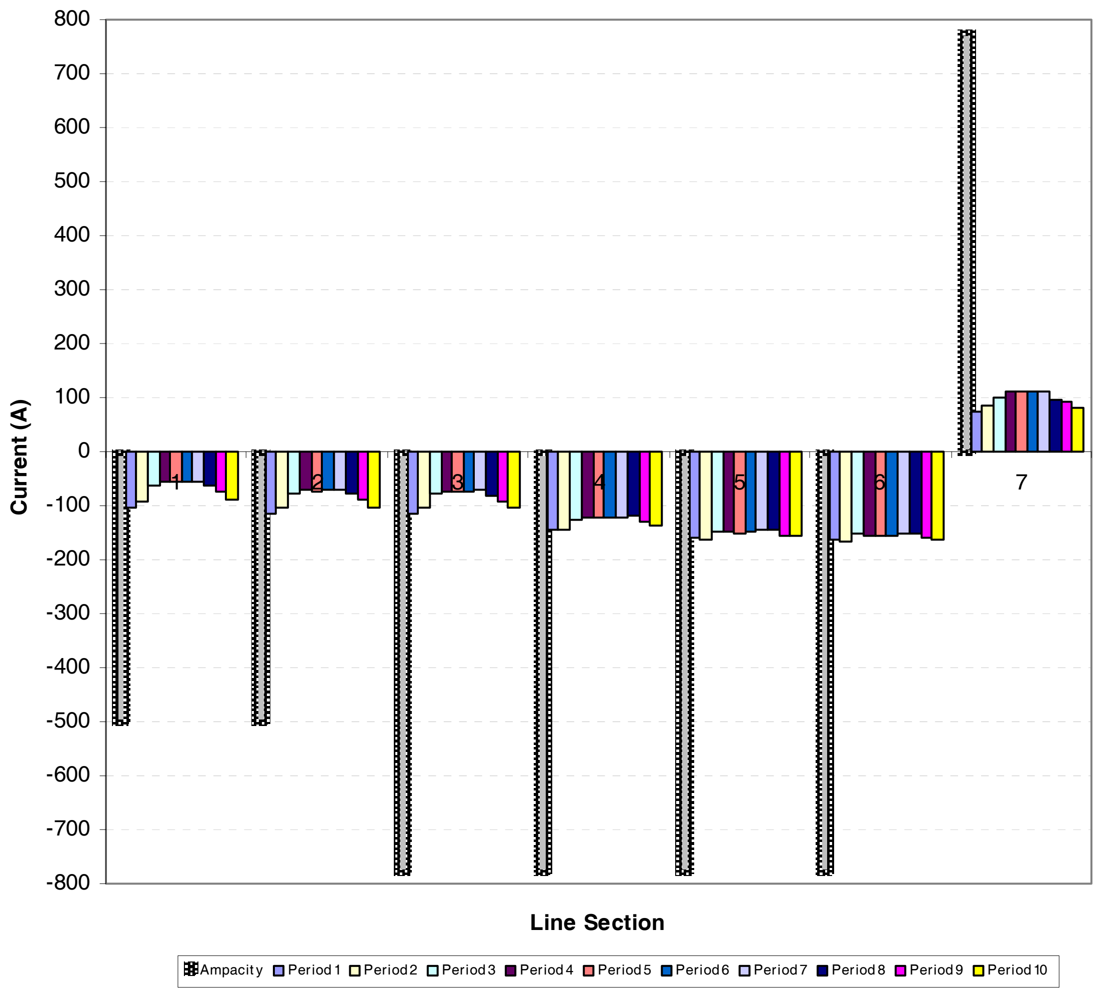


Figure 2.89 Feeder loading per section when 10.9 MW DG is installed after Section C6 and DS is connected of the feeder (after Section C6)

The study results from Figure 2.89 show that the presence of the DS unit allows for a larger DG unit to be installed at the industrial customer's site (15.8 MW vs. 14.6 MW), without violating the prescribed power export limit of 5 MW. This is the same DG power as when the 1 MW NaS battery operates with 100% DOD.

Maximum power export

A typical daily load diagram based on Table 2.3 is assumed. One DG unit and one 1 MW NaS battery-based DS unit are connected to the feeder. The same charge/discharge strategy, shown on Figure 2.88, is assumed for the DS unit. It is assumed that the DG export power is limited so that the feeder current is less than or equal to the feeder ampacity limit. The study results for the case when the DS unit is in the same location as the DG unit (at the end of section C6) are shown on Figure 2.90.

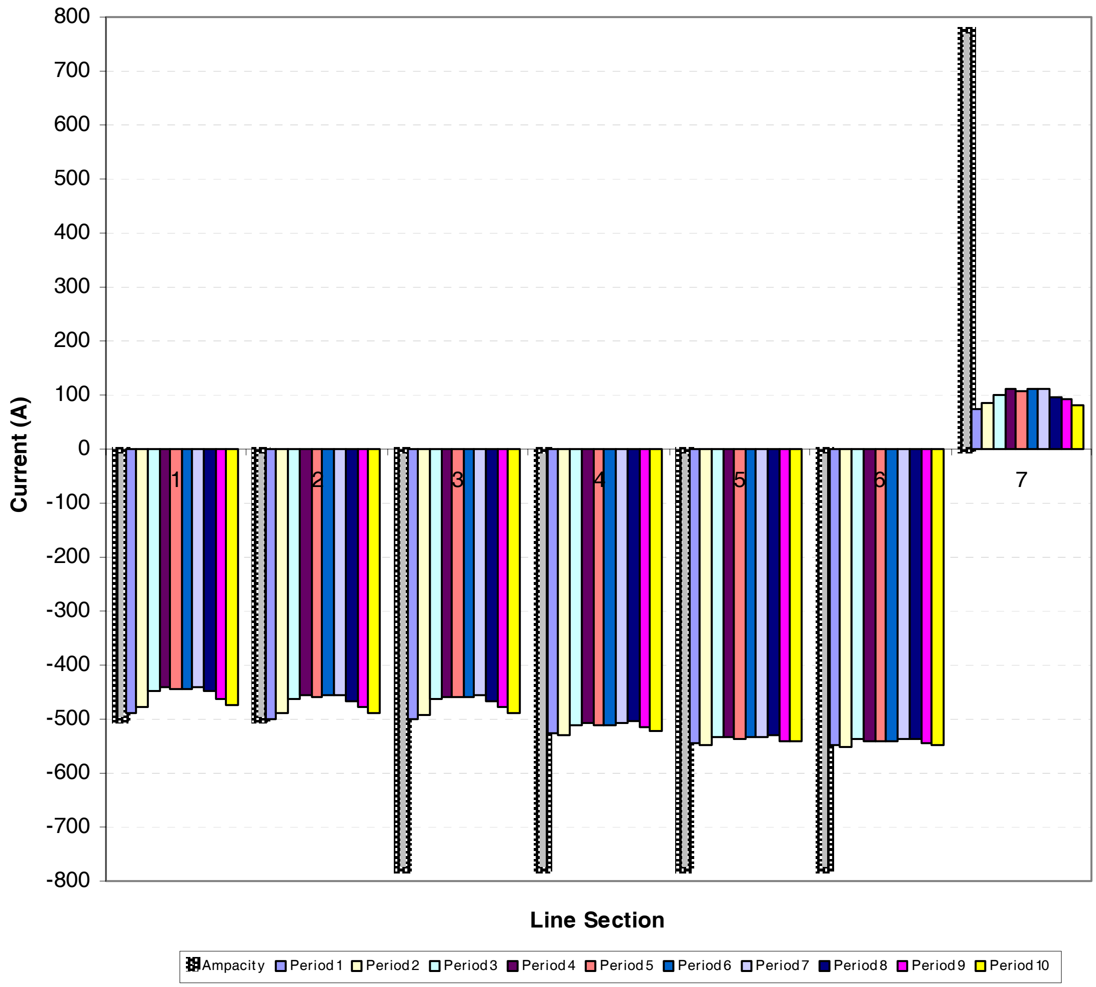


Figure 2.90 Feeder loading per section when 30.6 MW DG is installed after Section C6 and DS is connected of the feeder (after Section C6)

In the case of Figure 2.90, the DG power limit that does not overload the critical feeder section (C2 in this case) is 34.6 MW. This is 1.2 MW more than it would be allowed if the DS does not exist in the system (same as the case when the 1 MW NaS battery operates with 100% DOD).

2.3.5 Summary

The study results show the effect of integration of distributed storage (DS) on the typical industrial/residential feeder loading. It is demonstrated that the presence of the DS unit can reduce load fluctuation throughout the day, and depending on the DS characteristics/ratings, the maximum feeder loading can be increased:

- When a DS unit with the AC efficiency of 70% and without power and storage capacity constraints is used, the maximum allowed load peak power on the feeder is increased from the 23.6 MW to 26.6 MW. The DS parameters required for this case are: (i) the maximum charging power of 5.23 MW, (ii) the maximum discharging power of 2.97 MW, and (iii) the storage capacity of 26.58 MWh.
- When a DS unit of typical 1 MW NaS battery with 7.2 MWh storage capacity and 100% DOD is used, the maximum allowed load peak power on the feeder is increased from 23.6 MW to 24.6 MW.
- When the DS unit is a typical 1 MW NaS battery with 7.2 MWh storage capacity and 90% DOD, the maximum allowed load peak power on the feeder is increased from the 23.6 MW to 24.5 MW.

When the feeder includes DG units, the DS unit allows for a higher level of DG power export:

- When a DS unit with the AC efficiency of 70% and without power and storage capacity constraints is used, the maximum allowed DG power export is increased by 2.8 MW. The DS unit parameters required for this case are: (i) the maximum charging power of 2.77 MW, (ii) the maximum discharging power of 1.66 MW, and (iii) the storage capacity of 14.07 MWh.
- When the DS unit is a typical 1 MW NaS battery with 7.2 MWh storage capacity and 100% DOD, the maximum allowed DG power export is increased from 14.6 MW to 15.8 MW.
- When the DS unit is a typical 1 MW NaS battery with 7.2 MWh storage capacity and 90% DOD, the maximum allowed DG power export is increased from 14.6 MW to 15.8 MW.

The effect of the NaS battery on the maximum allowed DG power export is not affected by the change of DOD from 100% to 90%, because the limiting factor for the DG power export increase is the maximum discharging power.

The study results show that the location of the DS unit is significant when the feeder has more sections with reduced cable ampacities. The results show that placing the DS between sections with reduced ampacities may significantly reduce the benefit of the DS unit. For the Feeder C load (Figure 2.61) it is important to place the DS unit after section C2, to avoid overloading section C2 that contains one of the critical cable sections with the maximum current of 500 A. The location of DS can also affect the overall system losses but in all cases the effect of moving the DS from just after section C2 to just after section C6 is less than 2.4%. The most efficient location is always as close as possible to the source for the DS unit charging.

2.4 Feeder Type D - Industrial feeder

The fourth feeder type analyzed in this study is a purely Industrial feeder, Figure 2.91. The feeder consists of eight large industrial loads distributed along the feeder. At the middle of the feeder, one of the industrial load can include one large DG unit, as indicated on Figure 2.91.

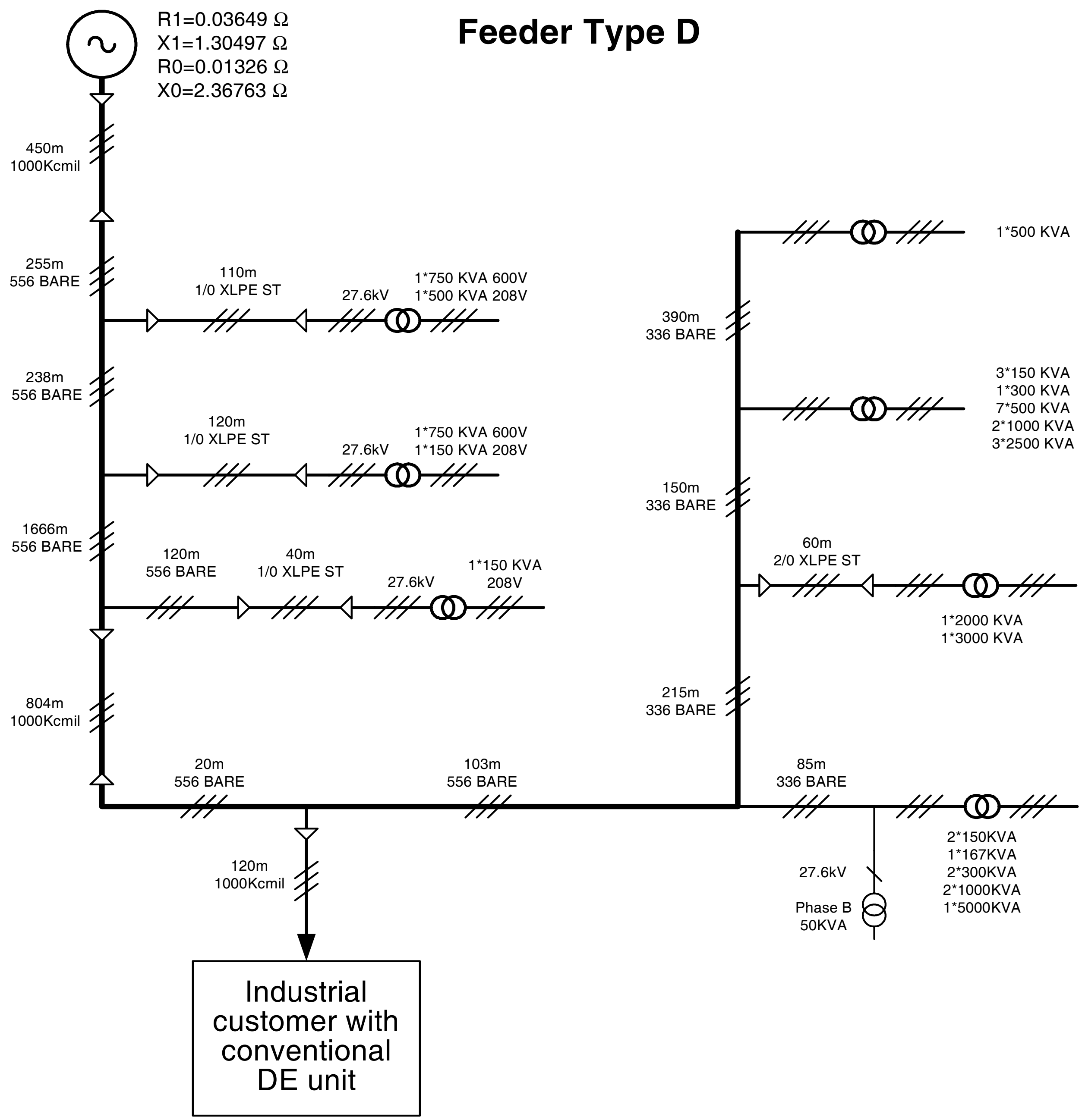


Figure 2.91 One-line diagram of Feeder Type D - Industrial feeder

To identify the cable ampacity limits and to specify potential DS unit locations, the feeder of Figure 2.91 is divided in multiple sections, as shown in Figure 2.92. Feeder is sectionized so that there is at least one feeder section between any two major loads or a group of loads. Seven sections are used for feeder type D. The maximum feeder loading for each section is based on the cable ampacity as shown in Table 2.17. The significant part of the feeder, sections D1 and D4, is the 1000 kcmil cable with the maximum current of 500 A. The minimal currents for all other sections are higher (565 A for sections D2, D3, and D5 and 777 A for sections D6 and D7), therefore sections D1 and D4 are the critical sections for all cable ampacity studies.

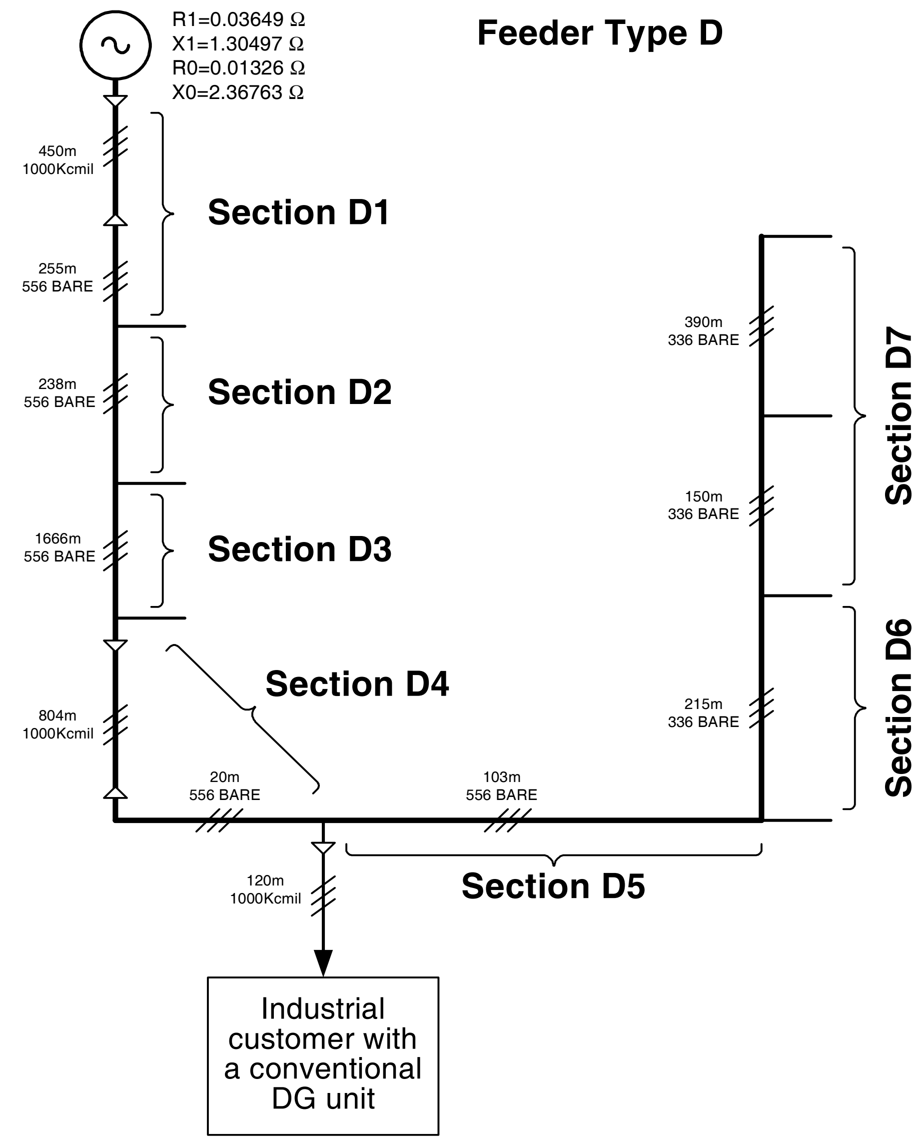


Figure 2.92 Sections of Feeder Type D - Industrial feeder

The industrial customer that includes a conventional DG unit is located between sections D4 and D5. Three potential locations for placing a DS unit are analyzed:

- end of section D7 (at the feeder end), the extreme case where the highest losses due to the DS are expected,
- end of section D4, just after section D4 with the critical cable ampacity limit (500 A) and at the location of the major industrial load with a DG,
- end of section D1, since section D1 has the critical cable ampacity limit (500 A).

Typical daily peak load for this feeder is 10.05 MW and the normal daily load diagram based on the typical load data, from Tables 1.1 and 2.1, is given in Table 2.18.

Table 2.17 Feeder cable ampacity per section

Section number	Cable Type	Cable Ampacity (A)	Maximum Power (MW)	Section Resistance (mΩ)
D1	1000kcmil	500	23.9	78.8
D2	556 Bare	777	37.1	24.3
D3	556 Bare	777	37.1	169.9
D4	1000kcmil	500	23.9	96.4
D5	556 Bare	777	37.1	10.5
D6	336 Bare	565	27.0	36.3
D7	336 Bare	565	27.0	91.3

Table 2.18 Normal daily load diagram for Feeder Type D

Time Period (hours)			Total Feeder Load, MW
Period #	From	To	
1	0	5	8.56
2	5	8	8.29
3	8	10	8.72
4	10	12	9.59
5	12	14	9.15
6	14	15	9.59
7	15	18	10.05
8	18	21	9.15
9	21	23	8.72
10	23	24	8.72

2.4.1 Battery Option 1 – No energy storage is available

The first set of simulations is performed under the assumption that there is no storage unit in the system. The results from this case study are used as the benchmark to evaluate the study results when the system includes DS.

Conventional operation

c) ***A normal daily loading* -** The total feeder loading is equal to the normal daily loading from Table 2.18. Both Industrial and Commercial loads are distributed among three-phase transformers, while the residential load is distributed among three-phase and single-phase transformers. No DG units are connected to the feeder.

The study results provide the feeder loading (in Amperes) for each of the seven sections of Feeder Type D (as defined in Figure 2.92), and for all 10 time periods (as specified in Table 2.18). The simulation results are presented in Figure 2.93.

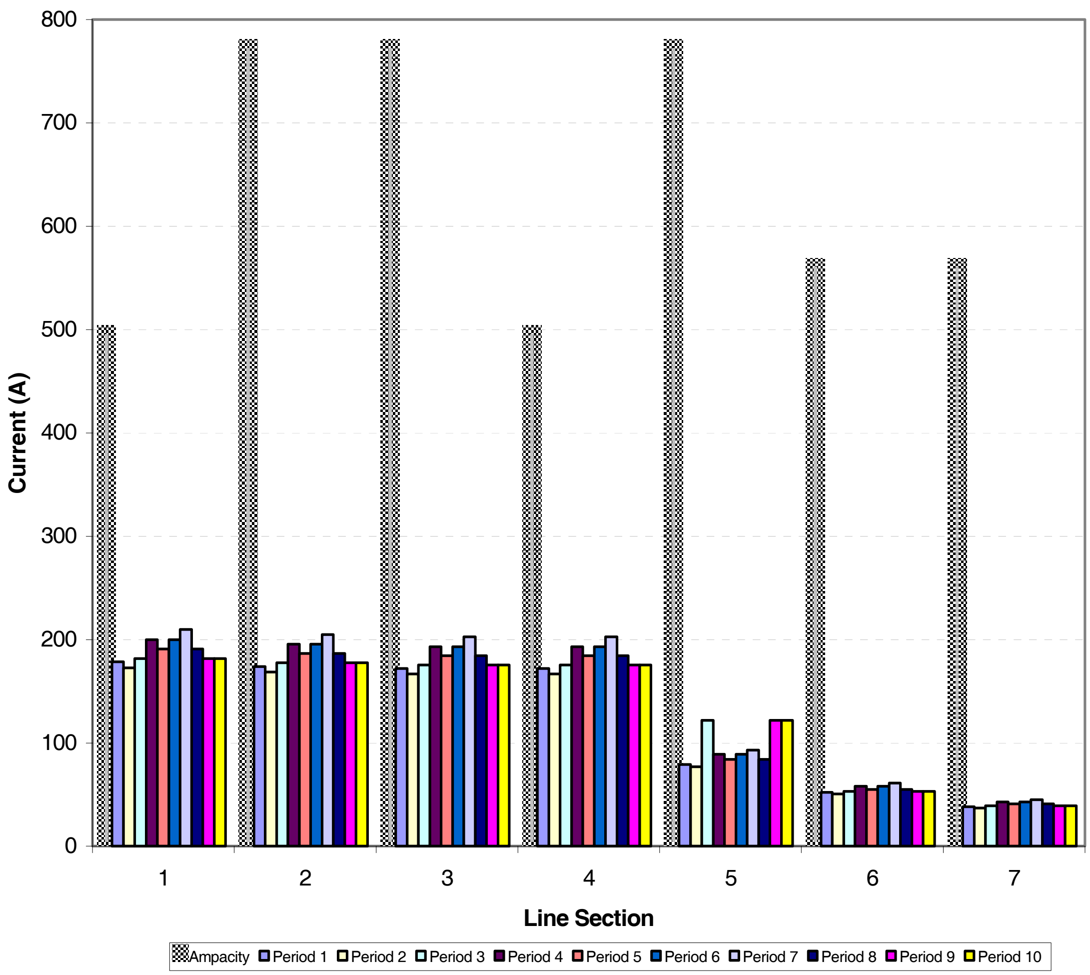


Figure 2.93 Feeder loading per section for normal loading (no DS or DG in the system)

Figure 2.93 compares the current associated with the normal daily loading compares with the cable ampacity in each feeder section. All cable sections are loaded with less than 50% of the ampacity limit.

d) ***The maximum allowable feeder loading*** – The load for this case study is obtained by scaling up all individual loads of case (a) until one of the cable ampacity limits is reached. The study results for this test case are presented on Figure 2.94.

e)

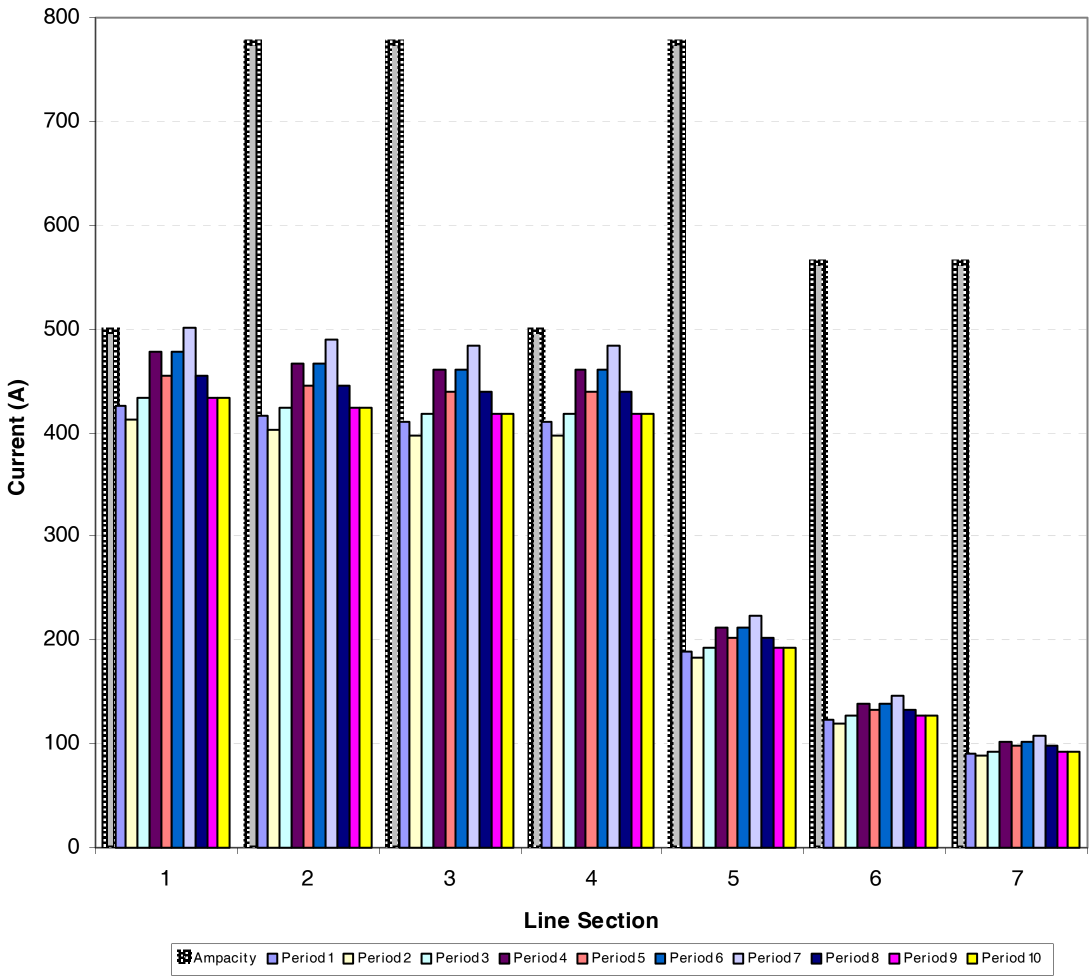


Figure 2.94 Feeder loading per section for cable ampacity loading and no DS or DG in the system

The results of Figure 2.94 show that the maximum cable loading in this case occurs on section D1, during the peak power period (period #4, between 10:00 and 12:00). The total load peak power that brings the cable ampacity of section D1 to a limit is 23.6 MW, as specified in Table 2.17. The maximum voltage drop for this case is 1.4%. It is calculated at the end of Section 7, during time period #7, between 15:00 and 18:00. This scenario is associated with the highest possible voltage drop for this feeder. Since 1.4% is significantly less than the maximum allowed 6% voltage drop, we conclude that voltage drop is not a factor in any of the case studies for this feeder.

