OPTIMAL CONTROL OF DISTRIBUTED ENERGY STORAGE

A Thesis by

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The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Electrical Engineering.

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ABSTRACT

It is shown in this research paper that, with the appropriate control system, a storage energy unit connected to a distribution system near the primary load, can completely level the load on a distribution feeder for any primary load profile. By doing simulations using an Excel spreadsheet, graphs were generated that show how the control system is able to achieve this objective in addition to quantifying the storage energy system to the primary load profile. Steps needed for future research projects to make the energy storage system economically viable are suggested.

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LIST OF ABBREVIATIONS

DES	Distributed Energy Storage
DG	Distributed Generation

CHAPTER 1

INTRODUCTION

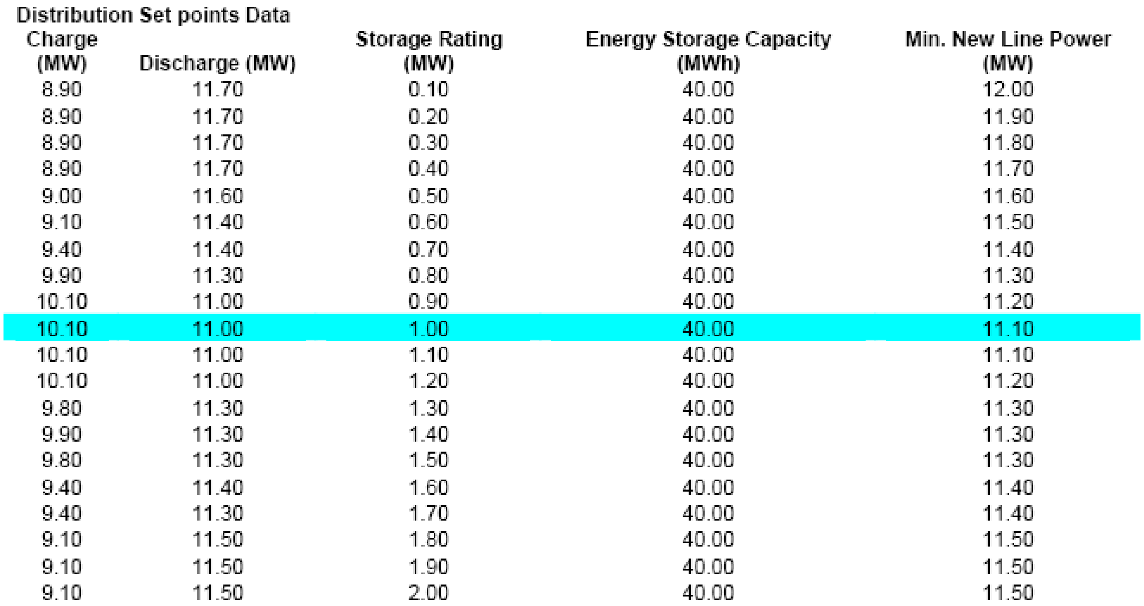
Recent studies made by The Electric Power Research Institute estimate about $190 billion as losses due to power outages per year [1]. These huge losses can be greatly reduced by distributed generation (DG) and distributed energy storage (DES), which have the potential of providing 460 GW of power during peak price periods [1]. DG has been heavily implemented, while DES has been looked down upon largely due to the fact that its technology is not up to desirable levels and is very expensive to implement on a large scale. Yet, DES benefits far outweigh those of DG especially in terms of emission costs [1], an issue that is becoming a major topic in the growing concerns of global warming. Providing emergency power, peak shaving, and load-following capabilities; increasing the longevity and efficiency of central generation stations; mitigating transmission congestions are some of the benefits derived from DES [1].

Some earlier research projects have dealt with the resources, control, economics, applications and benefits of distributed energy storage systems [2, 3, 4, 5, 6]. This thesis is a continuation of Sai Cheong Loh's research [3] that focuses on the load-leveling aspect of the controls of the distributed energy storage system.

CHAPTER 2

RESEARCH OBJECTIVE

Previous work [3] on the load-leveling capability of a storage system was aimed at keeping the total line load to an optimized constant minimum. Figure 2.1 [3] shows the results obtained.



Distribution Set points Data				
Charge (MW)	Discharge (MW)	Storage Rating (MW)	Energy Storage Capacity (MWh)	Min. New Line Power (MW)
8.90	11.70	0.10	40.00	12.00
8.90