Permissible power export

A normal daily loading is assumed for feeder of Figure 2.91. The typical daily load diagram is given in Table 2.18. One DG unit is connected to the feeder. The maximum allowed DG capacity is determined such that the power export from the feeder is either less than or equal to the value specified by the utility (e.g. 5 MW) at all times. The simulation results for this test case are presented on Figure 2.95.

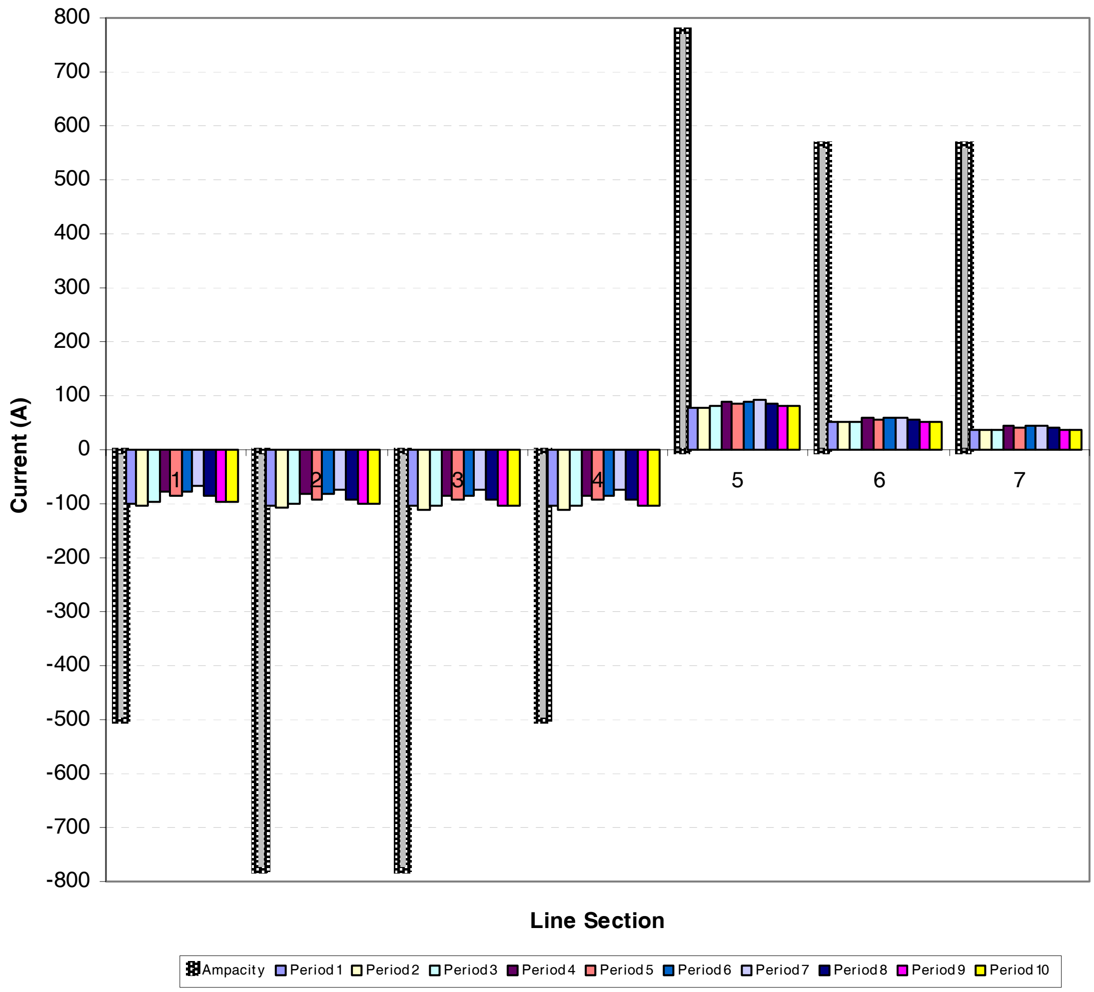


Figure 2.95 Feeder loading per section when 13.25 MW DG is installed after Section D4 and no DS is connected to the feeder

The results of Figure 2.95 show that when 13.25 MW is produced by the DG unit, under normal daily load condition, the maximum power export is 5 MW, as specified by the utility. The critical time period when the maximum power export limit is reached is at night (period #2, between 5:00 and 8:00).

Maximum power export

A normal daily loading is assumed for feeder of Figure 2.91. The typical daily load diagram is given in Table 2.18. One DG unit is connected to the feeder at the end of feeder section D4. The maximum allowed DG capacity is determined such that the power export from the feeder is less than the cable ampacity of the 1000 kcmil cables of feeder sections D1 and D4. The study results for this test case are presented on Figure 2.96.

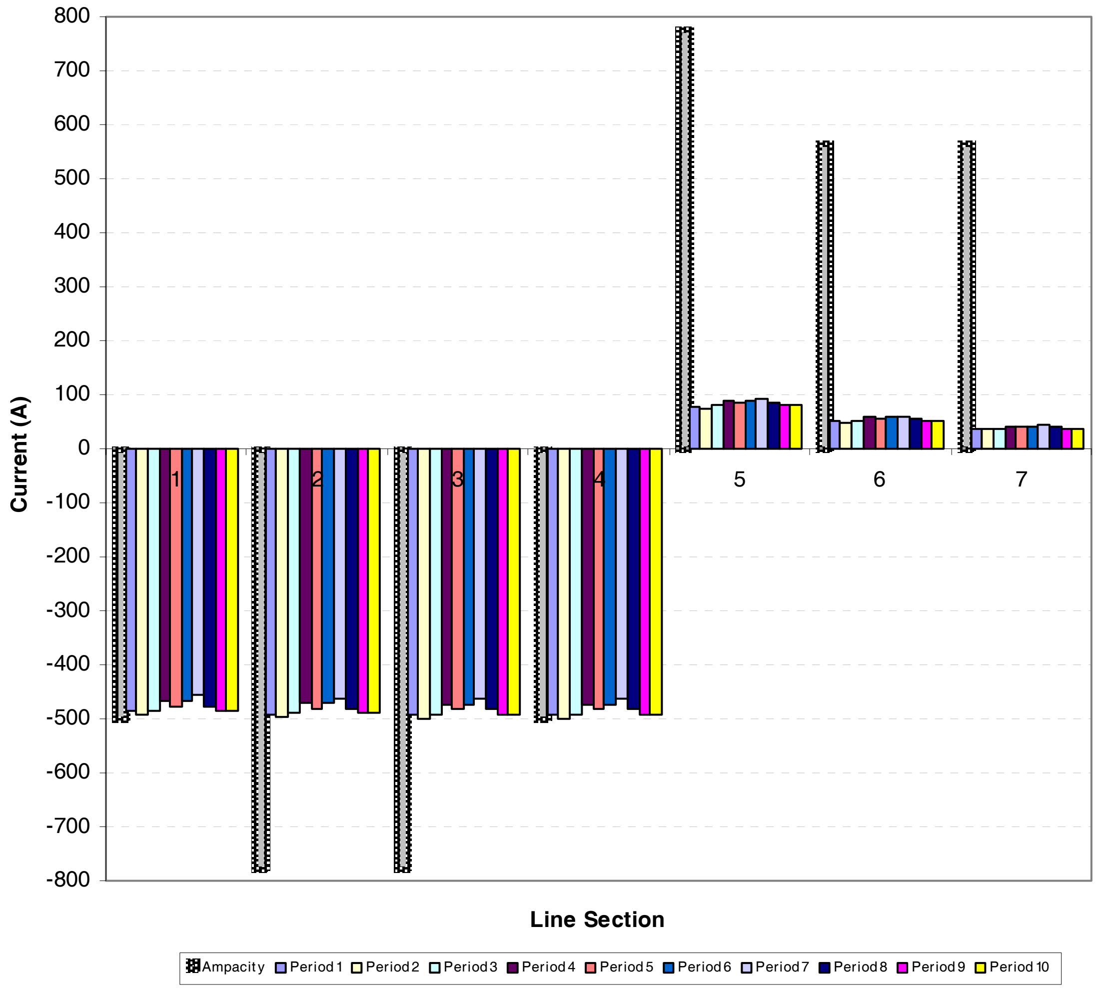


Figure 2.96 Feeder loading per section when 32.4 MW DG is installed after Section D4 and no DS is connected to the feeder

The results of Figure 2.96 show that when 32.1 MW produced by the DG unit, under normal daily load condition, the maximum power export is only 23.4 MW, which is less then the cable ampacity of section D1 (23.9 MW, as per Table 2.12). This is due to the cable ampacity limit of section D4 that is reached before the cable ampacity limit of section D1. Loads connected between sections D1 and D4 reduce the power from 23.9 MW (section D4) to 23.4 MW (section D1). The critical time period when the maximum power export limit is reached is at night (period #2, between 5:00 and 8:00).

2.4.2 Battery Option 2 – Generic case with no power or energy limits

The second set of studies is performed under the assumption that one large DS unit is used and power and energy constrains have not been imposed. An AC efficiency of 70% is assumed for this generic case.

Conventional operation

Based on the feeder cable ampacity (Table 2.17), the maximum permissible power in sections D1 and D4 is 23.9 MW. In the case study of Figure 2.91, without the storage, the daily peak is 23.6 MW. By placing the DS unit on the feeder, the maximum load can be increased. Figure 2.97 shows the input of the storage charge/discharge control strategy based on the procedures from Section 1.2.1.

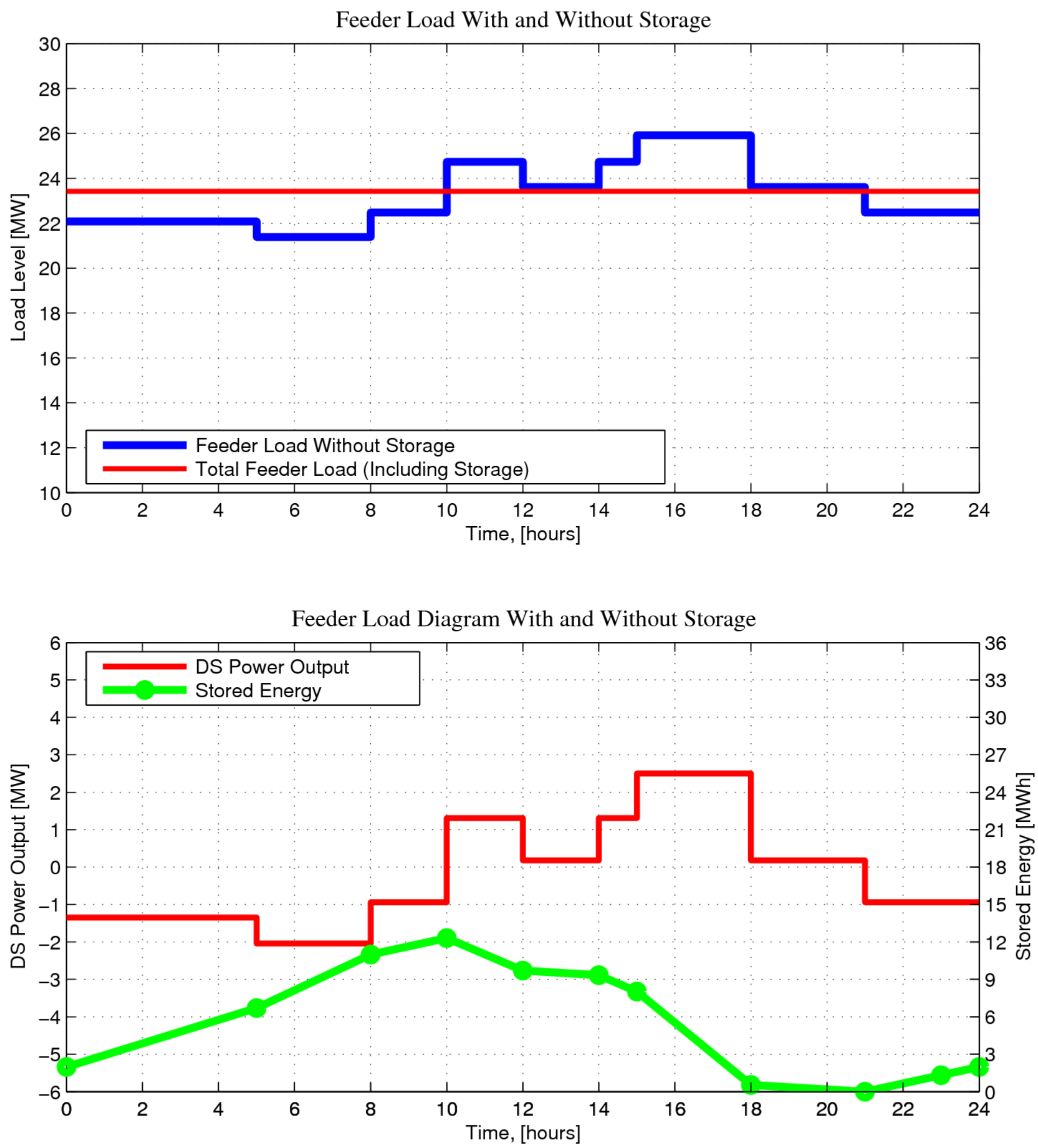


Figure 2.97 DS charge/discharge strategy and the effect of DS unit on feeder loading

On Figure 2.97, the permissible daily peak load in the presence of the DS unit can be increased to 26.1 MW, compared to 23.6 MW for the case without the storage. The total energy produced by the DS unit during the battery discharge period is 70% of the consumed energy during the battery charge period. To achieve the storage charge/discharge performance of Figure 2.97, the DS unit rating should be:

- maximum charging power 2.04 MW,
- maximum discharging power 2.50 MW,
- storage capacity 12.83 MWh.

As explained before, three locations are considered for the DS unit:

- end of section D7, where the highest losses are expected (Figure 2.98),
- end of section D4, where the major industrial load with a DG is located and section D4 has the critical cable ampacity limit (Figure 2.99),
- end of section D1, since it has the critical cable ampacity limit (Figure 2.100).

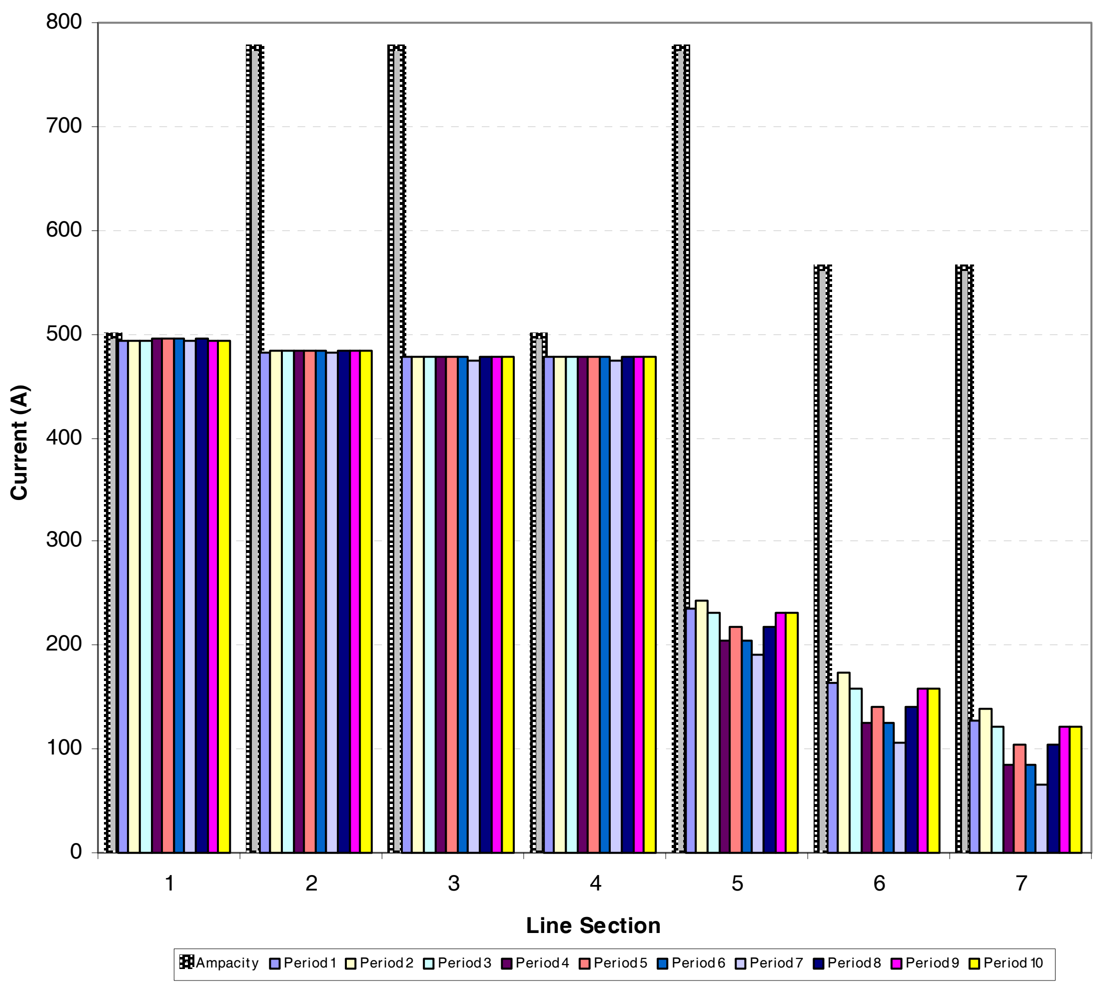


Figure 2.98 Feeder loading per section for cable ampacity loading with one DS unit (70% efficiency and no power/energy limits), located after section D7 and no DG in the system

Figure 2.98 shows that locating the DS unit at the end of the feeder (after section D7) reduces the feeder loading on all feeder sections during the mid-day period. This results in a higher total load limit (25.9 MW), compared to the case without the storage (23.4 MW). The feeder loading at night is increased in sections D1 to D7 (due to DS charging).

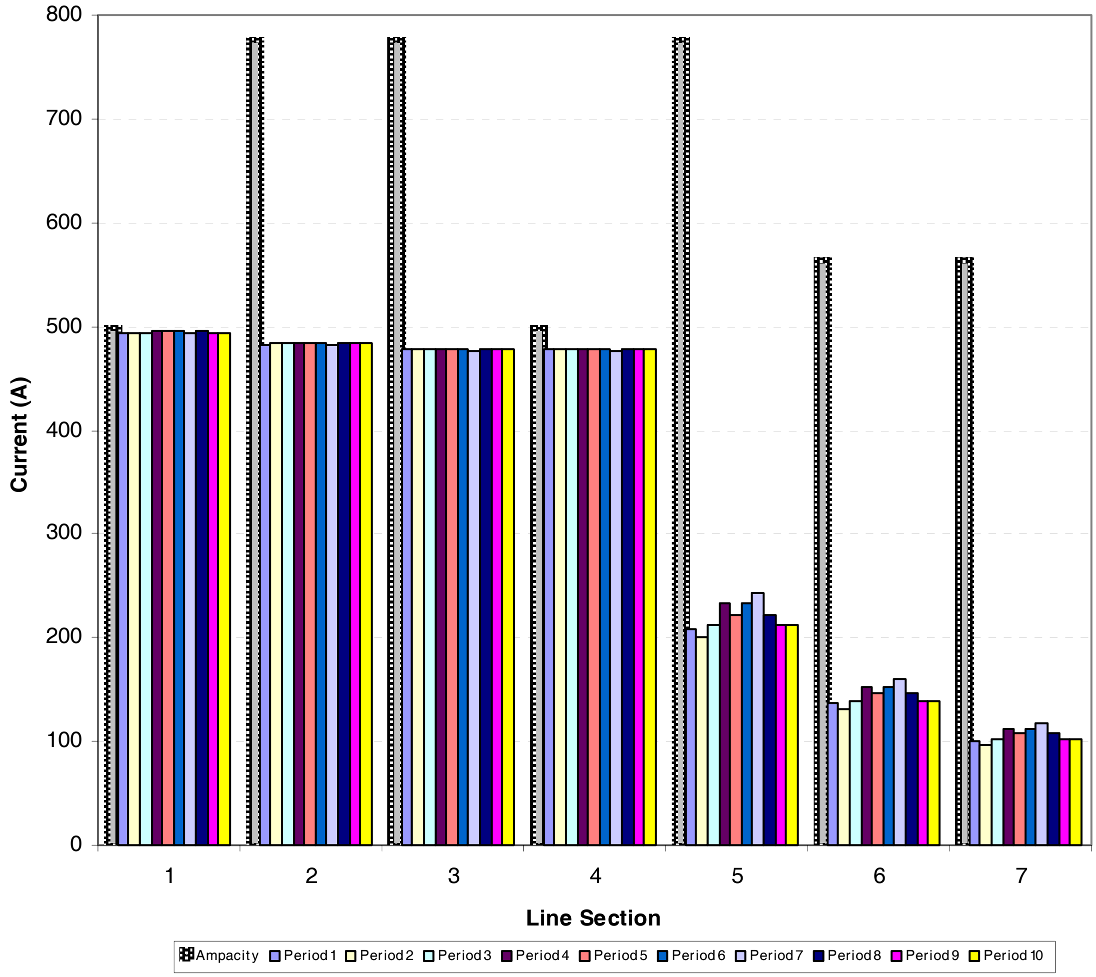


Figure 2.99 Feeder loading per section for cable ampacity loading with one DS unit (70% efficiency and no power/energy limits), located after section D4 and no DG in the system

Figure 2.69 shows that locating the DS unit after section D4 reduces the loadings of feeder sections D1, D2, D3, and D4 during the mid-day. Same sections experience higher loadings at night (due to the DS charging) similar to the previous case. Loadings of feeder sections D5, D6 and D7 are not affected by the presence of the DS unit.

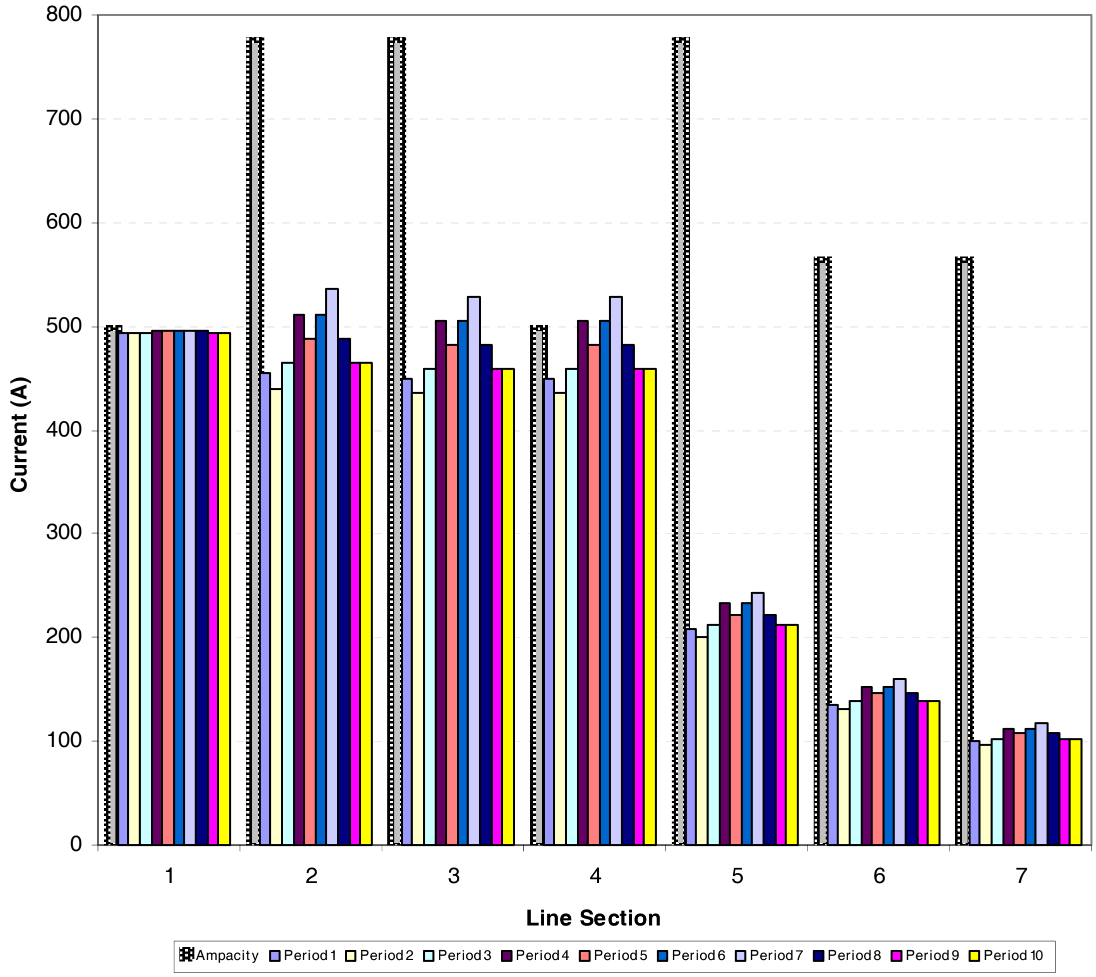


Figure 2.100 Feeder loading per section for cable ampacity loading with one DS unit (70% efficiency and no power/energy limits), located after section D1 and no DG in the system

Figure 2.100 shows that locating the DS unit after section D1 reduces the feeder loading on feeder section D1 only. The loadings of the downstream sections (D2, D3, D4, D5, D6 and D7) are not affected by the presence of the DS unit. When the same load of 26.1 MW is applied to the feeder, the ampacity limit of feeder section D4 is exceeded by 28.8 A (1.4 MW). This means that locating the DS unit after section D1 is not as effective as locating it after sections D4 or D7.

The study results from Figures 2.98 to 2.100 show that in all case studies the presence of the DS unit after sections D4 or D7 allows for higher load levels (26.1 MW vs. 23.6 MW) without overloading the critical feeder sections D1 and D4. When the DS unit is located between feeder sections D1 and D4, the maximum allowed load is significantly less than 26.1 MW due to ampacity limit of section D4.

To further evaluate the effect of the DS unit location, the detailed analysis of system losses for the two scenarios that result in the higher load levels (26.1 MW) has been performed. The system losses for the two DS locations (after section D4 and after section D7) and all ten time periods are presented in Table 2.19. Distribution of power losses throughout the day for the two DS unit location scenarios (after section D4 and after section D7) is given on Figure 2.101.

Table 2.19 System losses for all three DS unit location scenarios

Time Period	Hours	Power loss (kW)		Energy loss per day (kWh)	
		DS after D4	DS after D7	DS after D4	DS after D7
1	5	283	286	1414	1430
2	3	282	287	846	860
3	2	284	286	568	573
4	2	290	287	579	573
5	2	287	286	574	573
6	1	290	287	290	287
7	3	290	285	870	854
8	3	287	286	860	859
9	2	284	286	568	573
10	1	284	286	284	286
			Total	6854	6868

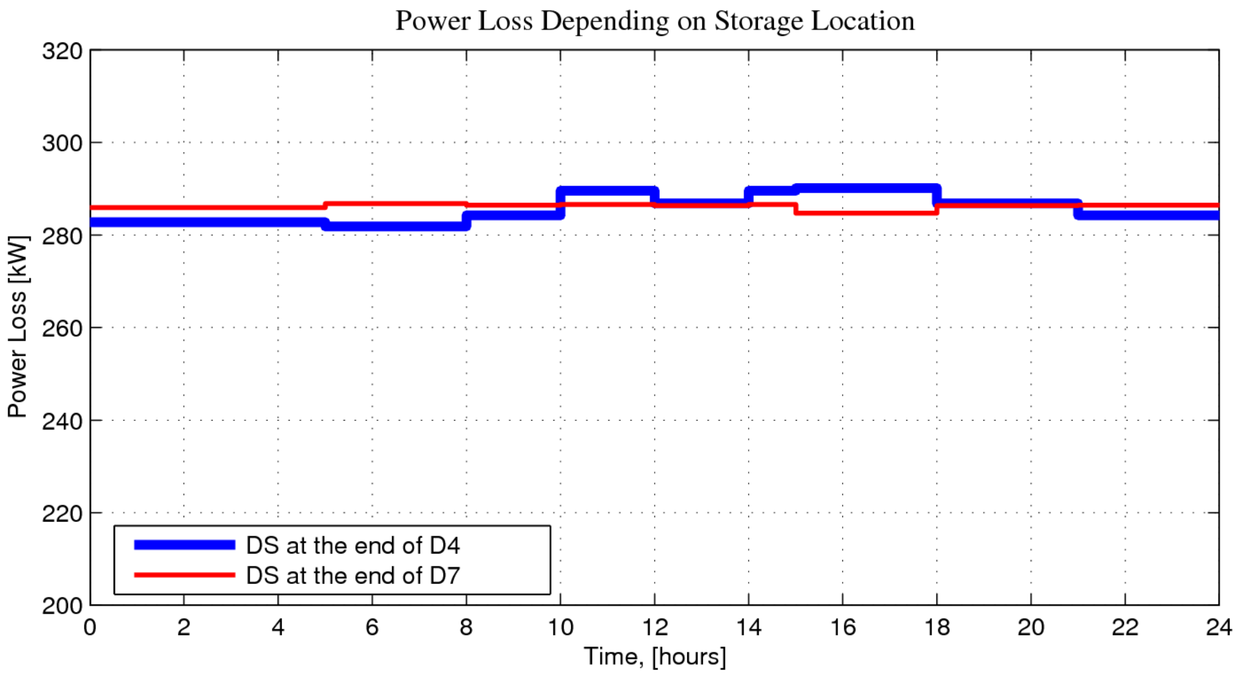


Figure 2.101 Distribution of system losses for all three DS unit location scenarios

Table 2.19 and Figure 2.101 show that the most efficient operation is when the DS unit is located just after the critical section (D4 in this case). The reason is that the charging current is higher than the discharging current (due to the DS unit efficiency). The difference between the lowest and the highest loss values is 0.2%. This indicates that from the point of view of the maximum allowable feeder loading, the DS unit should be located as close to the critical feeder section as possible. If this is not possible due to other constraints, placing the DS unit at any other location after the critical section is would be viable.

Permissible power export

A typical daily load diagram based on Table 2.18 is assumed. One DG unit and one DS unit are connected to the feeder. The criterion for the DS charge/discharge strategy is to enable the DG unit to export maximum constant power throughout the day. Figure 2.102 shows the loading of section D1, the required DS charging/discharging power, and the energy stored in the DS (so that the combined power of the load and the DS is constant).

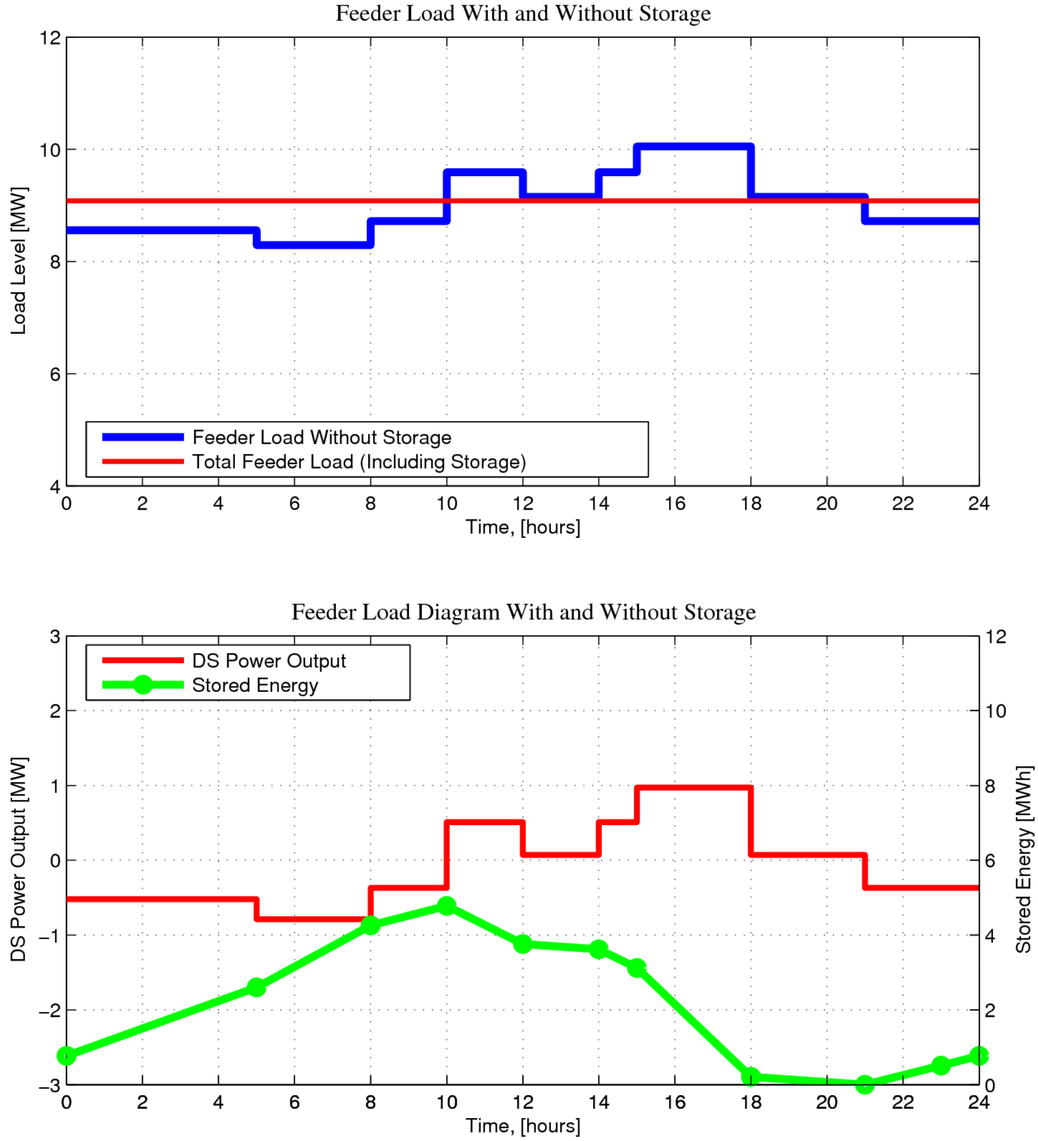


Figure 2.102 DS charge/discharge strategy and the effect of DS unit on feeder loading

Figure 2.102 shows that a constant power of 9.08 MW can be achieved for the mixture of the load and the DS unit. The parameters of the DS unit that satisfy the charge/discharge strategy of Figure 2.102 are:

- maximum charging power 0.79 MW,
- maximum discharging power 0.97 MW,
- storage capacity 4.78 MWh.

The total power export from the feeder is the difference between the exported power from the DG unit and the combined power of the load and the DS unit. From Figure 2.102, to keep the maximum power export at the utility at the permissible value of 5 MW, the exported power from the DG should be 14.1 MW. This is an approximate value, as it does not take into consideration that the DG reverses the power flow in feeder sections D1, D2, D3, and D4, thus losses in the system are different with and without the DG unit in service. The actual DG power limit is determined from the power flow studies and is slightly smaller, 14.0 MW. This is 0.8 MW more than it would be allowed if the DS does not exist in the system.

In power flow studies, three locations are considered for the DS unit:

- end of section D7, where the highest losses are expected (Figure 2.103),
- end of section D4, where the major industrial load with a DG is located and section D4 has the critical cable ampacity limit (Figure 2.104),
- end of section D1, since it has the critical cable ampacity limit (Figure 2.105).

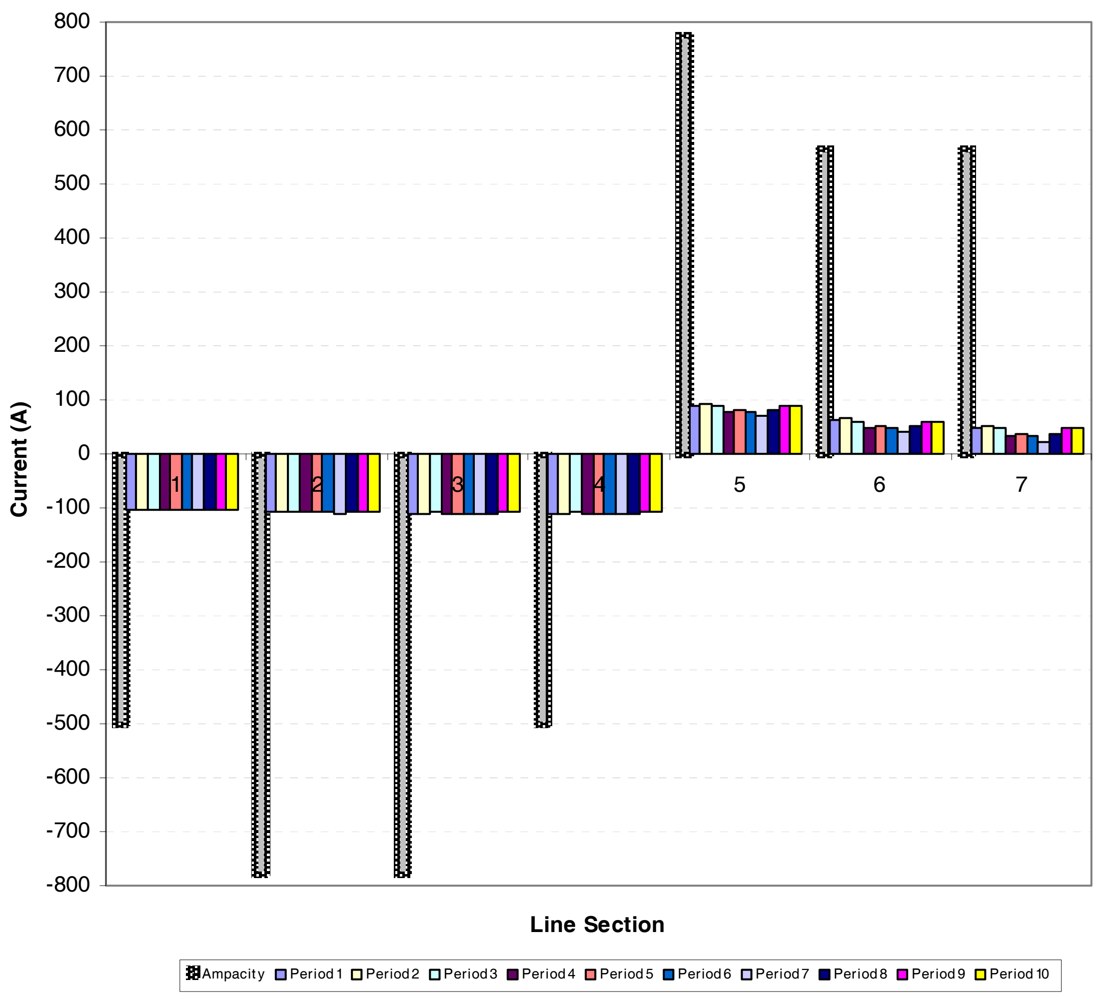


Figure 2.103 Feeder loading per section when 14.0 MW DG is installed after Section D4 and DS is connected of the feeder (after Section D7)

In the case of Figure 2.103, the DS unit is located at the end of the feeder (after section D7), the power generated by the DS unit, during the mid-day period, reduces the feeder loading of sections D5, D6, and D7. The same feeder sections have to carry additional current for charging the DS unit during the period of light load. The Feeder loadings are at all times much lighter than the cable ampacity limits.

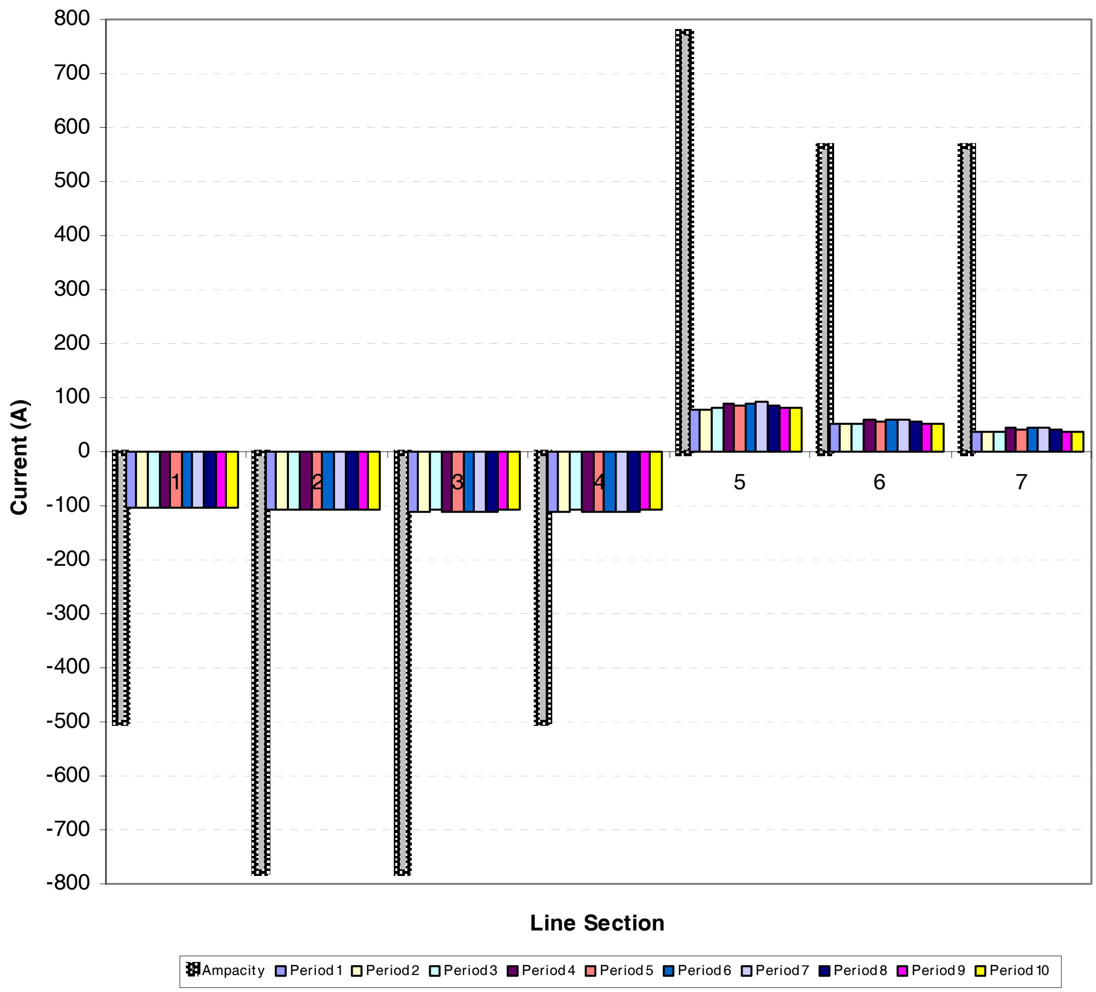


Figure 2.104 Feeder loading per section when 14.0 MW DG is installed after Section D4 and DS is connected of the feeder (after Section D4)

In the case of Figure 2.104, the DS unit is located after section D4 and during the period of light load the DS unit absorbs a portion of power generated by the DG unit. This reduces the loadings of the feeder sections D1, D2, D3, and D4. Loadings of feeder sections D5, D6, and D7 are not affected by the presence of the DS or the DG unit. Feeder loadings at all times are much less than the cable ampacity limits.

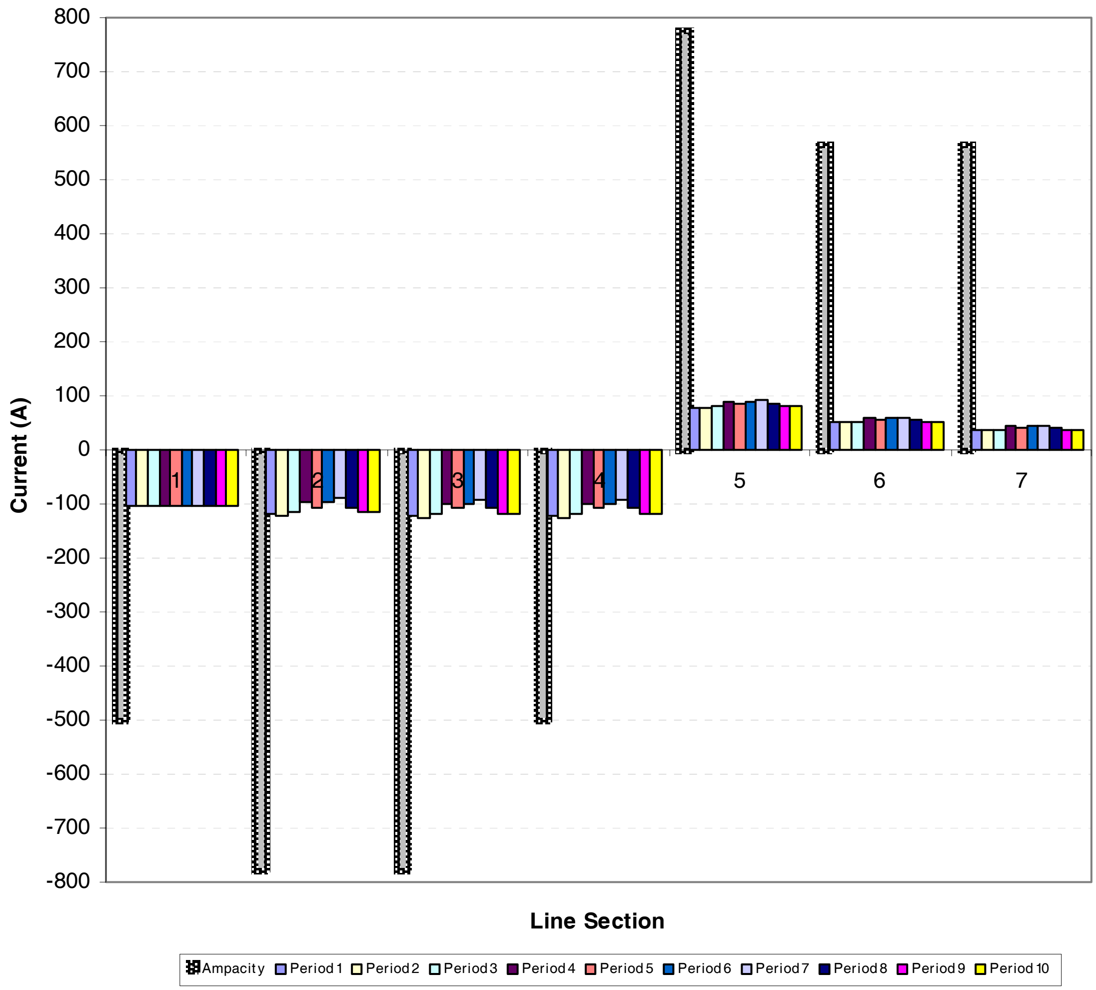


Figure 2.105 Feeder loading per section when 14.0 MW DG is installed after Section D4 and DS is connected of the feeder (after Section D1)

In the case of Figure 2.105, the DS unit is located immediately after feeder section D1 and during the period of the light load the DS unit absorbs a portion of the power generated by the DG unit. Similar to the previous two study cases, this reduces the feeder power export to the permissible limit of 5 MVA. The loadings of sections D5, D6, and D7 are not affected by the presence of the DS or the DG unit. The loadings of sections D2, D3, and D4 are reduced during the heavy-load period (discharging the DS unit) but increased during the light-load period (charging the DS unit). The feeder loadings at all times are much less than the cables ampacity limits.

The study results show that in all cases the presence of the DS unit allows for a larger DG unit to be installed at the industrial customer's site (14.0 MW vs. 13.2 MW) without violating the prescribed power export limit of 5 MW.

To evaluate the effect of the DS unit location, a detailed loss analysis for all the three scenarios has been performed. The system losses for all the three DS location scenarios and all ten time periods are presented in Table 2.20. Distribution of power losses throughout the day for the three DS unit locations is given on Figure 2.106.

Table 2.20 System losses for all three DS unit location scenarios

Time Period	Hours	Power loss (kW)			Energy loss per day (kWh)		
		DS after D1	DS after D4	DS after D7	DS after D1	DS after D4	DS after D7
1	5	4.5	4.2	4.8	22.4	20.9	23.8
2	3	4.4	3.9	4.9	13.3	11.8	14.6
3	2	4.5	4.3	4.8	9.1	8.6	9.6
4	2	5.1	5.2	4.7	10.3	10.5	9.4
5	2	4.8	4.8	4.7	9.5	9.6	9.4
6	1	5.1	5.2	4.7	5.1	5.2	4.7
7	3	5.7	5.8	4.7	17.2	17.4	14.2
8	3	4.8	4.8	4.7	14.3	14.4	14.1
9	2	4.5	4.3	4.8	9.1	8.6	9.6
10	1	4.5	4.3	4.8	4.5	4.3	4.8
				Total	114.8	111.5	114.0

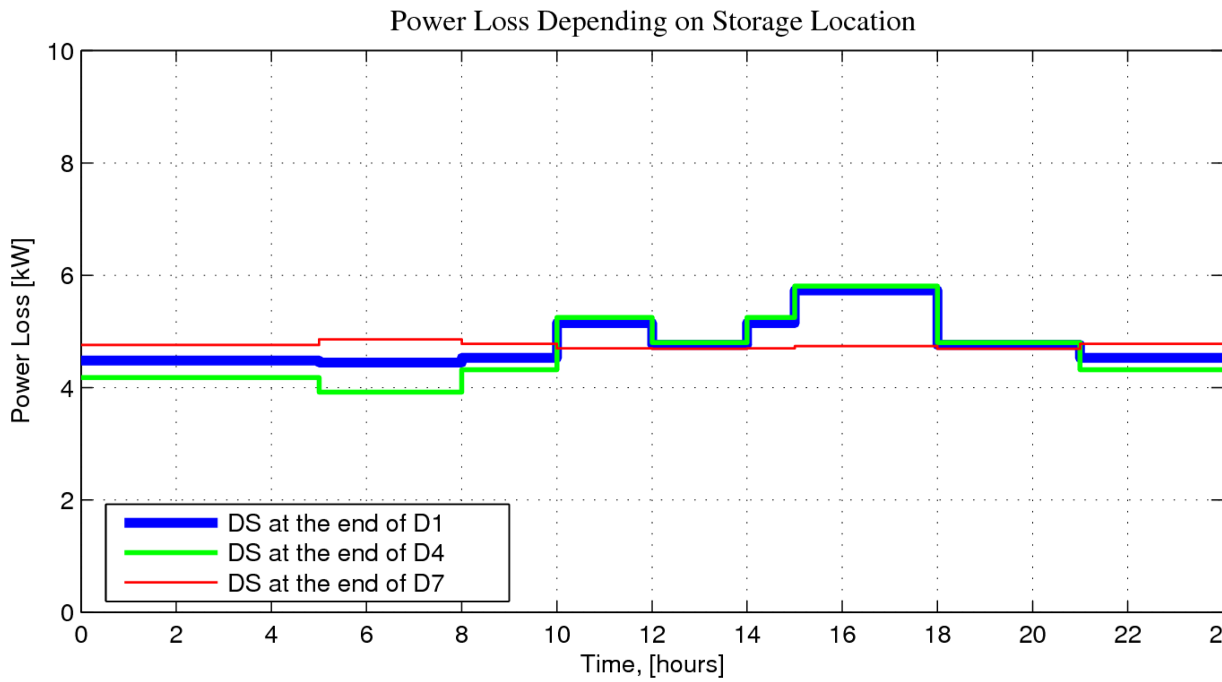


Figure 2.106 Distribution of system losses for all three DS unit location scenarios

Table 2.20 and Figure 2.106 show that the most efficient operation is when the DS unit is located after section D4. The reason is that the charging current is higher than the discharging current and locating the DS unit at the same location as the DG unit exists minimizes losses during charging. The difference between the lowest and the highest loss values is 2.2%. This indicates that the DG location is not a significant factor in the system energy loss.

Maximum power export

A typical daily load diagram based on Table 2.18 is assumed. One DG unit and one DS unit are connected to the feeder. The same DS unit charge/discharge strategy as shown on Figure 2.102 is adopted to keep the combined power of the load and the DS constant. It is assumed that the DG export power is limited so that the feeder current is less than or equal to the feeder ampacity limit. To keep the critical feeder sections (D1 and D4 in this case) from overloading, the DG power limit is determined from the power flow studies and is 32.8 MW. This is 0.7 MW more than it would be allowed if the DS does not exist in the system.

In power flow studies, three locations are considered for the DS unit:

- end of section D7, where the highest losses are expected (Figure 2.107),
- end of section D4, where the major industrial load with a DG is located and section D4 has the critical cable ampacity limit (Figure 2.108),
- end of section D1, since it has the critical cable ampacity limit (Figure 2.109).

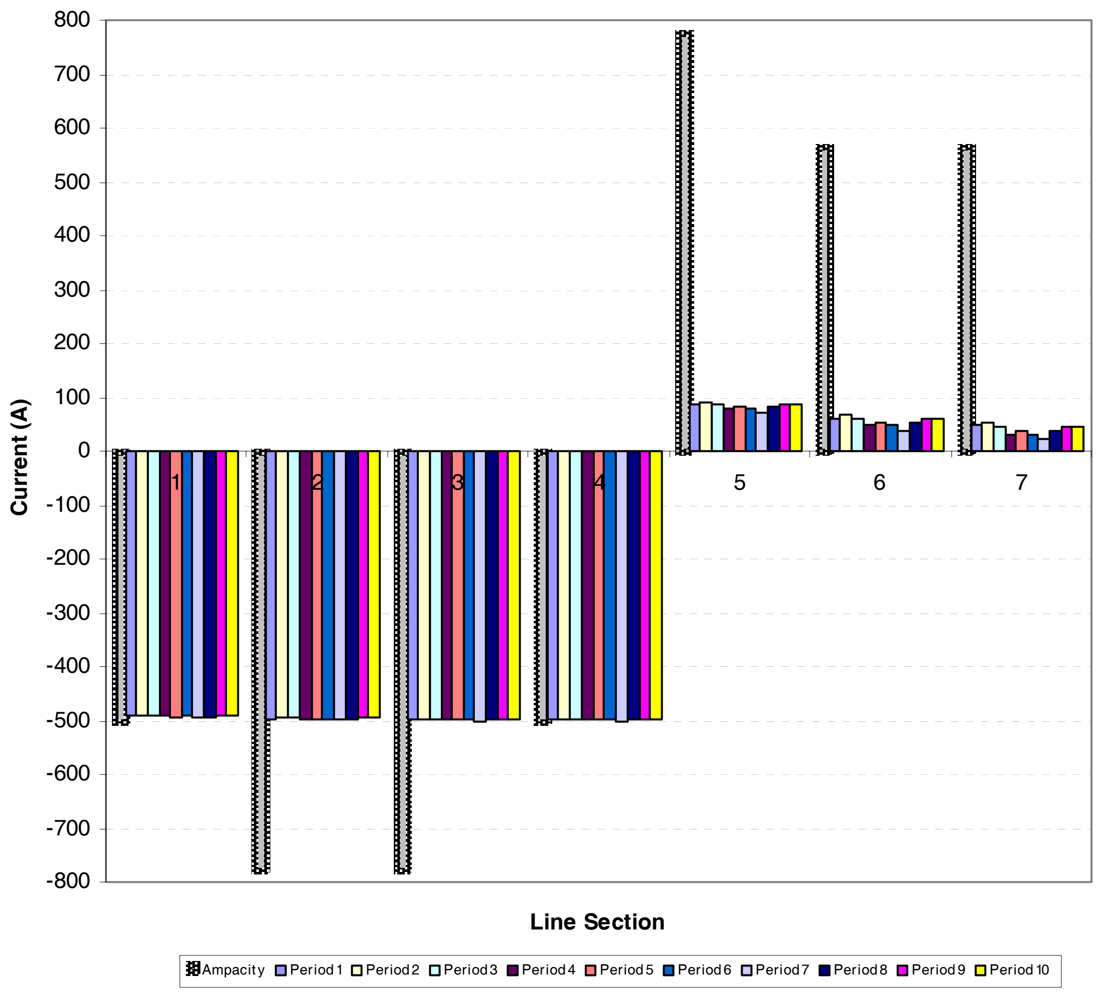


Figure 2.107 Feeder loading per section when 32.8 MW DG is installed after Section D4 and DS is connected of the feeder (after Section D7)

In the case of Figure 2.107, the DS unit is located at the end of the feeder (after section D7), the power generated by the DS unit during the mid-day period reduces the feeder loading on feeder sections D5, D6, and D7. The same feeder sections have to carry additional currents for charging the DS unit during the light load periods.

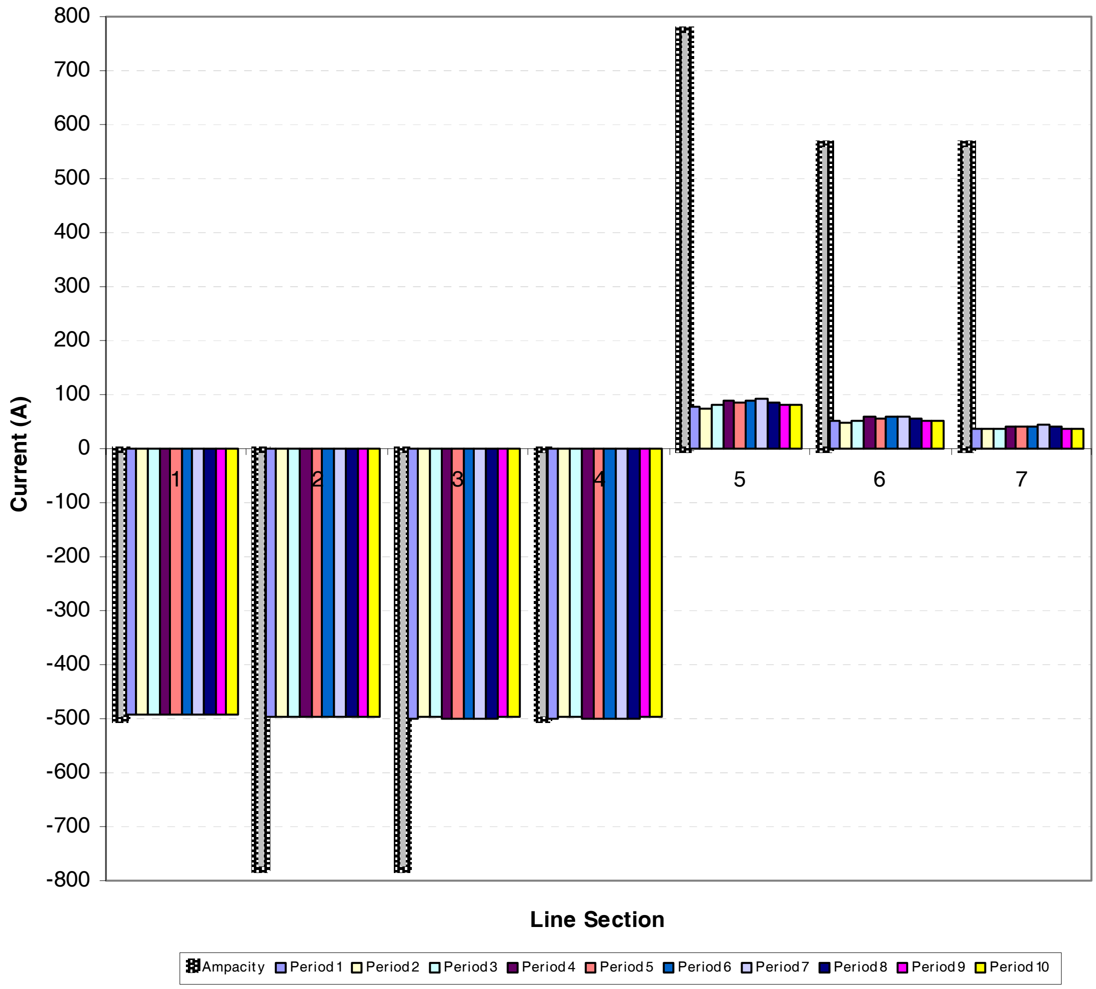


Figure 2.108 Feeder loading per section when 32.8 MW DG is installed after Section D4 and DS is connected of the feeder (after Section D4)

In the case of Figure 2.108, the DS unit is located after section D4 and during the period of light load the DS unit absorbs a portion of the power generated by the DG unit. This reduces the loadings of feeder sections D1, D2, D3, and D4. The loadings of feeder sections D5, D6, and D7 are not affected by the presence of the DS or the DG unit.

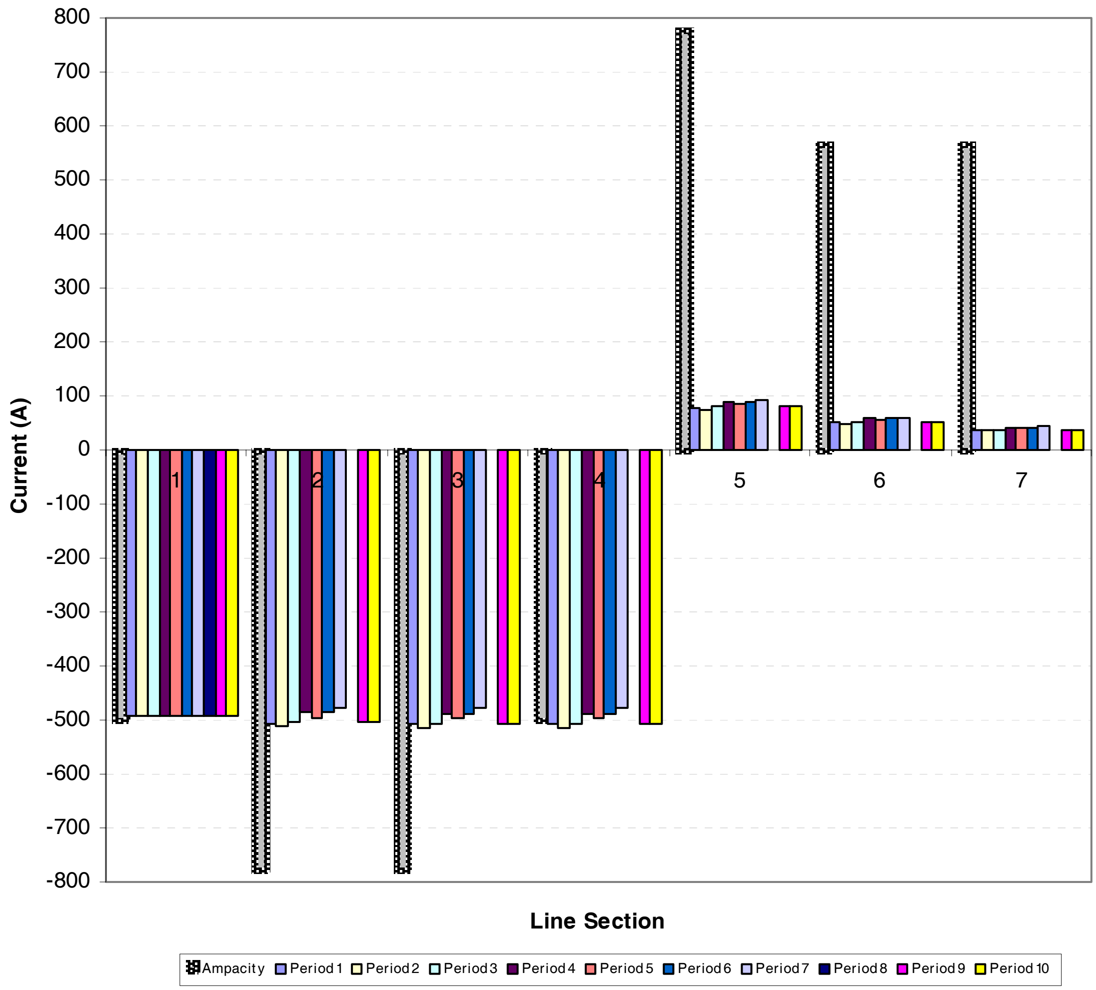


Figure 2.109 Feeder loading per section when 32.8 MW DG is installed after Section D4 and DS is connected of the feeder (after Section D1)

In the case of Figure 2.109, the DS unit is located immediately after section D1 and during light load periods the DS unit absorbs a portion of the power generated by the DG unit. This reduces section D1 current to the cable ampacity limit of 500 A (Table 2.17). Loading of the feeder section D4 exceeds the cable ampacity limit during the light-load periods, so this DS location is not acceptable.

To further evaluate the effect of the DS unit location, the detailed analysis of system losses for two scenarios that result in the higher DG power export (32.8 MW) has been performed. The system losses for the two scenarios corresponding to the DS unit locations (after section D4 and after section D7) and all ten time periods are presented in Table 2.21. Distribution of power losses throughout the day for the two DS unit location scenarios (after section D4 and after section D7) is given on Figure 2.110.

Table 2.21 System losses for all three DS unit location scenarios

Time Period	Hours	Power loss (kW)		Energy loss per day (kWh)	
		DS after D4	DS after D7	DS after D4	DS after D7
1	5	290	291	1500	1452
2	3	289	291	913	868
3	2	290	290	594	579
4	2	292	291	566	584
5	2	292	292	580	584
6	1	292	291	283	292
7	3	294	292	827	882
8	3	292	292	870	876
9	2	290	290	594	579
10	1	290	290	297	290
			Total	7024	6986

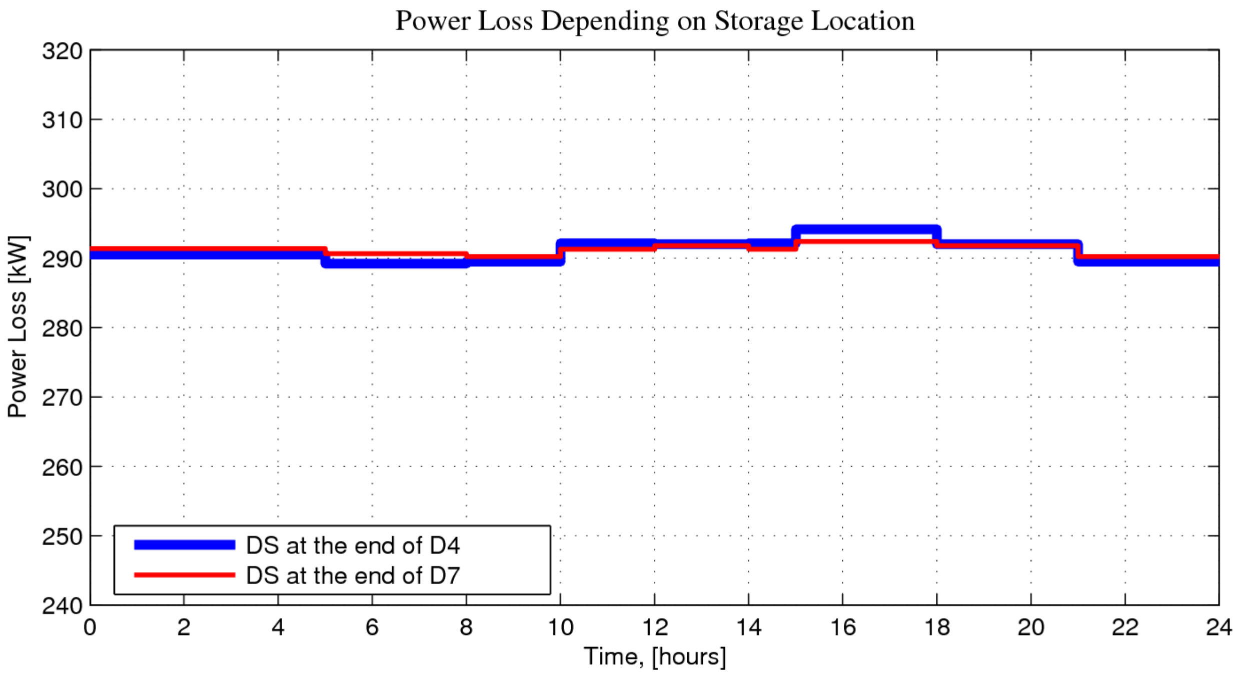


Figure 2.110 Distribution of system losses for all three DS unit location scenarios

Table 2.21 and Figure 2.110 show that the most efficient operation is when the DS unit is located after section D7, but the differences between the two scenarios are insignificant.

2.4.3 Battery Option 3 – 1 MW NaS Battery

The third set of studies is performed under the assumption that one large 1 MW NaS battery-based on the main technical data from Section 1.2.2 is used. Charging power (on the AC side) is limited to 1.2 MW, while discharging power limit (on the AC side) is 1.2 MW for up to 3 hours and 1 MW perpetually. The available stored energy is up to 7.2 MWh (100% DOD). An AC efficiency of 80% is assumed for this case.

Conventional operation

Based on the feeder cable ampacity (Table 2.17), the maximum permissible power in section D1 is 23.9 MW. In the case study that analyzes the maximum permissible feeder loading without the storage (Figure 2.94), the daily peak is equal to 23.6 MW. By placing the DS unit on the feeder, the maximum load can be increased. Figure 2.111 shows the input of the storage charge/discharge control strategy based on the procedures of Section 1.2.2.

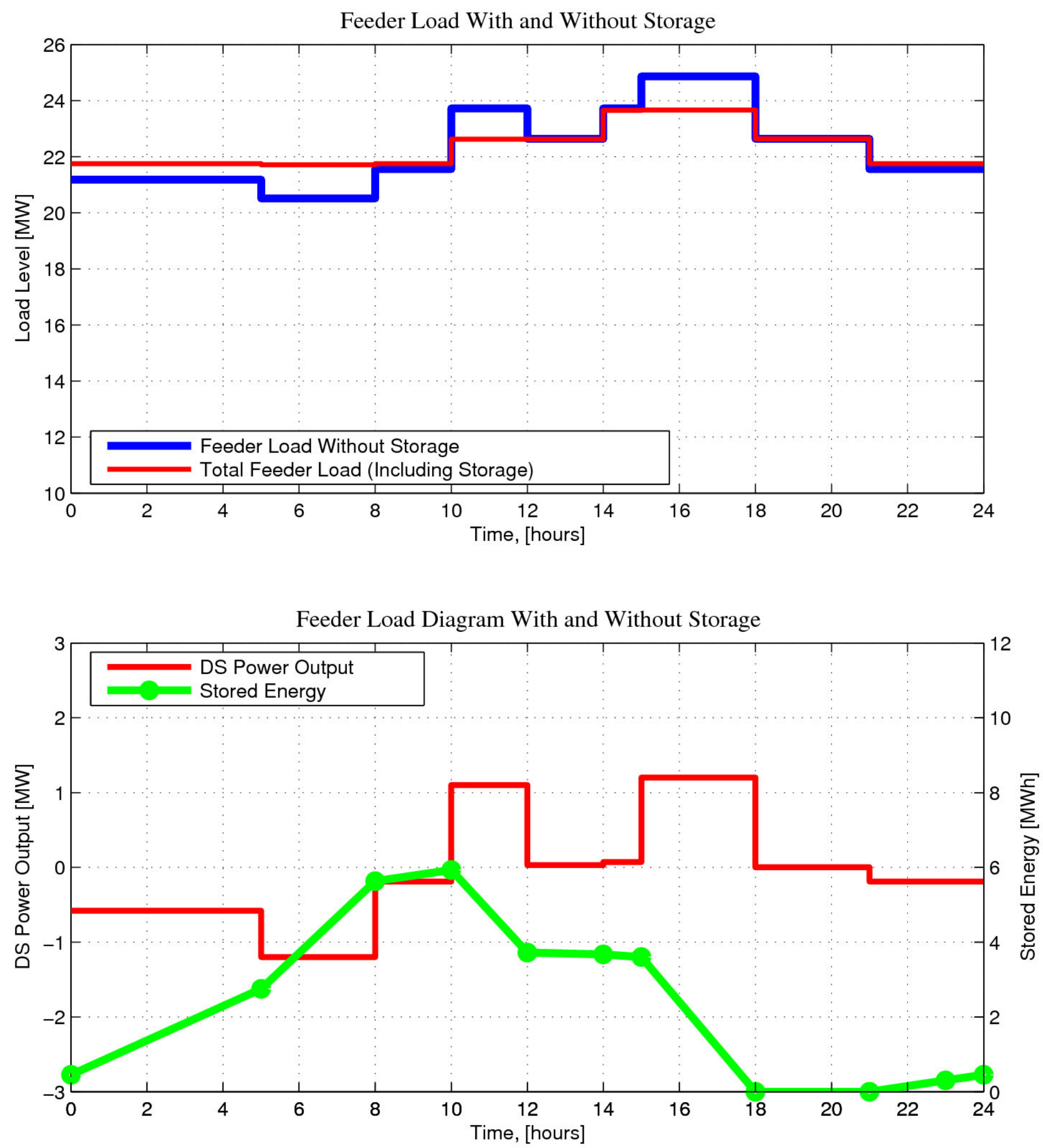


Figure 2.111 DS charge/discharge strategy and the effect of DS unit on feeder loading

On Figure 2.111, the permissible daily peak load in the presence of the 1 MW NaS battery-based DS unit can be increased to 24.8 MW, compared to 23.6 MW for the case without the storage. The total energy produced by the DS unit during discharging period is 80% of the consumed energy during the charging period. The stored energy peaks at 10:00 and is below 6 MWh (less than 90% DOD).

Based on the analysis from Section 2.4.2, the DS unit location associated with the minimal losses is considered (end of section D4). The loadings and the cable ampacities for all sections are shown on Figure 2.112.

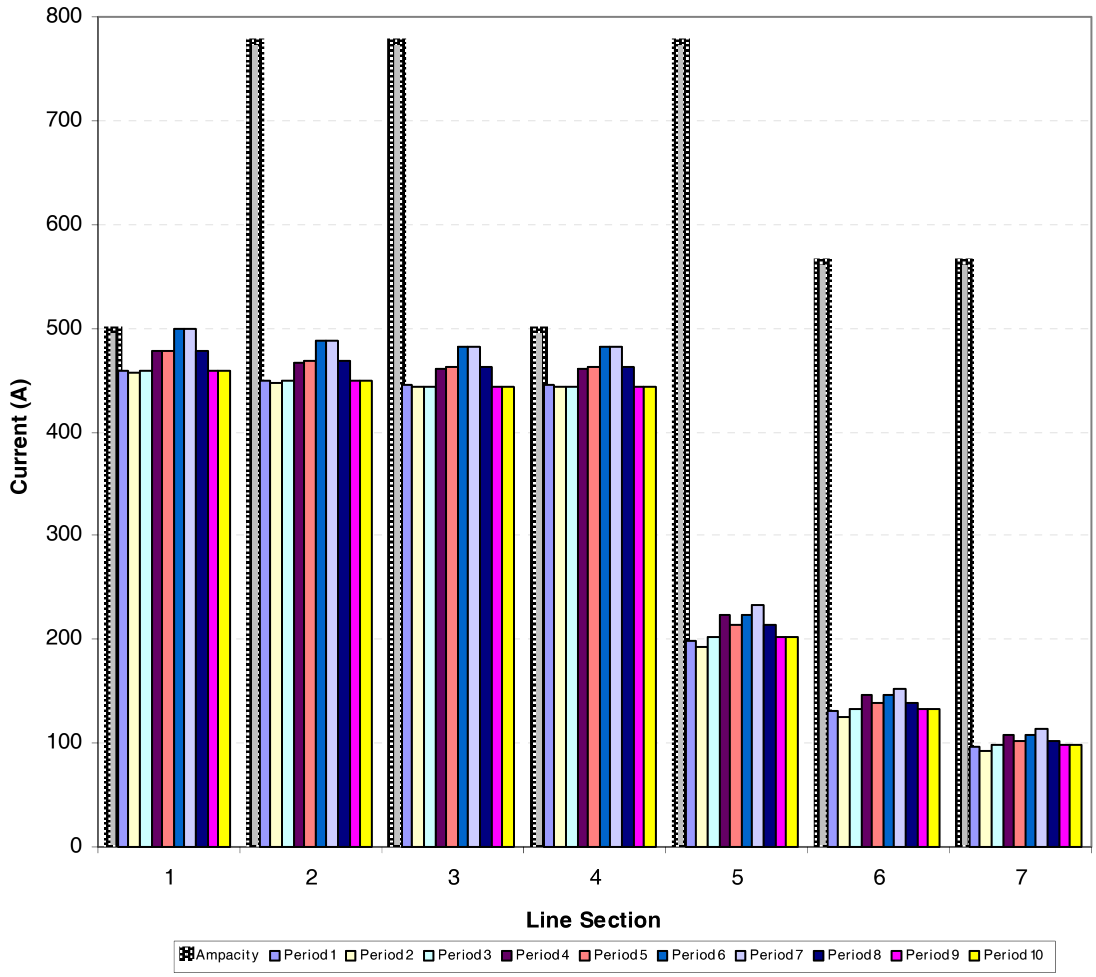


Figure 2.112 Feeder loading per section for cable ampacity loading with one DS unit (1 MW NaS battery with 100% DOD), located after section D4 and no DG in the system

The study results of Figure 2.112 confirm that with the presence of the 1 MW NaS battery-based DS unit, the cable ampacity limits are not violated even if the load peak is as high as 24.8 MW.

Permissible power export

A typical daily load diagram based on Table 2.17 is assumed. One DG unit and one 1 MW NaS battery-based DS unit are connected to the feeder. Without the DG unit, Figure 2.113 shows the loading of section D1, the DS charging/discharging power, and the energy stored in the DS (so that the combined power of the load and the DS is as level as possible). For exporting power from the feeder, the critical period is during the night when the combined load and the DS unit power is 9.1 MW. The stored energy peaks at 10:00 and is below 5 MWh (less than 90% DOD). On Figure 2.113, the DS output power during charging period is shown as a negative value.

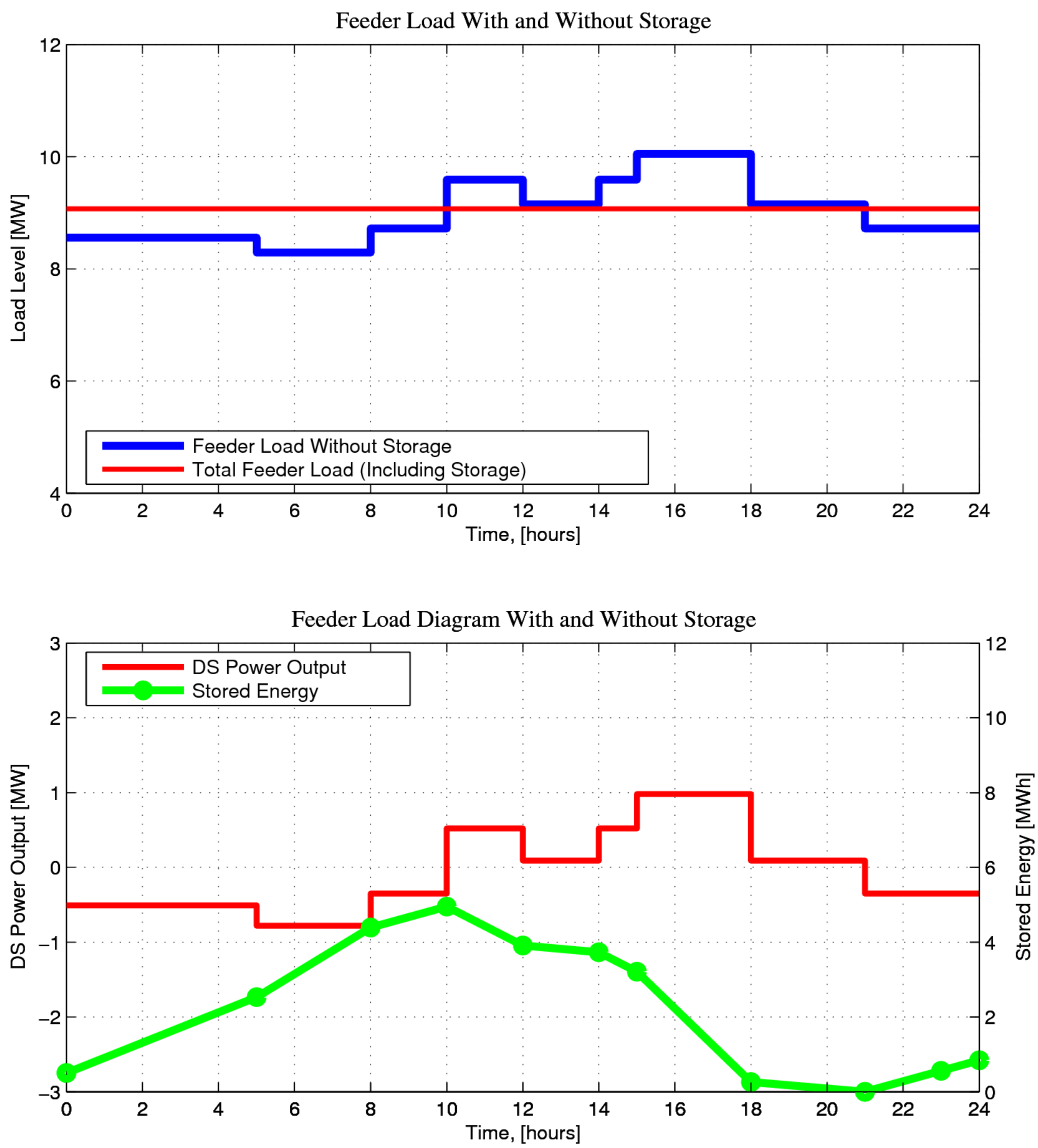


Figure 2.113 DS charge/discharge strategy and the effect of DS unit on feeder loading

The total power export from the feeder is the difference between the exported power from the DG unit and the combined power of the load and the DS during the period of minimal load (9.1 MW). To keep the maximum power export at the prescribed value of 5 MW, the exported power from the DG should be 14.1 MW. This is an approximate value, as it does not take into consideration that due to the reversed power flow in the first three sections, losses in the system are changed. The realistic DG power limit is determined from the power flow studies and is slightly smaller, 14.0 MW. This is 0.75 MW more than it would be allowed if the DS unit is not included in the system. The study results, with the DS unit connected to the feeder after section D4, are shown on Figure 2.114.

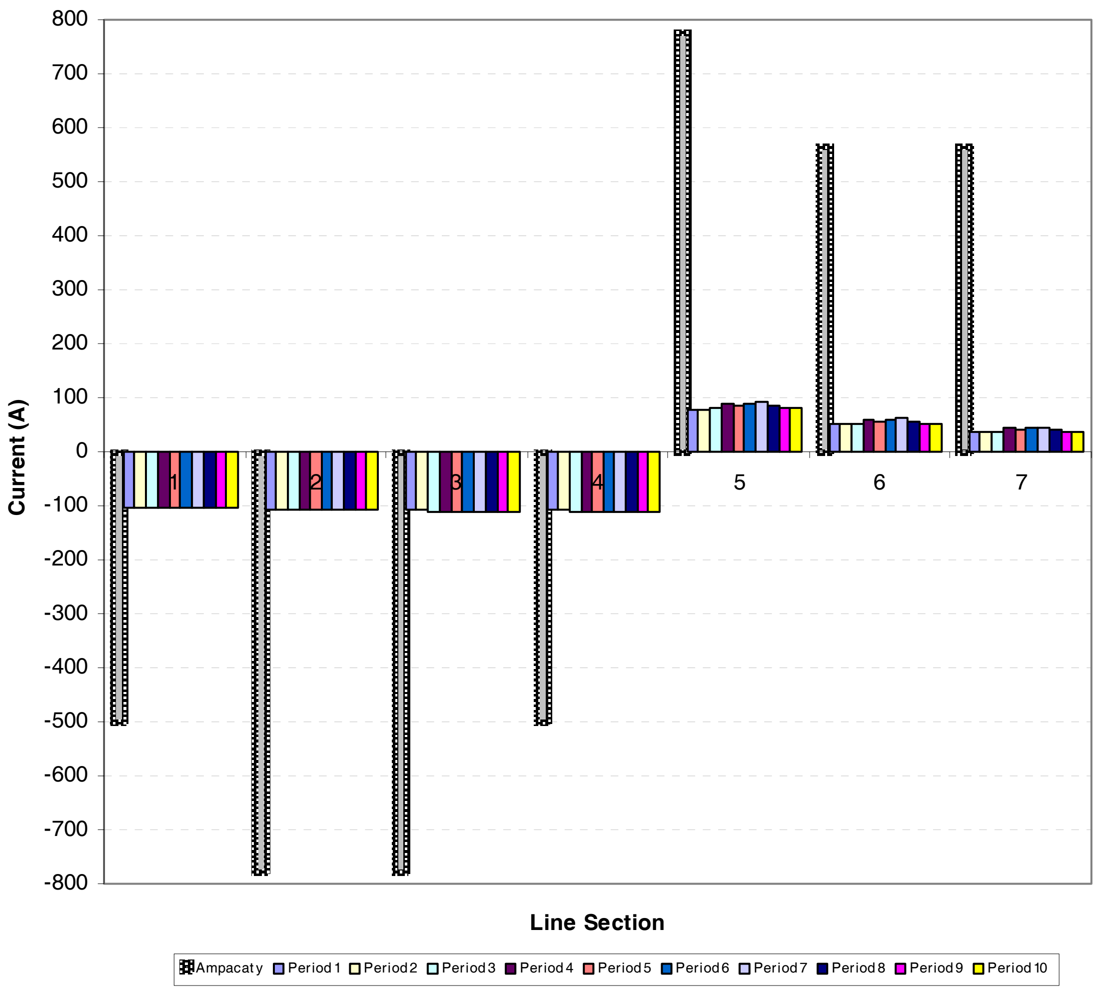


Figure 2.114 Feeder loading per section when 11 MW DG is installed after Section D4 and DS is connected of the feeder (after Section D4)

The study results show that the presence of the DS unit allows for a larger DG unit to be installed at the industrial customer's site (14.0 MW vs. 13.25 MW), without violating the prescribed power export limit of 5 MW.

Maximum power export

A typical daily load diagram based on Table 2.18 is assumed. One DG unit and one 1 MW NaS battery-based DS unit are connected to the feeder. The same charge/discharge strategy, shown on Figure 2.113, is assumed for the DS unit. It is assumed that the DG export power is limited so that the feeder current is less than or equal to the feeder ampacity limit. The study results for the case when the DS unit is in the same location as the DG unit (at the end of section D4) are shown on Figure 2.115.

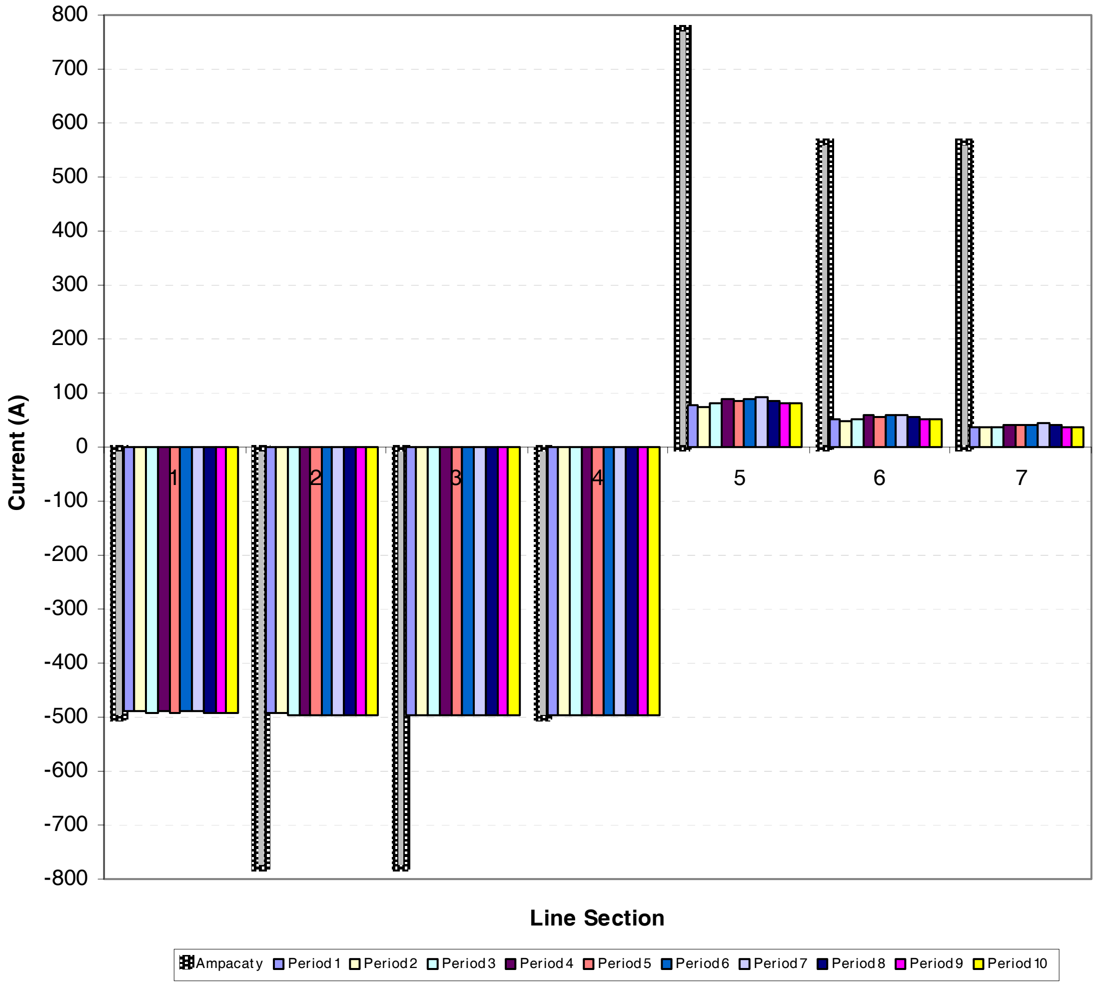


Figure 2.115 Feeder loading per section when 30.8 MW DG is installed after Section D4 and DS is connected of the feeder (after Section D4)

In the case of Figure 2.115, the DG power limit that does not overload the critical feeder section (D4 in this case) is 32.7 MW. This is 0.6 MW more than it would be allowed if the DS does not exist in the system.

2.4.4 Summary

The study results show the effect of integration of distributed storage (DS) on typical industrial feeder loading. It is demonstrated that due to relatively flat industrial load profile, the ability of the DS to reduce load fluctuation throughout the day is not as beneficial as in the case of previously analyzed feeder types, i.e.

- When a DS unit with the AC efficiency of 70% and without power and storage capacity constraints is used, the maximum allowed load peak power on the feeder is increased from the 23.6 MW to 26.1 MW. The DS parameters required for this case are: (i) the maximum charging power of 2.04 MW, (ii) the maximum discharging power of 2.5 MW, and (iii) the storage capacity of 12.83 MWh.
- When a DS unit of typical 1 MW NaS battery with 7.2 MWh storage capacity is used, the maximum allowed load peak power on the feeder is increased from 23.6 MW to 24.8 MW.

The effect of the NaS battery on the maximum allowed load peak power is not affected by the change of DOD beyond 90%, because the energy stored in the NaS batteries never exceeded 6 MWh (83.33% DOD).

When the feeder includes DG units, the DS unit allows for a slightly higher level of DG power export, i.e.

- When a DS unit with the AC efficiency of 70% and without power and storage capacity constraints is used, the maximum allowed DG power export is increased by 0.7 MW to 0.75 MW, depending on the permissible power export from the feeder. The DS unit parameters required for this case are: (i) the maximum charging power of 0.79 MW, (ii) the maximum discharging power of 0.97 MW, and (iii) the storage capacity of 4.78 MWh.
- When the DS unit is a typical 1 MW NaS battery with 7.2 MWh storage capacity, the maximum allowed DG power export is increased by 0.6 MW to 0.75 MW, depending on the permissible power export from the feeder.

The study results show that the DS unit has to be located with respect to the feeder sections with lower ampacity limits. For feeder type D, any location between the main TS and the end of section D4 is not acceptable. From the end of section D4 to the end of the feeder, the location change may affect the overall system losses by 2.2%. However, in all cases this effect is less than 1%. The most efficient location is a location as close as possible to the source that charges the DS unit.

3. Conclusions

The studies conclude that:

- Presence of the DS on the feeder can reduce load fluctuation throughout the day, and depending on the DS characteristics/ratings, the maximum feeder loading can be increased.
- The allowed net export power from the embedded DG unit is typically increased proportional to the size of the DS unit.
- Due to the relatively flat industrial load profile, the ability of the DS to reduce load fluctuations throughout the day is not as beneficial in the case of a purely industrial load, e.g. in the case of feeders with larger residential and/or commercial load content.
- The DS unit location with respect to the feeder sections with lower ampacity limits is significant. For feeder types that include several critical sections with lower cable ampacities, the DS unit should not be located between the main TS and any of the critical feeder sections.
- The location of the DS unit can change the overall system losses. The most efficient location is as close as possible to the source that charges the DS unit. The loss does not change significantly with the change of the DS location.
- In the case of a NaS battery, it is often not justified to run the battery with 100% DOD as similar performance is achieved with 90% DOD and the battery life is typically doubled.

Appendix A

Application of Distributed Storage in a Rural Distribution System

A.1 Feeder Type E – Rural Distribution System
A.2 Battery Option 1 – No energy storage is available
A.3 Battery Option 2 – Generic case with no power or energy limits
A.4 Battery Option 3 – 1 MW NaS Battery with 100% DOD
A.5 Battery Option 4 – 1 MW NaS Battery with 90% DOD
A.6 Summary

A.1 Feeder Type E – Rural Distribution System

The 27.6 kV feeder analyzed in this study is a typical rural feeder with only residential loads. The one line diagram of the feeder is shown as in Figure A.1. A regulating station is located around 12 km along the main trunk. The regulating station setting is adjusted to boost the voltage by 2.5%. One large DG unit is installed at Coordination Path 3.

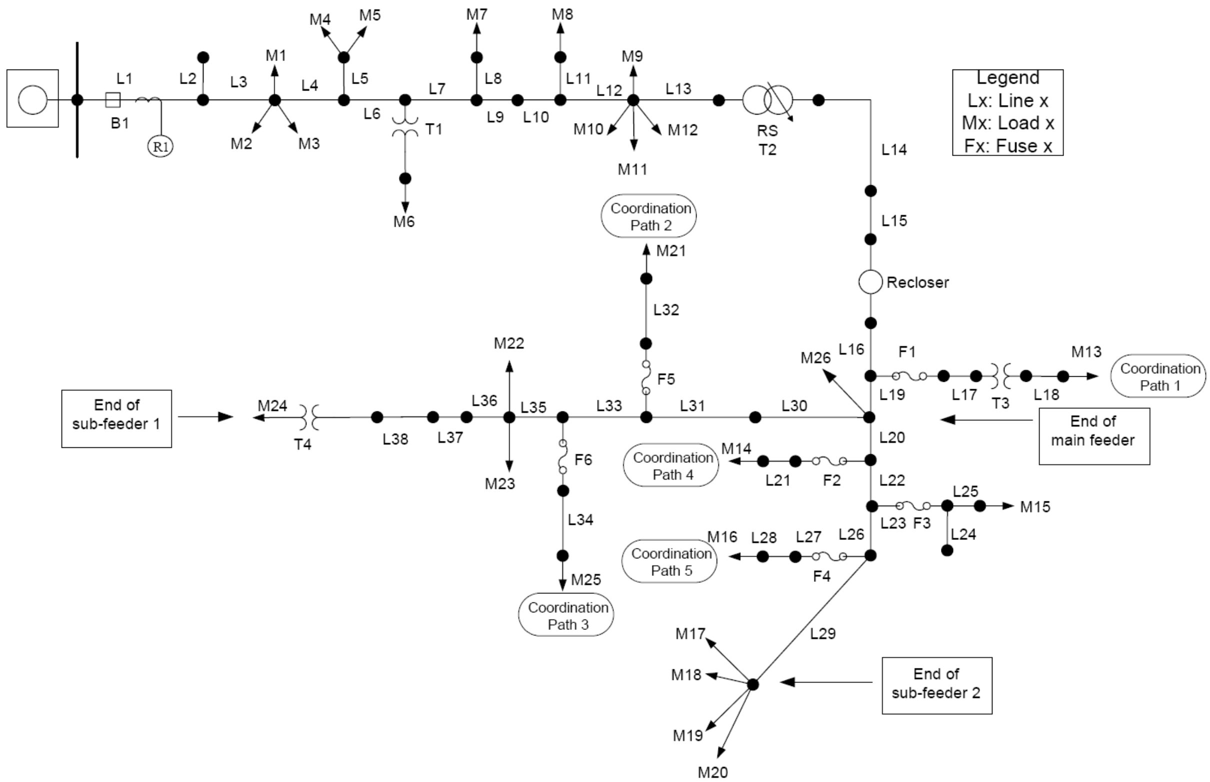


Figure A.1 One-line diagram of Feeder Type E - Rural feeder

To identify the cable ampacity limits and to specify potential DS unit locations, the feeder of Figure A.1 is divided into multiple sections, as shown in Figure A.2. The feeder is sectionized so that there is at least one feeder section between any two major loads or a group of loads. Seven sections are used for feeder type E. The maximum feeder loading for each section is based on the cable ampacity as shown in Table A.1. The significant part of the feeder section E5, closest to the end of main feeder, utilizes 30 ASR 427 conductor with the maximum current of 100 A. The minimal currents for all other sections are higher (452 A). Therefore section E5 is the critical section for all cable ampacity studies.

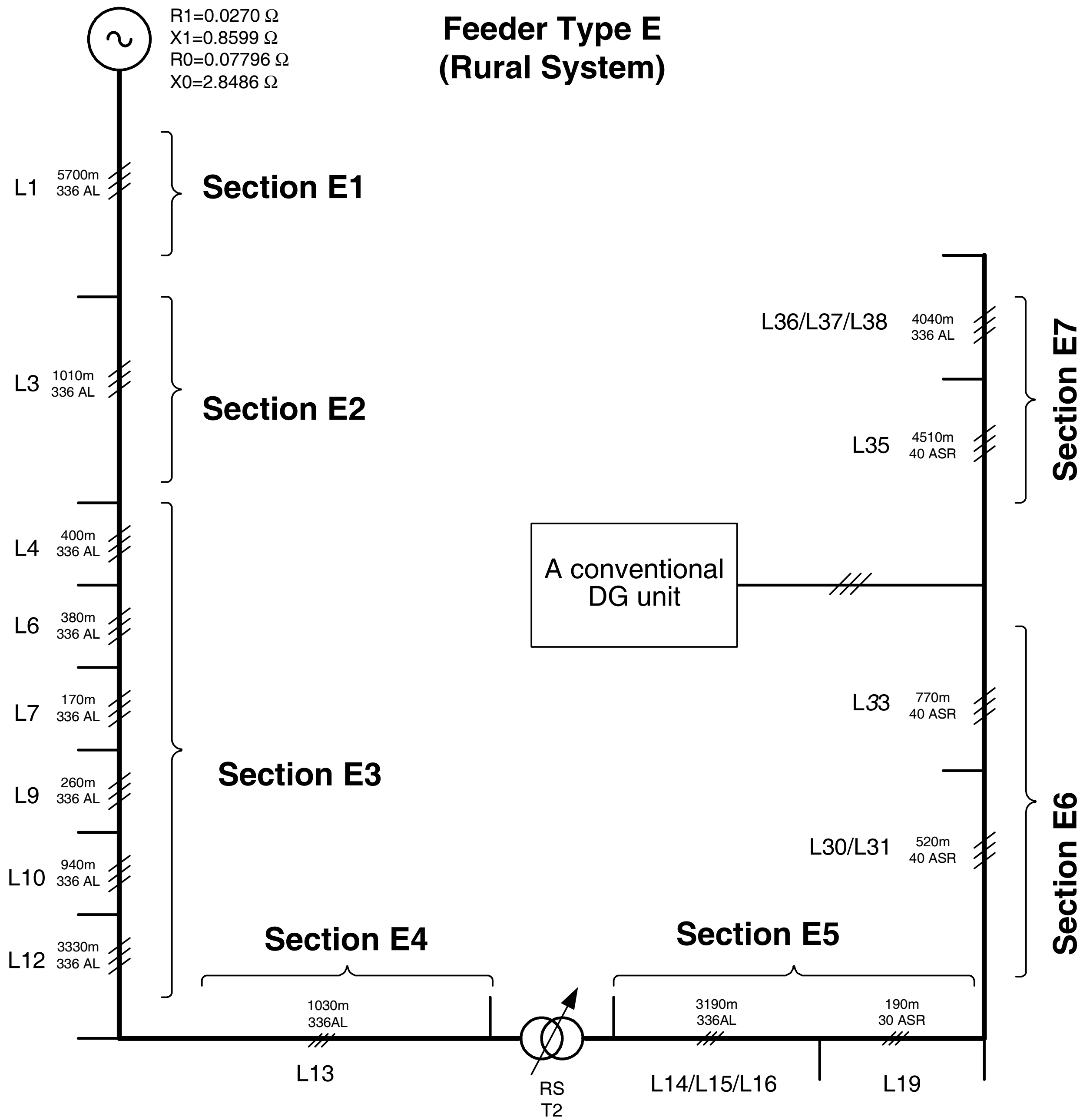


Figure A.2 Sections of Feeder Type E - Rural feeder

Since section E5 is the critical section for all cable ampacity studies. Three potential locations for placing a DS unit are analyzed:

- end of section E7 (at the feeder end),
- end of section E6, where the DG is located,
- end of section E5, since section E5 has the lowest cable ampacity limit (100 A).

Typical daily peak load for this feeder is 4.60 MW and the normal daily load diagram based on the typical residential load data is given in Table A.2.

Table A.1 Feeder cable ampacity per section

Section number	Cable Type	Cable Ampacity (A)	Maximum Power (MW)
E1	336 AL 427	665	31.8
E2	336 AL 427	665	31.8
E3	336 AL 427	665	31.8
E4	336 AL 427	665	31.8
E5	30 ASR 427	100	4.8
E6	40 ASR 427	452	21.6
E7	336 AL 427	665	31.8

Table A.2 Normal daily load diagram for Feeder Type E - Rural feeder

Time Period (hours)			Feeder Load (MW)
Period #	From	To	
1	0	5	2.89
2	5	8	3.18
3	8	10	3.80
4	10	12	4.37
5	12	14	4.43
6	14	15	4.20
7	15	18	4.08
8	18	21	4.60
9	21	23	4.37
10	23	24	3.52

A.2 Battery Option 1 – No energy storage is available

The first set of studies is performed under the assumption that there is no storage unit in the system. The results from this case study are used as the benchmark to evaluate the study results when the system includes DS.

Conventional operation

a) ***A normal daily loading*** **-** The total feeder loading is equal to the normal daily loading from Table A.2. The residential load is distributed among three-phase and single-phase transformers. No DG units are connected to the feeder.

The study results provide the feeder loading (in Amperes) for each of the seven sections of Feeder Type E (as defined in Figure A.2), and for all 10 time periods (as specified in Table A.2). The simulation results are presented in Figure A.3. Since loads of the three phases are not balanced, Figure A.3 presents the load current of phase C (Max. current of the three phases).

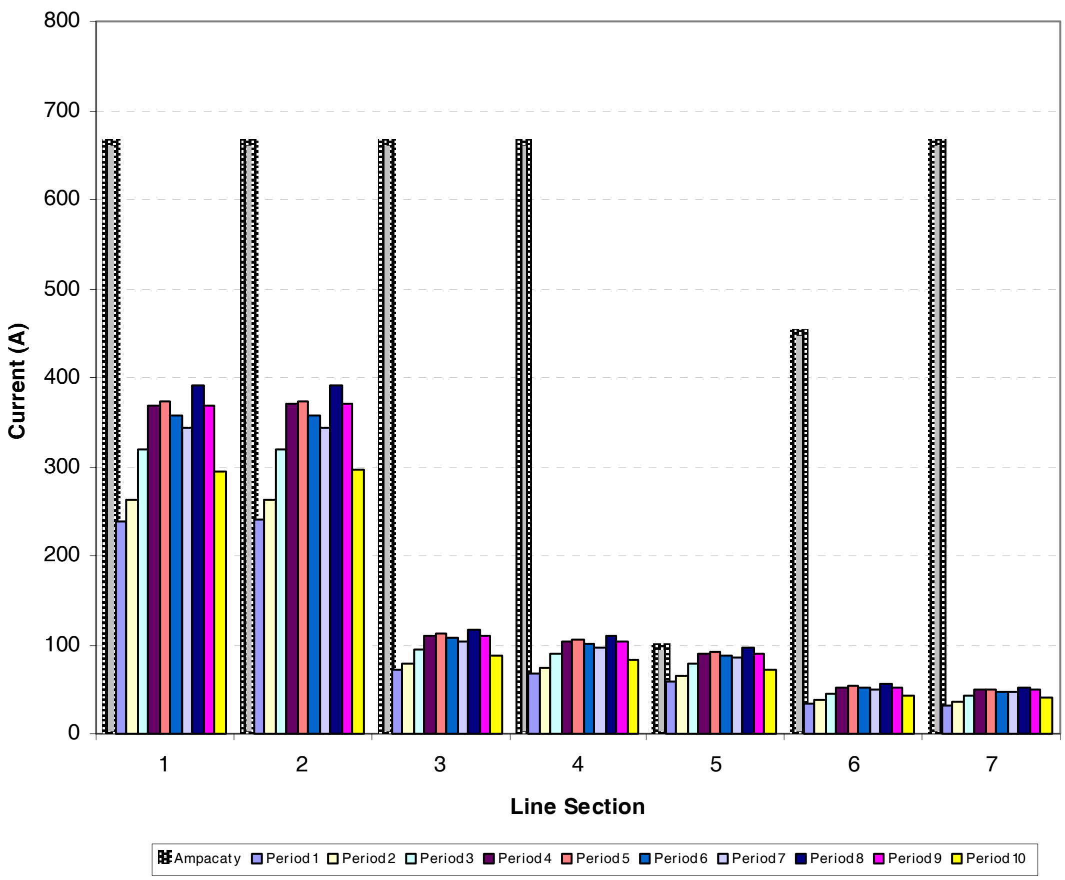


Figure A.3 Feeder loading per section for normal loading (no DS or DG in the system)

Figure A.3 compares the current associated with the normal daily loading with the cable ampacity in each feeder section. Cable section E5 is loaded about 96% of the ampacity limit.

b) ***The maximum allowable feeder loading*** – The load for this case study is obtained by scaling up all individual loads of case (a) until one of the cable ampacity limits is reached. The study results for this test case are presented on Figure A.4.

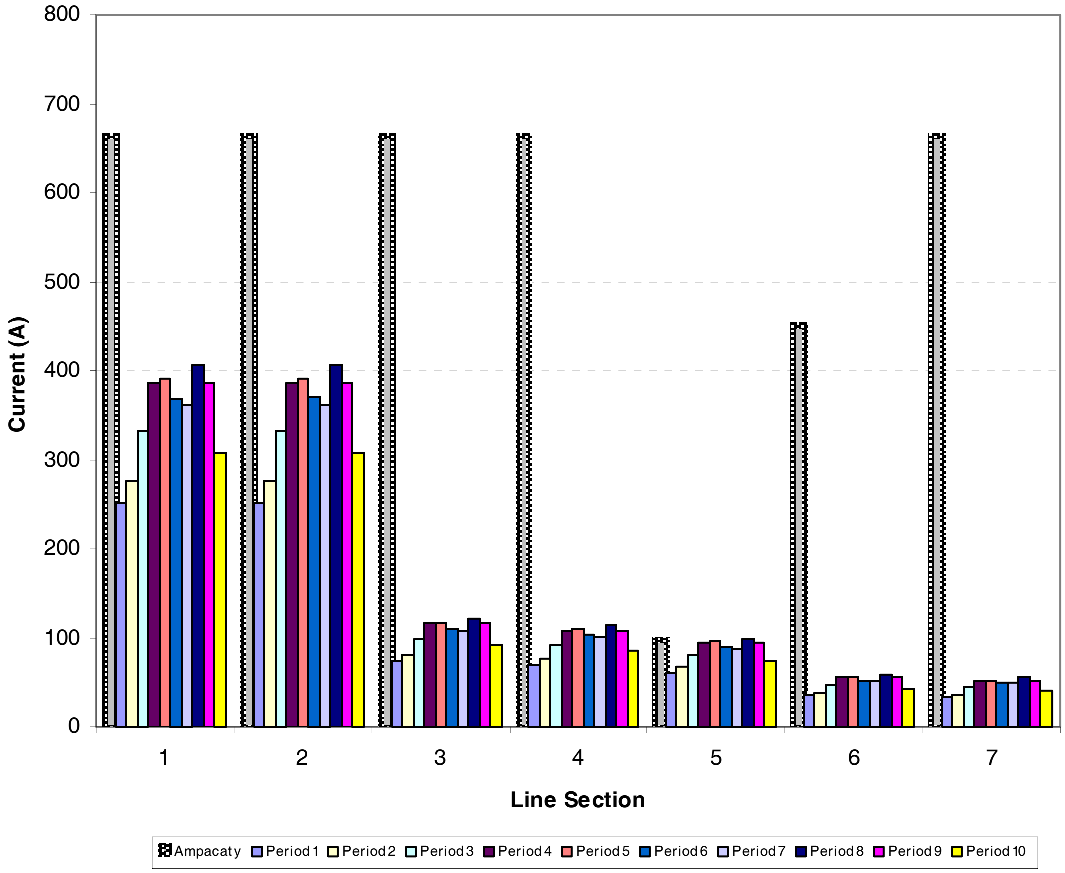


Figure A.4 Feeder loading per section for cable ampacity loading and no DS or DG in the system

Figure A.4 shows that the maximum cable loading in phase C, in this case, occurs on feeder section E5, during the peak power period (period #8, between 18:00 and 21:00 hours). The total load peak power that brings the cable ampacity of the feeder section E5 to a limit is 4.8 MW, as specified in Table A.1.

Because of the unbalanced nature of the feeder loading, the voltage drops are different for each phase. Figure A.5 presents the three-phase voltage drops and Figure A.6 presents the load current profile along the feeder. The maximum voltage drop for this case is 6.2%, in phase C. It occurs within Section 4, before regulating station, during time period #8, between 18:00 and 21:00. This scenario corresponds to the highest possible voltage drop for this feeder. Since 6.2% is higher than the maximum allowed 6% voltage drop, we conclude that voltage drop may be a limiting factor in the case studies for this feeder, when the TS bus voltage is 1 p.u.

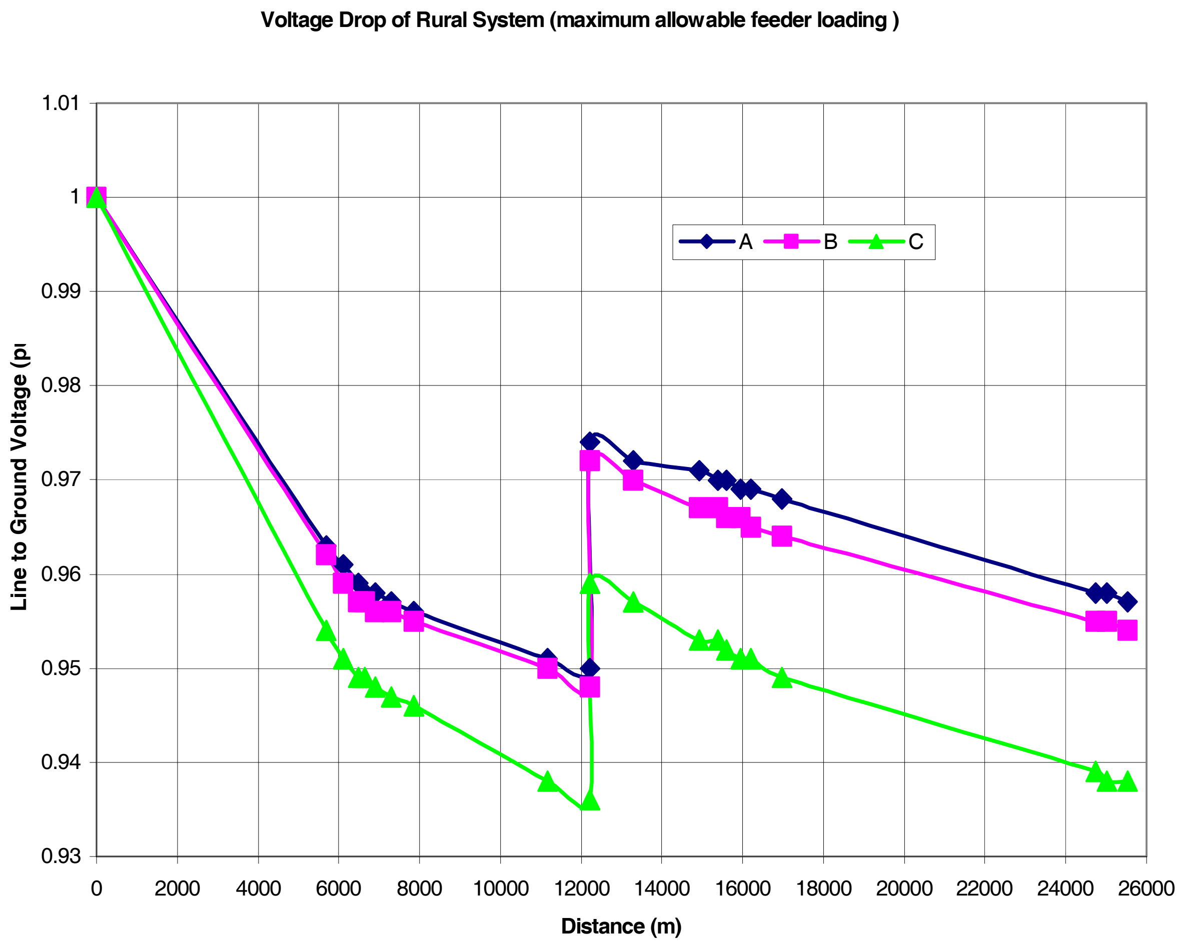


Figure A.5 Voltage Drop during the peak power period (period #8, between 18:00 and 21:00 hours)

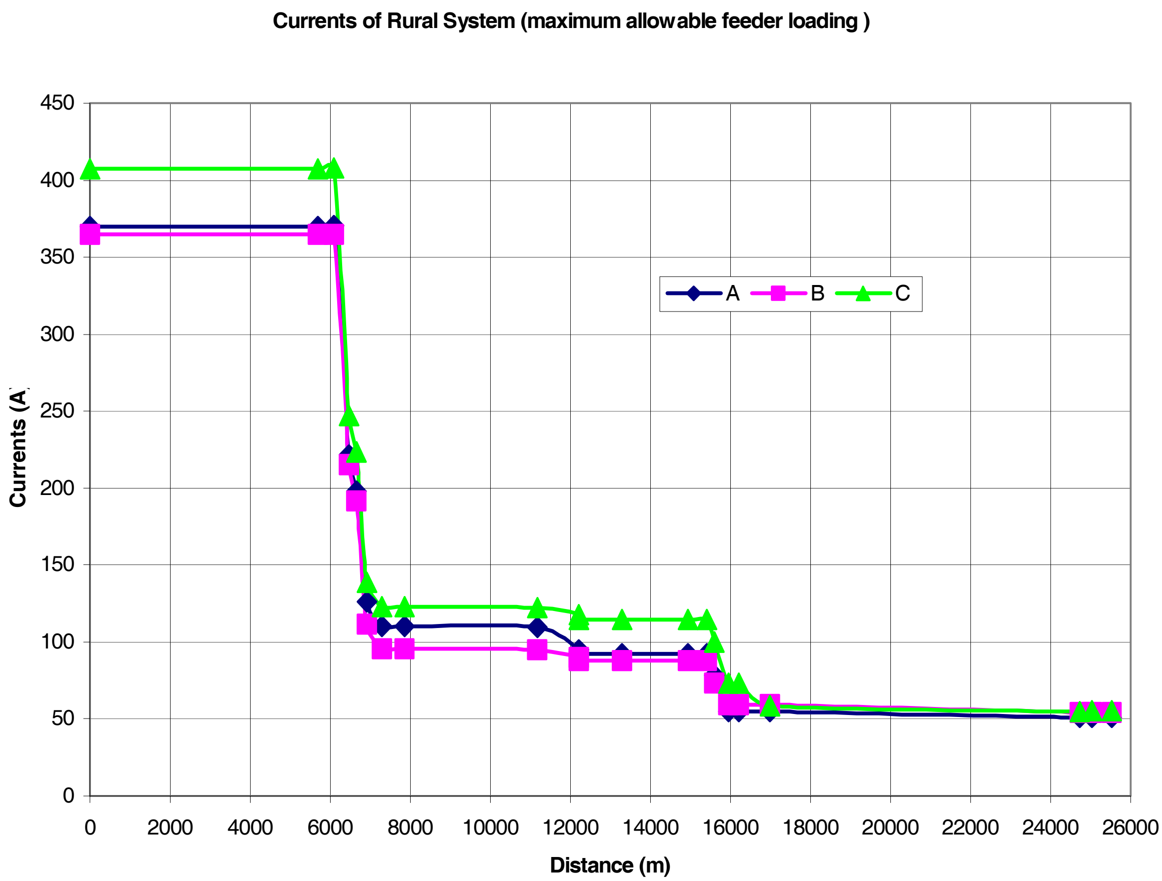


Figure A.6 Load current distribution during the peak power period (period #8, between 18:00 and 21:00 hours)

Maximum power export

A normal daily loading is assumed for the feeder of Figure A.1. The typical daily load diagram is given in Table A.3. One DG unit is connected to the feeder at the end of feeder section E6. The maximum allowed DG capacity is determined such that the power export from the feeder is less than the cable ampacity of the 30 ASR cable of section E5 of the feeder. The study results for this test case are presented on Figure A.7. Since three phase loads are not balanced, Figure A.7 presents the current of phase B (Minimum load current of the three phases).

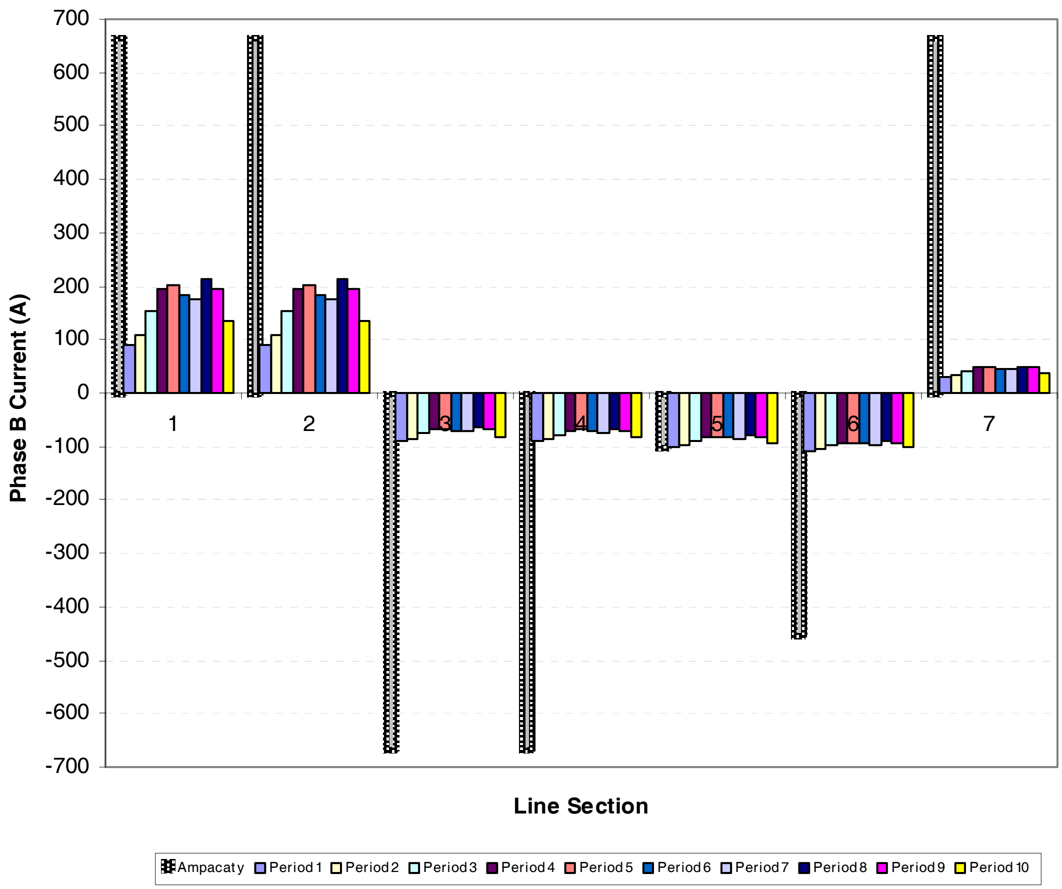


Figure A.7 Feeder loading per section when 6.75 MW DG is installed after Section E6 and no DS is connected to the feeder

The results of Figure A.7 show that when 6.75 MW is produced by the DG unit, under normal daily load condition, the maximum power export is 4.8 MW, which is equal to the cable ampacity of section E5 of the feeder (Table A.1). The critical time period, when the maximum power export limit is reached, is at night (period #1, between midnight and 5:00 am).

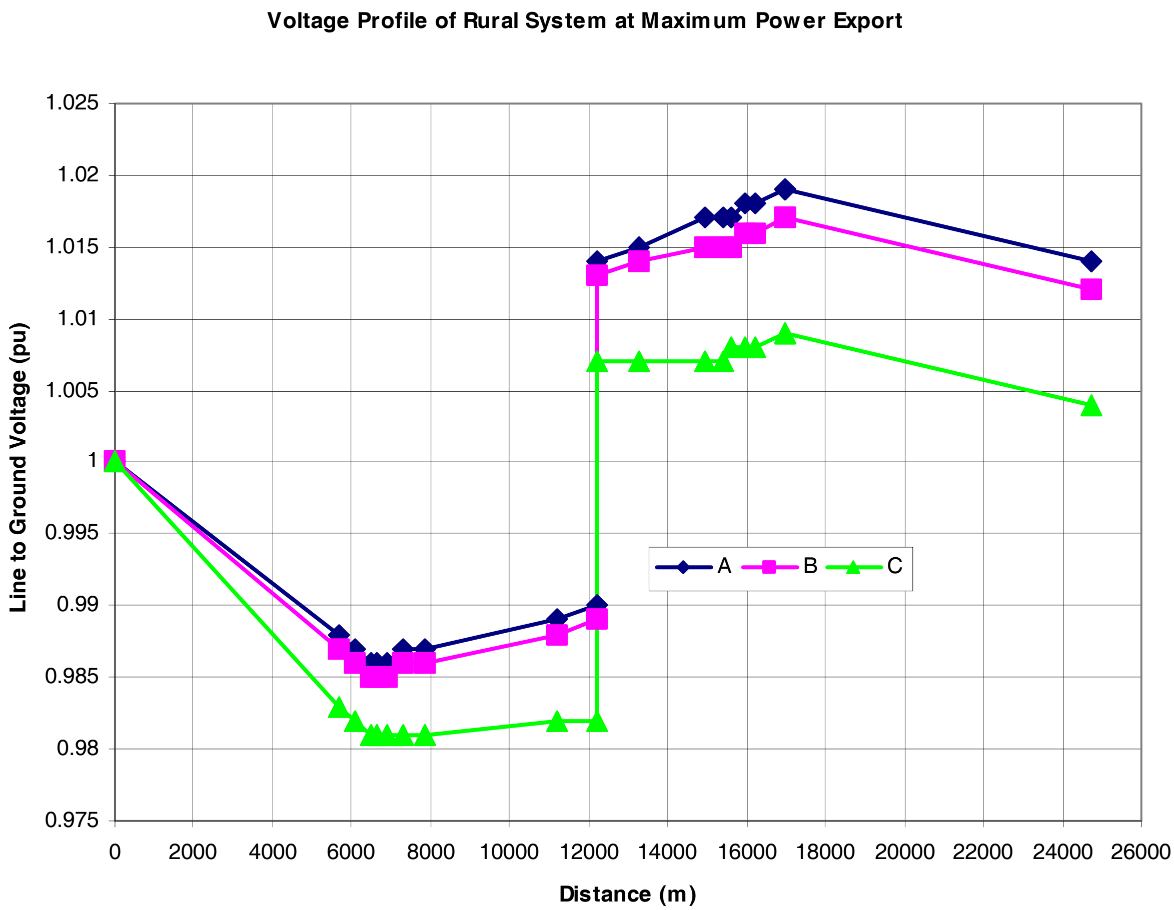


Figure A.8 Voltage profile of the Feeder when 6.75 MW DG is installed after Section E6 and no DS is connected to the feeder

Figure A.8 shows the voltage profile when the maximum power export reaches cable ampacity, 4.8 MW. It can be seen that the voltage profile is within the limits (1.06 p.u > V > 0.94 p.u).

A.3 Battery Option 2 – Generic case with no power or energy limits

The second set of studies is performed under the assumption that one large DS unit is used and no power/energy constrains imposed. The battery AC side efficiency of 70% is assumed for this generic case.

Conventional operation

Based on the feeder cable ampacity (Table 1), the maximum permissible power in section E5 is 4.8 MW. In the case study of Figure A.4, without the storage, the daily peak is equal to the maximum permissible power in section E5 (4.8 MW). By placing the DS unit on the feeder, the maximum load can be increased. Figure A.9 shows the implementation of storage charge/discharge control strategy based on the procedure from Section 1.2.1.

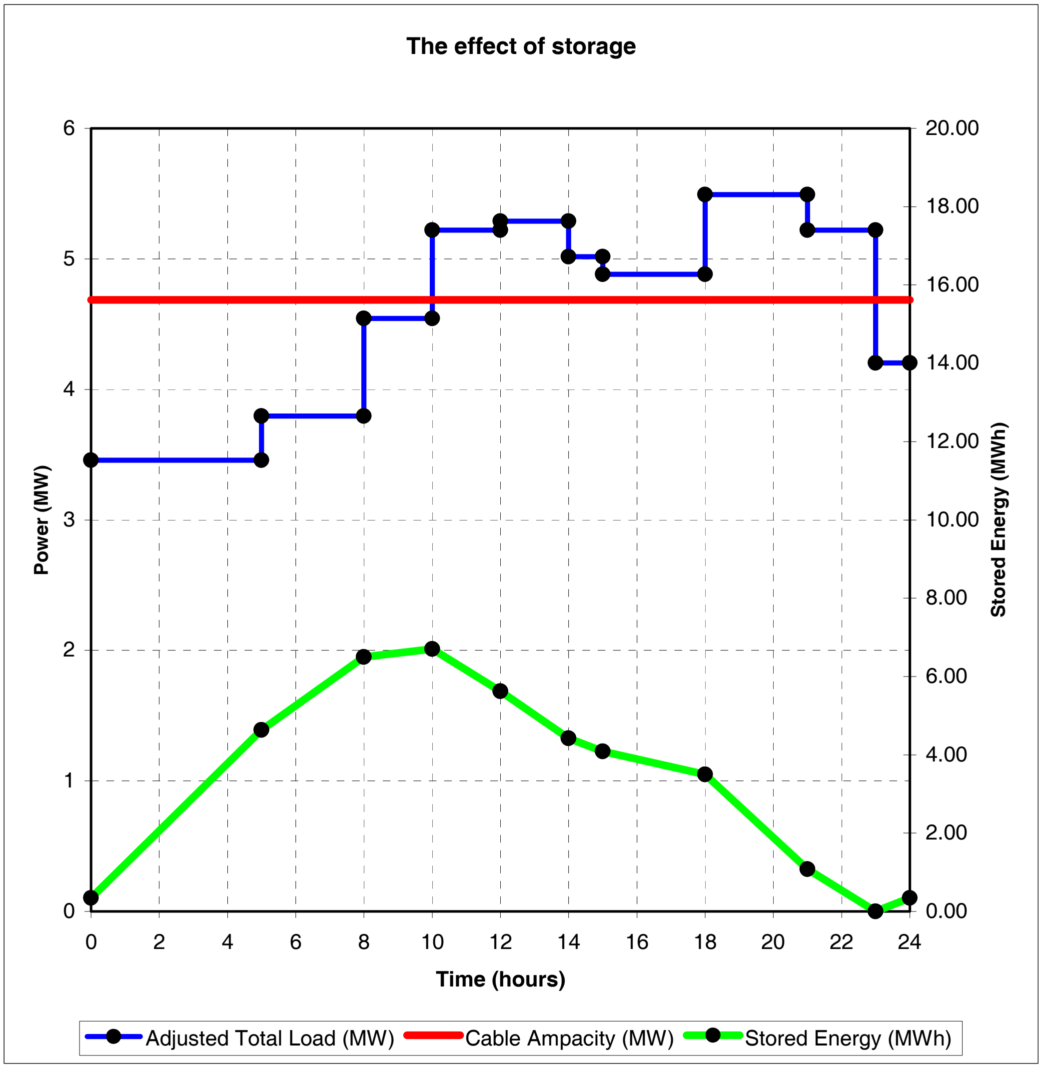


Figure A.9 DS charge/discharge strategy and the effect of DS unit on feeder loading

On Figure A.9, the permissible daily peak load in the presence of the DS unit can be increased to 5.5 MW when compared to 4.8 MW for the case without the storage. The total energy produced by the DS unit during the battery discharge period is 70% of the consumed energy during the battery charge period. To achieve the storage charge/discharge performance characteristic from Figure A.9, the DS unit rating should be:

- maximum charging power 1.9 MW,
- maximum discharging power 0.7 MW,
- storage capacity 6.7 MWh.

As explained before, three locations are considered for the DS unit:

- end of section E7, close to the end of the feeder (Figure A.10),
- end of section E6, where DG is located (Figure A.11),
- end of section E5, since it has the lowest cable ampacity limit (Figure A.12).

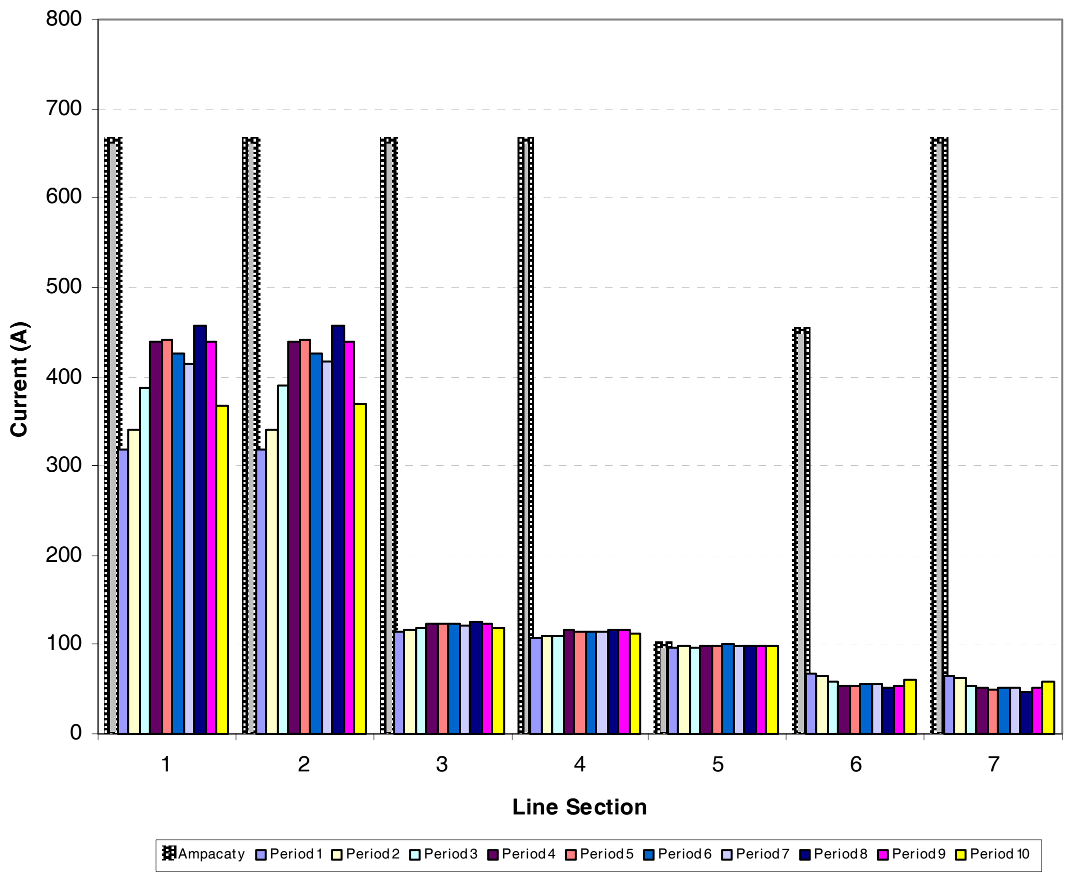


Figure A.10 Feeder loading per section for cable ampacity loading with one DS unit (70% efficiency and no power/energy limits), located after section E7 and no DG in the system

Figure A.10 shows that locating the DS unit at the end of the feeder (after section E7) reduces the feeder loading on all feeder sections except section 7 during the mid-day period. Since there is a major load at the end of section 7, the DS at this location can not adjust this load. Therefore, the load within section 7 nearly keeps the same profile. On the other hand, this results in a higher total load limit (5.5MW), compared to the case without storage (4.8 MW). The feeder loading at night is increased on all sections (due to DS charging).

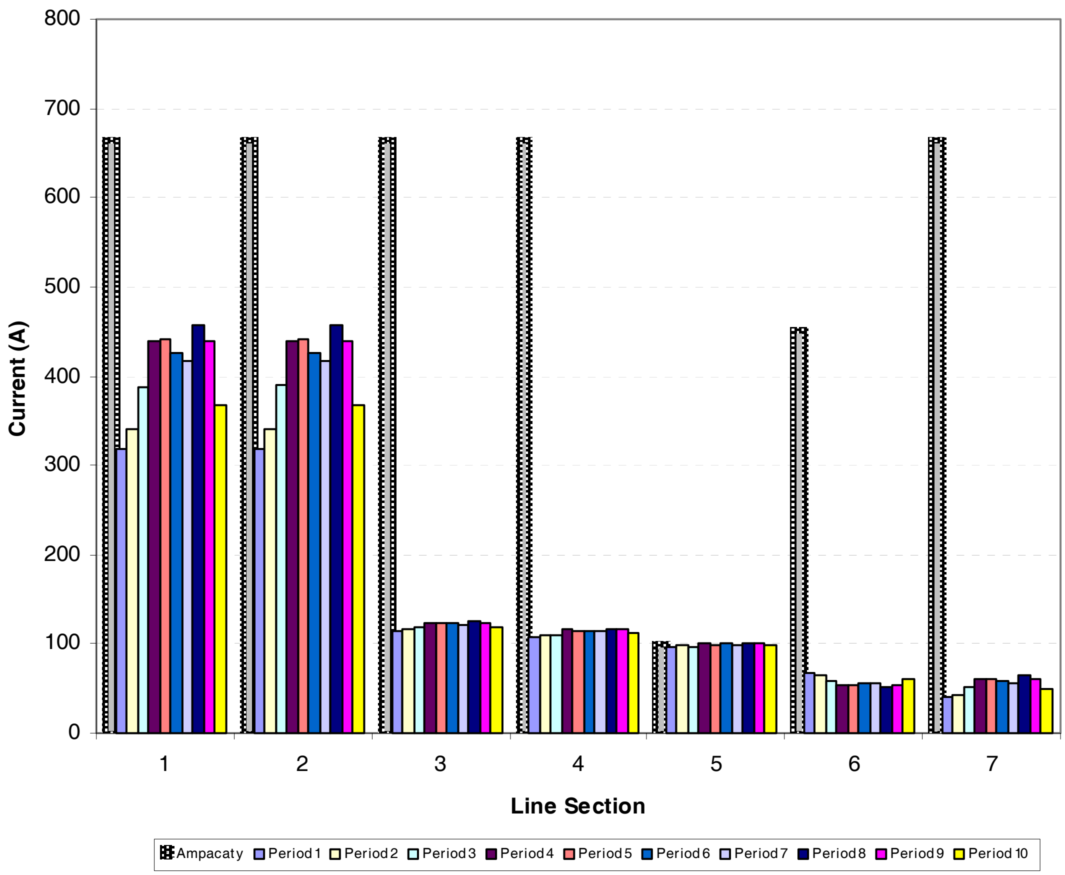


Figure A.11 Feeder loading per section for cable ampacity loading with one DS unit (70% efficiency and no power/energy limits), located after section E6 and no DG in the system

Figure A.11 shows that locating the DS unit after section E6 noticeably reduces the loading of section E5 during the mid-day. Section E6 experience higher loading at night (due to the DS charging), in a similar way as in the previous case. Loadings of section E7 is not affected by the presence of the DS unit after section E6.

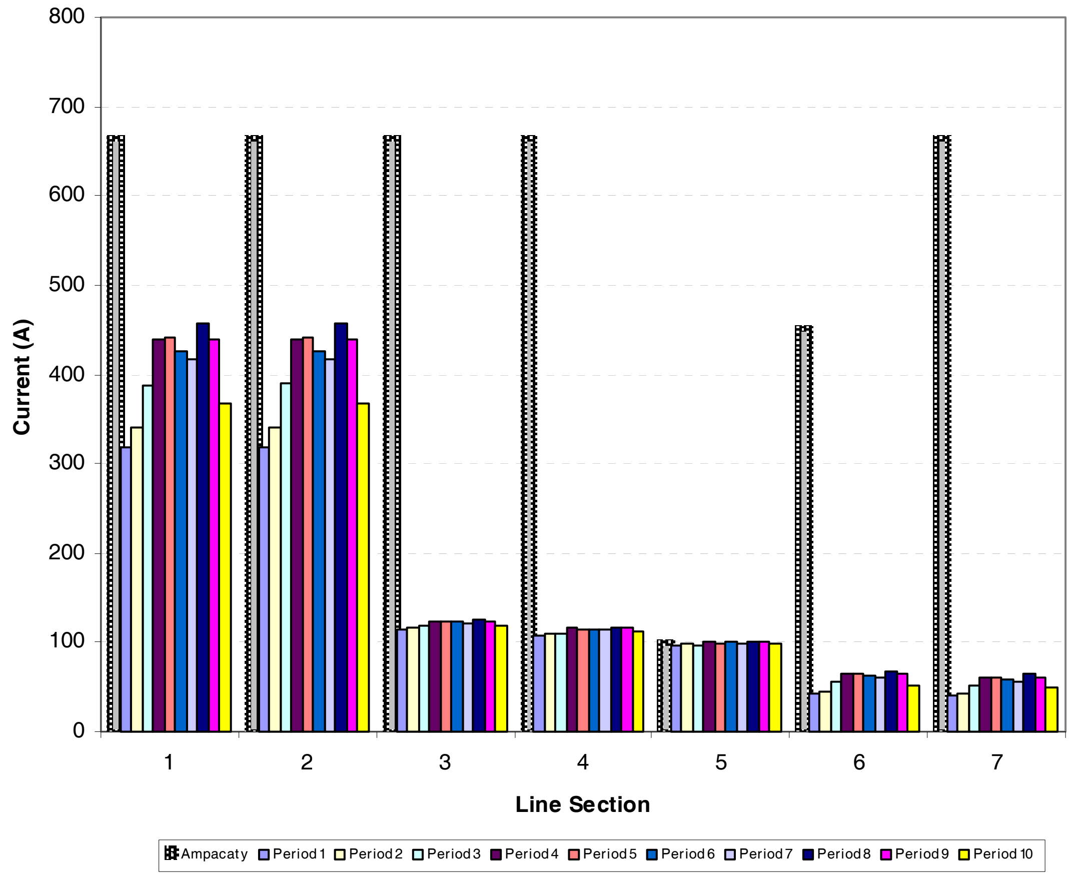


Figure A.12 Feeder loading per section for cable ampacity loading with one DS unit (70% efficiency and no power/energy limits), located after section E5 and no DG in the system

Figure A.12 shows that locating the DS unit after section E5 reduces the feeder loading on feeder sections E5, E4, and E3. The loadings of the downstream sections (E6 and E7) are not affected by the presence of the DS unit.

The study results from Figures A.10 to A.12 show that in all case studies the presence of the DS unit allows for higher load levels (5.5 MW vs. 4.8 MW) without overloading the critical section (E5). With respect to the load within section E7, locating the DS unit after section E6 and section E7 nearly has the same effect.

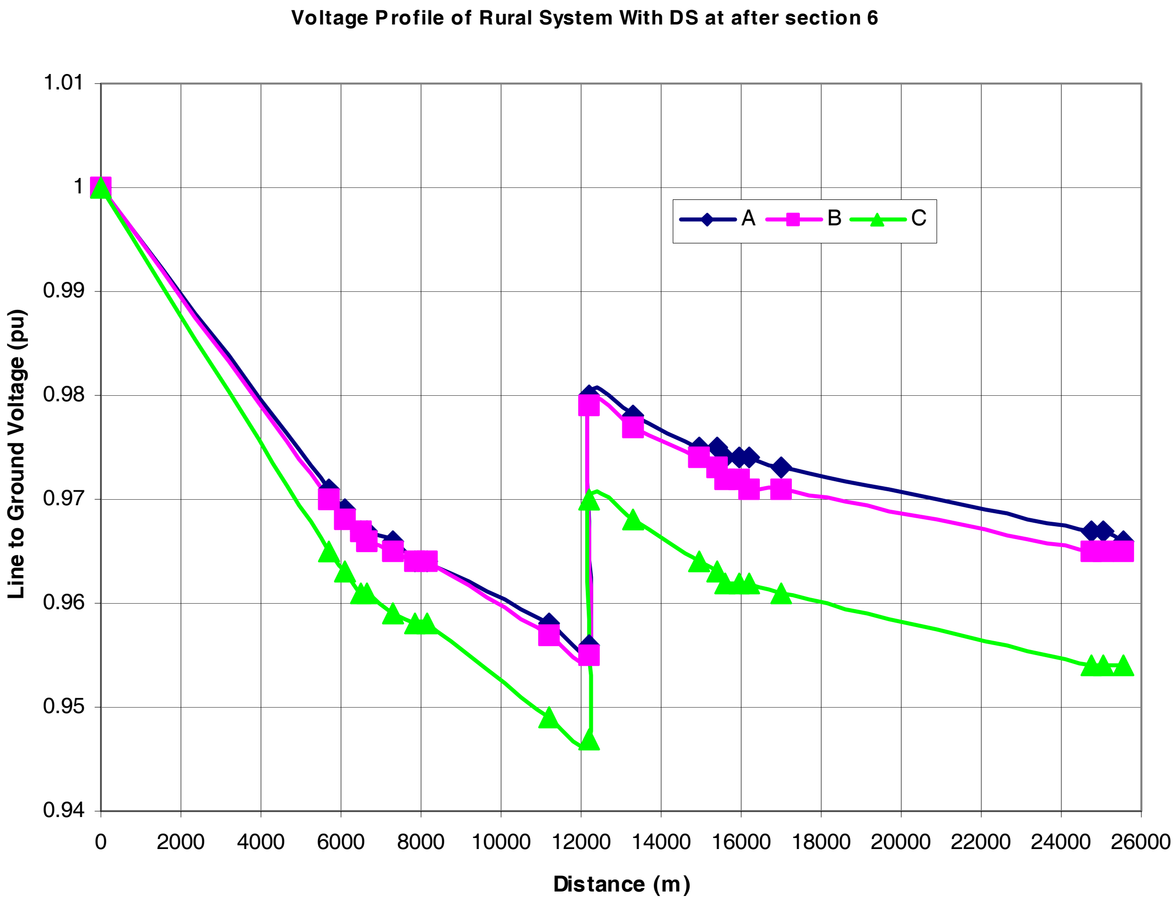


Figure A.13 Voltage profile of the Feeder loading per section for cable ampacity loading with one DS unit (70% efficiency and no power/energy limits), located after section E6 and no DG in the system

Figure A.13 shows the voltage profile when the maximum cable loading reaches cable ampacity, 4. 8 MW, and the feeder is with one DS unit (70% efficiency and no power/energy limits), located after section E6 and no DG is in the system. It can be seen that the maximal voltage drop is 5.1% and it exceeds the limits (+1.06 p.u > V > 0.94 p.u), when the TS bus voltage is 1 p.u.

Comparing the results of Figure A.13 with that of Figure A.5, we can conclude that DS unit can increase the maximum cable loading and the maximal voltage drop.

Maximum power export

A typical daily load diagram based on Table A.2 is assumed. One DG unit and one DS unit are connected to the feeder. The same DS unit charge/discharge strategy, as shown on Figure A.9, is adopted to keep the combined power of the load and the DS constant. It is assumed that the DG export power is limited so that the feeder current is less than or equal to the feeder ampacity limit. To keep the critical feeder section (E5 in this case) from overloading, the DG power limit is determined from the power flow studies and is 7.04 MW. This is 0.29 MW more that it would be allowed if the DS does not exist in the system.

In power flow studies, three locations are considered for the DS unit:

- end of section E7, close to the end of the feeder (Figure A.14),
- end of section E6, where DG is located (Figure A.15),
- end of section E5, since section E5 has the lowest cable ampacity limit (Figure A.16).

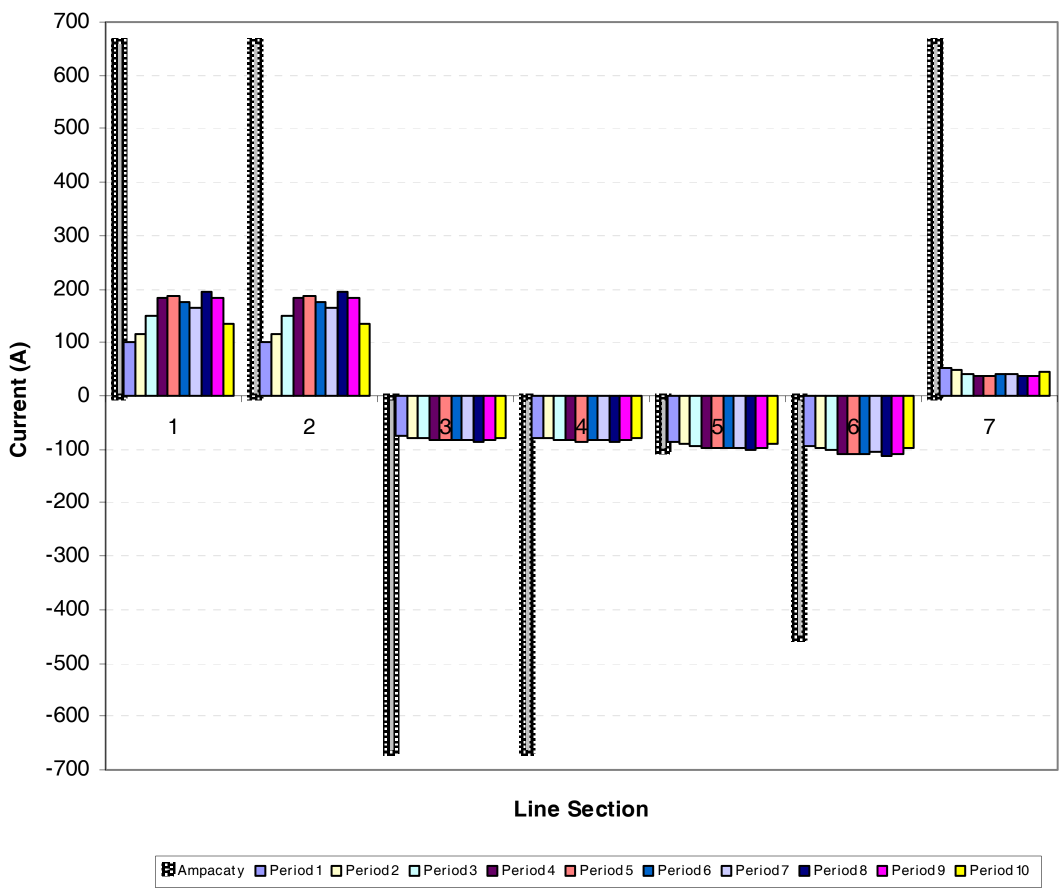


Figure A.14 Feeder loading per section when 7.04 MW DG is installed after Section E6 and DS is connected to end of the feeder (after Section E7)

In the case of Figure A.14, the DS unit is located at the end of the feeder (after section E7), the power generated by the DS unit during the mid-day period reduces the loading on feeder sections E3, E4, E5, E6, and E7. The same feeder sections have to carry additional currents for charging the DS unit during the light load periods.

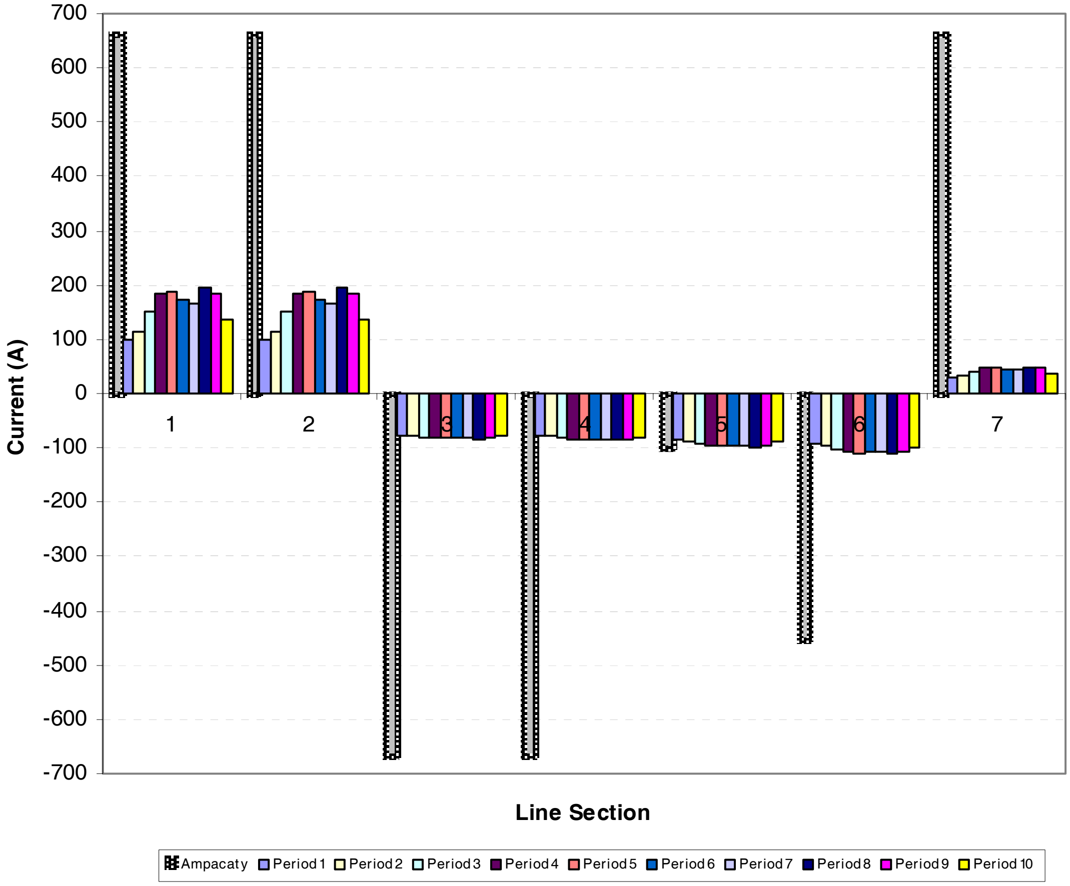


Figure A.15 Feeder loading per section when 7. 04 MW DG is installed after Section E6 and DS is connected of the feeder (after Section E6)

In the case of Figure A.15, the DS unit is located after section E6 and during the period of light load the DS unit absorbs a portion of the power generated by the DG unit. This reduces the loadings of feeder sections E1, E2, E3, E4, E5, and E6. The loadings of feeder sections E7 is not affected by the presence of the DS or the DG unit.

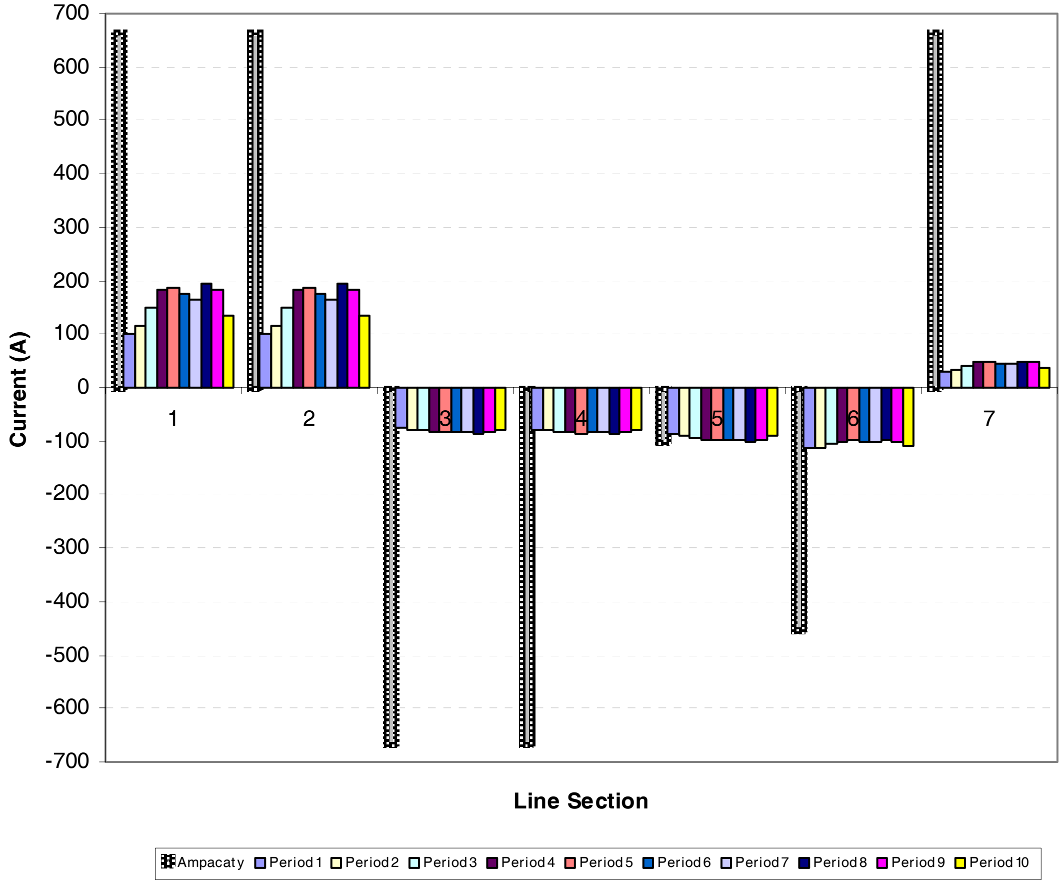


Figure A.16 Feeder loading per section when 7. 04 MW DG is installed after Section E6 and DS is connected of the feeder (after Section E5)

In the case of Figure A.16, the DS unit is located immediately after section E5 and during light load periods the DS unit absorbs a portion of the power generated by the DG unit. This reduces section E5 current to the cable ampacity limit of 100 A (Table 1). Loading of the downstream feeder section E7 is not affected by the presence of the DS or the DG unit. Feeder loadings of section E6 is reduced during heavy-load periods but increased, due to the DS charging, during the light-load periods.

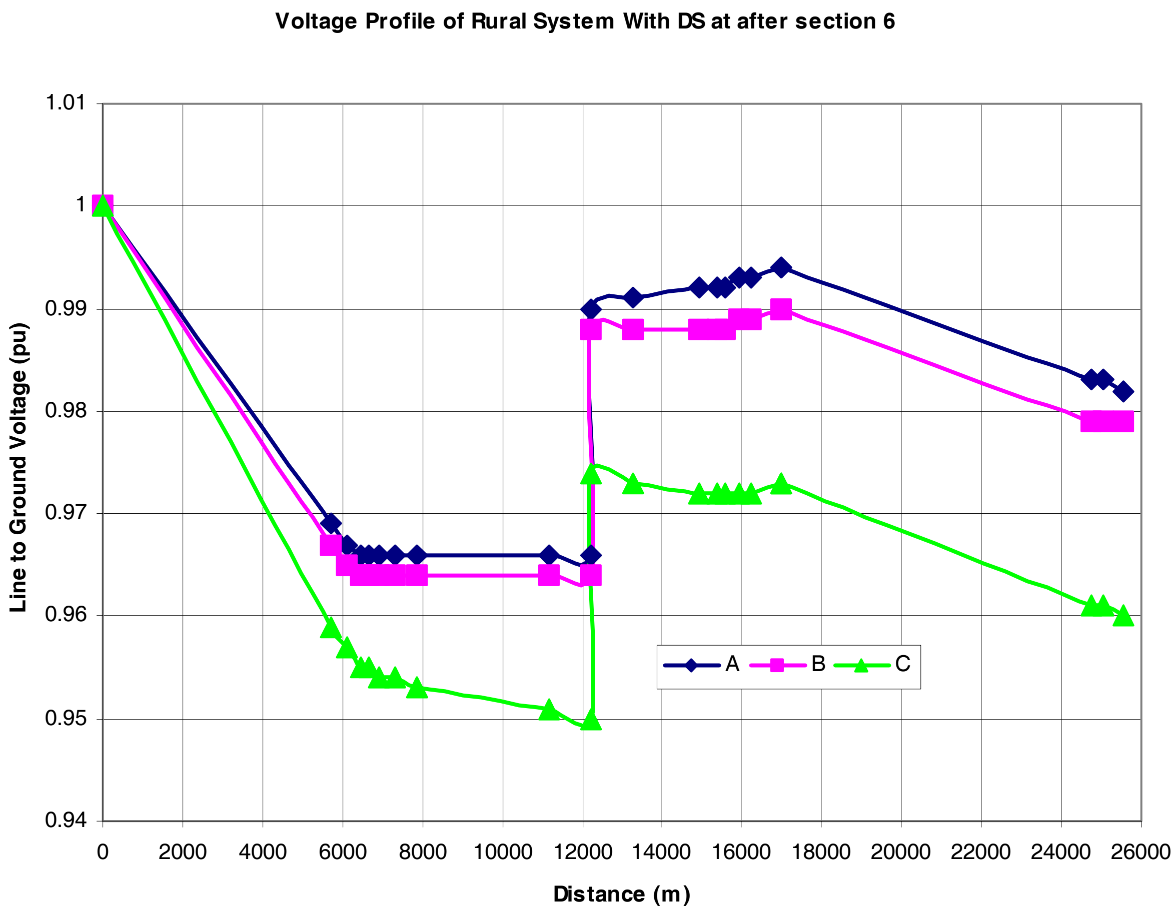


Figure A.17 Voltage profile of the Feeder loading per section when 7. 04 MW DG is installed after Section E6 and DS is connected of the feeder (after Section E6)

Figure A.17 shows the voltage profile when the maximum power export reaches the cable ampacity, 4.8 MW. It can be seen that the voltage profile is within the limits (+1.06 p.u > V > 0.94 p.u).

A.4 Battery Option 3 – 1 MW NaS Battery with 100% DOD

The third set of studies is performed under the assumption that one large 1 MW NaS battery-based on the main technical data from Section 1.2.2 is used. Charging power (on the AC side) is limited to 1.2 MW, while discharging power limit (on the AC side) is 1.2 MW for up to 3 hours and 1 MW perpetually. The available stored energy is up to 7.2 MWh (100% DOD). AC efficiency of 80% is assumed for this case.

Conventional operation

Based on feeder cable ampacity (Table A.1) the maximum permissible power in section E5 is 4.8 MW. In the case study that analyzes the maximum permissible feeder loading without storage (Figure A.4), the daily peak is equal to the maximum permissible power in section E5 (4.8 MW). By placing the DS unit on the feeder, the maximum load can be increased. Figure A.18 shows the implementation of storage charge/discharge control strategy based on the procedures of Section 1.2.2.

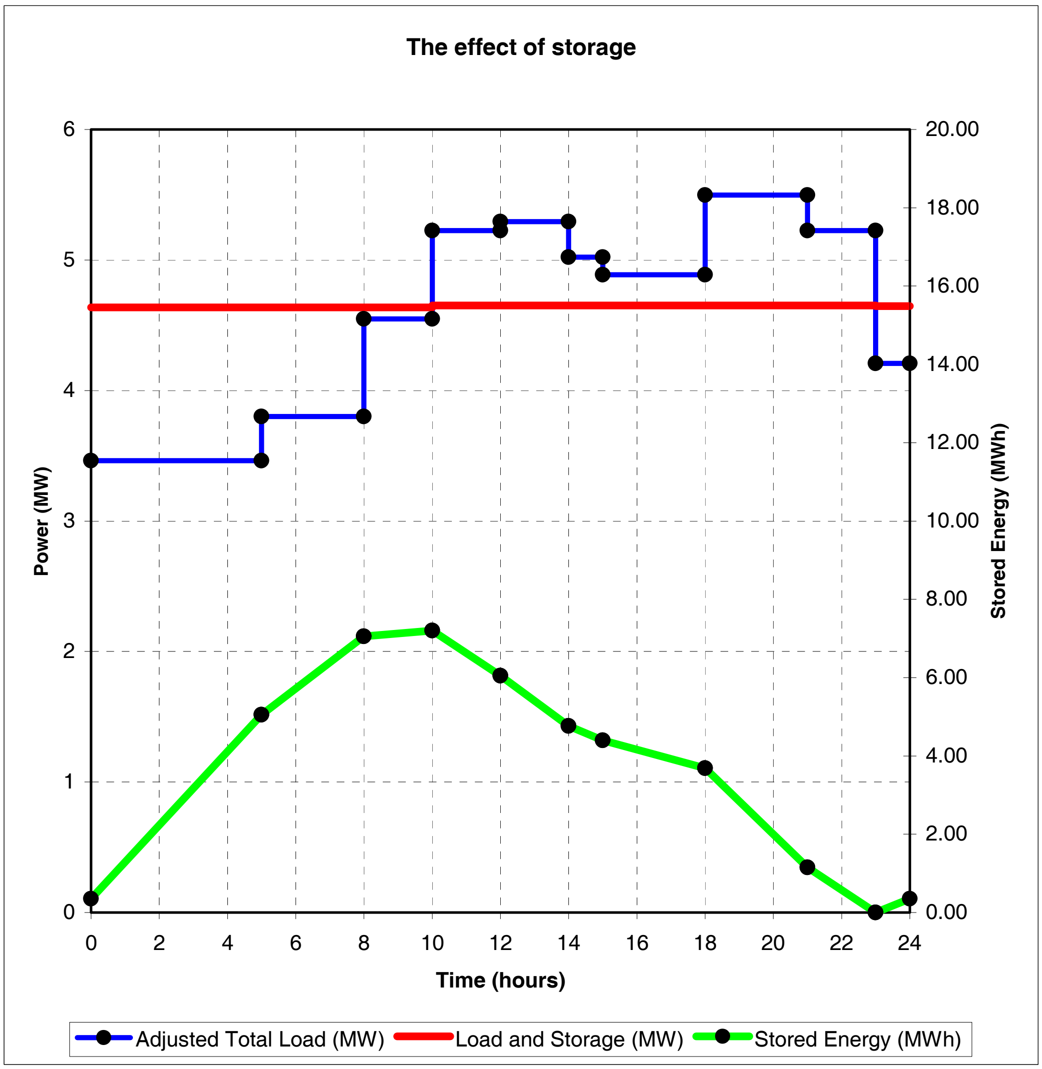


Figure A.18 DS charge/discharge strategy and the effect of DS unit on feeder loading

On Figure A.18, the permissible daily peak load in the presence of the 1 MW NaS battery-based DS unit can be increased to 5.5 MW, compared to 4.8 MW for the case without storage. The total energy produced by the DS unit during discharging period is 80% of the consumed energy during charging period.

Based on analysis from Section 2.1.2, the DS unit location associated with the minimal losses is considered (end of section E6). The loadings and the cable ampacities for all sections are shown on Figure A.19.

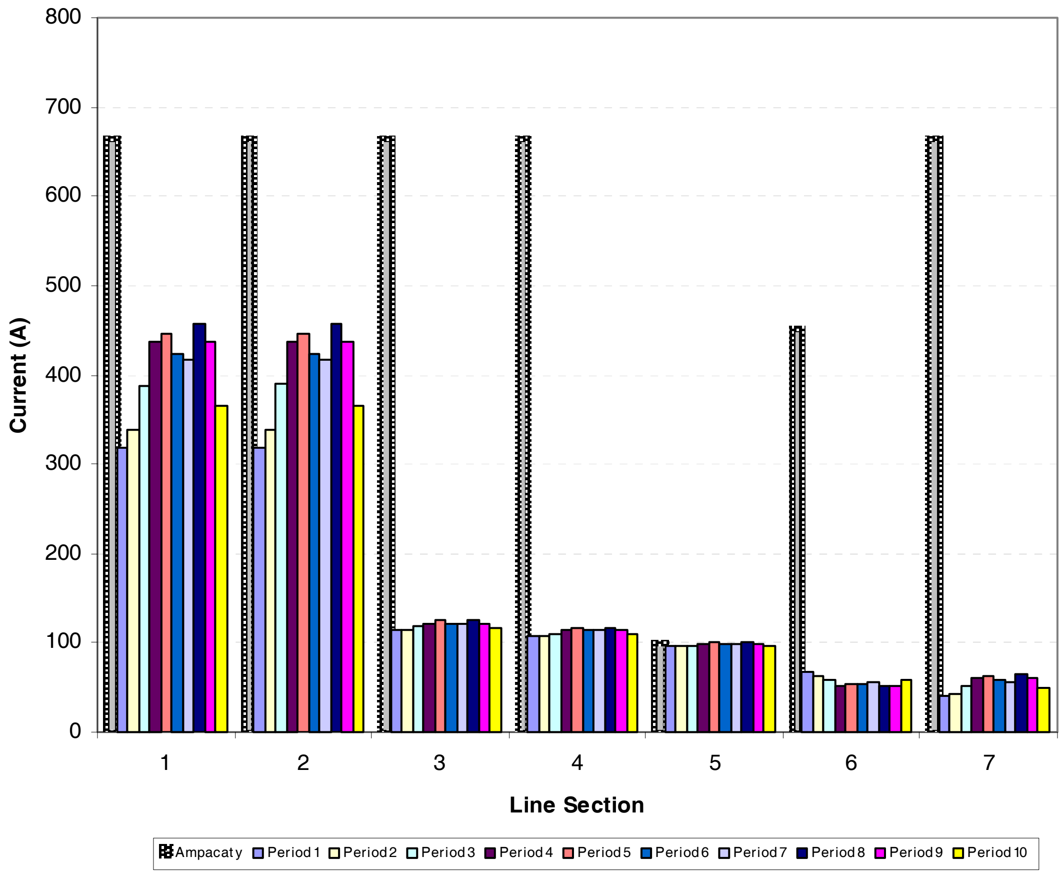


Figure A.19 Feeder loading per section for cable ampacity loading with one DS unit (1 MW NaS battery with 100% DOD), located after section E6 and no DG in the system

The study results of Figure A.19 confirm that with the presence of the 1 MW NaS battery-based DS unit, the cable ampacity limits are not violated even if the load peak is as high as 5.5 MW.

Maximum power export

A typical daily load diagram based on Table A.2 is assumed. One DG unit and one 1 MW NaS battery-based DS unit are connected to the feeder. The same charge/discharge strategy, shown on Figure A18, is assumed for the DS unit. It is assumed that the DG export power is limited so that the feeder current is less than or equal to the feeder ampacity limit. The study results for the case when the DS unit is in the same location as the DG unit (at the end of section E6) are shown on Figure A.20.

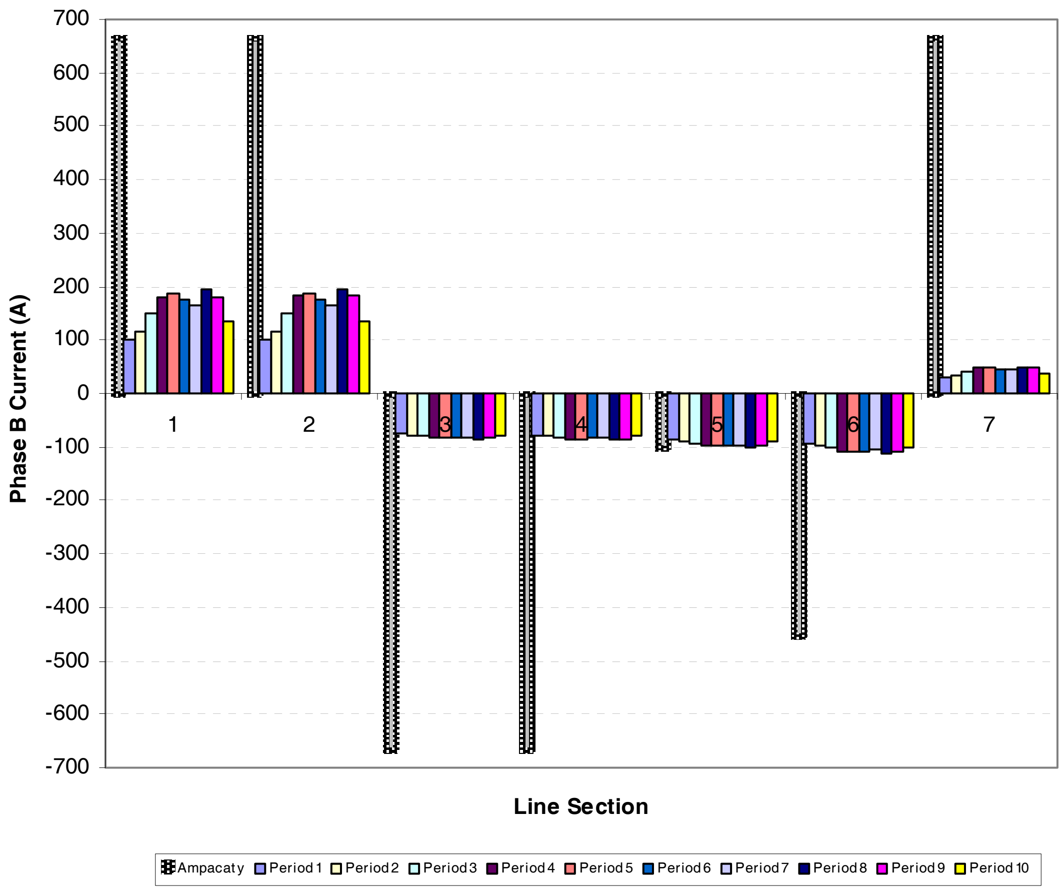


Figure A.20 Feeder loading per section when 7.04 MW DG is installed after Section E6 and DS, (1 MW NaS battery with 100% DOD), is located after section E6

In the case of Figure A.20, the DG power limit that does not overload the critical feeder section (E5 in this case) is 7.04 MW. This is 0.29 MW more than it would be allowed if the DS does not exist in the system.

A.5 Battery Option 4 – 1 MW NaS Battery with 90% DOD

The fourth set of simulations is performed under the assumption that the same 1 MW NaS battery of Section 2.1.3 is used. The charging power (on the AC side) is limited to 1.2 MW, while the discharging power limit (on the AC side) is 1.2 MW for up to 3 hours and 1 MW perpetually. The available stored energy is up to 6.48 MWh (battery capacity is 7.2 MWh, but only 90% DOD is allowed to increase the life of the battery). An AC efficiency of 80% is assumed for this case.

Conventional operation

Based on the feeder cable ampacity (Table 1), the maximum allowed power in section E5 is 4.8 MW. If we implement a storage charge/discharge control strategy based on the procedure from Section 1.2.3, Figure A.21 shows the peak load in the presence of 1 MW NaS battery (90% DOD) as 5.5 MW. The relative load diagram applicable for Feeder E is scaled up so that the peak load is the same as the maximum allowed peak loading.

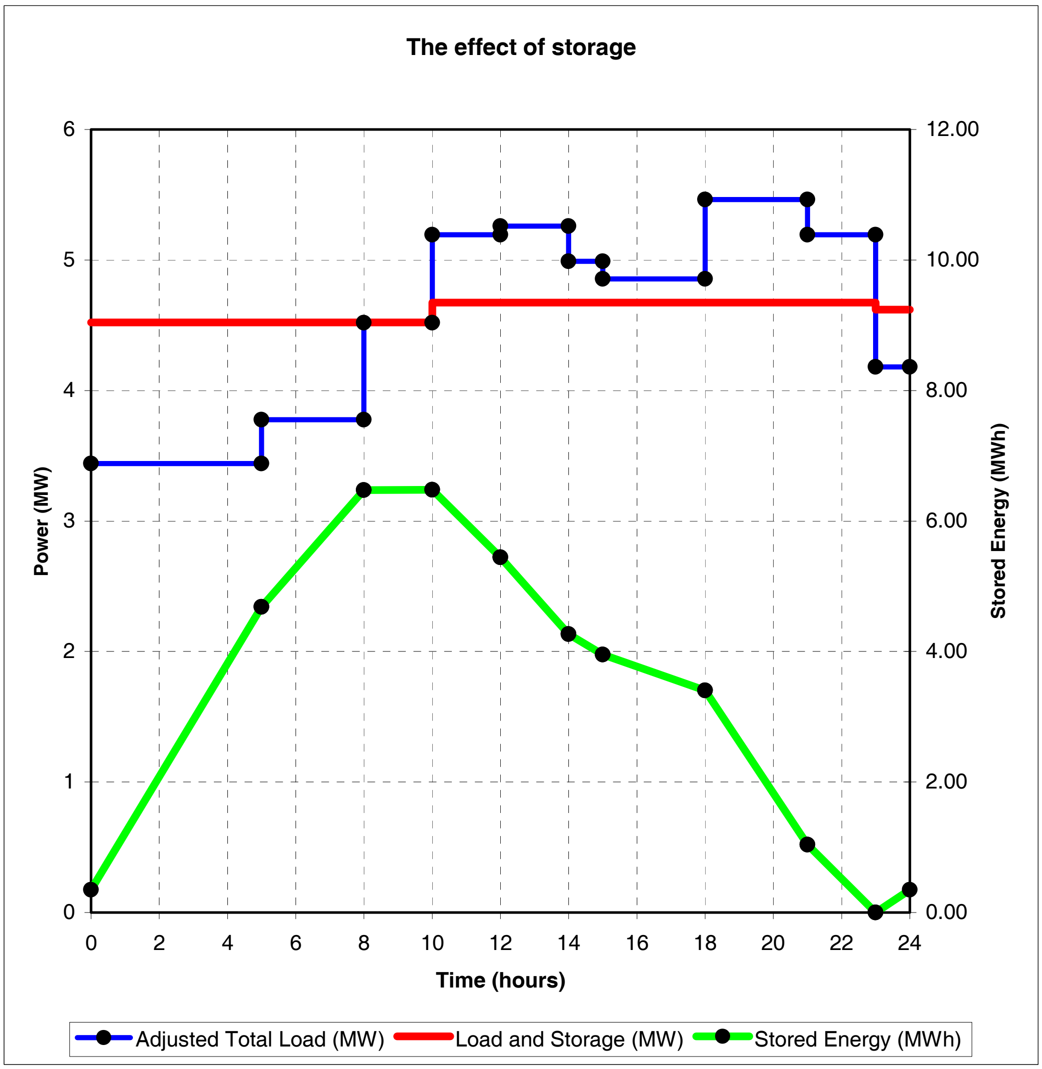


Figure A.21 DS charge/discharge strategy and the effect of DS unit on feeder loading

Based on the analysis of Section 2.1.2, the DS unit location associated with the minimal losses is considered (after section E6). The loadings of all sections throughout the day are shown on Figure A.22.

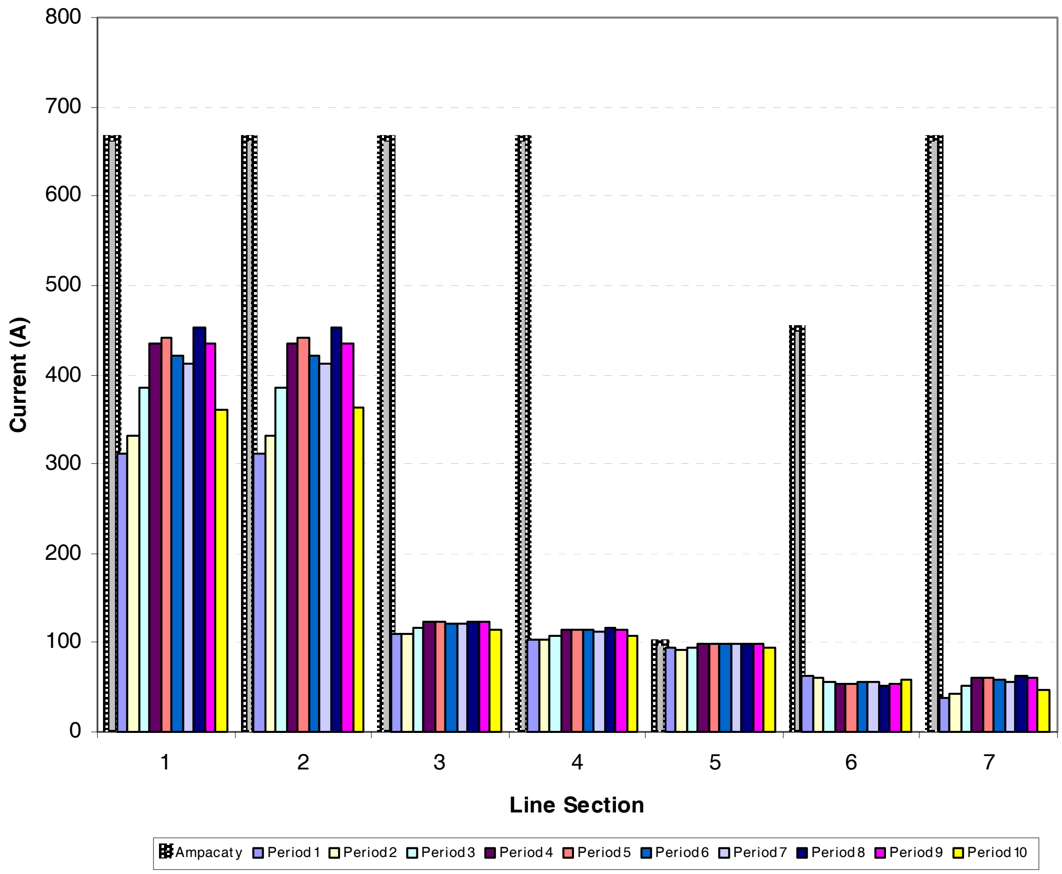


Figure A.22 Feeder loading per section for cable ampacity loading with one DS unit (1 MW NaS battery with 90% DOD), located after section E6 and no DG in the system

The study results from Figure A.22 confirm that with the presence of the 1 MW NaS battery-based DS unit, the cable ampacity limits are not violated even if the load peak is as high as 5.5 MW. For the conventional operation of feeder E, the critical parameter is not the maximum stored energy but the maximum output power. Therefore, the effect of reducing DOD from 100% DOD to 90% is negligible.

Maximum power export

The results are the same as that of 100% DOD.

A.6 Summary

The study results show the effect of integration of distributed storage (DS) on a typical rural feeder loading. It is demonstrated that the presence of DS can reduce load fluctuations throughout the day, and depending on the DS characteristics/ratings, the maximum feeder loading can be increased. The studies show that:

- When a DS unit with the AC efficiency of 70% and without power and storage capacity constraints is used, the maximum allowed load peak power on the feeder is increased from the 4.8 MW to 5.5 MW. The DS parameters required for this case are: (i) maximum charging power of 1.9 MW, (ii) maximum discharging power of 0.7 MW, and (iii) storage capacity of 6.7 MWh.
- When a DS unit of a typical 1 MW NaS battery with 7.2 MWh storage capacity and 100% DOD is used, the maximum allowed load peak power on the feeder is increased from 4.8 MW to 5.5 MW. The same result is obtained if DOD is reduced to 90%.

The effect of the NaS battery on the maximum allowed load peak power is not affected by the change of DOD from 100% to 90%, because the limiting factor for reducing the peak load is the maximum discharging power.

When the feeder includes DG units, the DS unit allows for a higher level of DG power export. Furthermore:

- When a DS unit with the AC efficiency of 70% and without power and storage capacity constraints is used, the maximum allowed DG power export is increased by 0.29 MW. The DS unit parameters required for this case are: (i) the maximum charging power of 1.0 MW, (ii) the maximum discharging power of 0.7 MW, and (iii) the storage capacity of 5.6 MWh.
- When the DS unit is a typical 1 MW NaS battery with 7.2 MWh storage capacity and 100% DOD, the maximum allowed DG power export is increased up to 0.29 MW. The same result is obtained if DOD is reduced to 90%.

The study results also show the effect of integration of distributed storage (DS) on the voltage drop of a rural feeder. It is demonstrated that when a DS unit is used, the maximum voltage drop under conventional operation with maximum load of 4.8 MW, is reduced from 6.2% to 5.3%.

When the feeder includes DG units, the presence of DS unit results in lower voltages at DG terminal. This characteristic makes the voltage profile smoother.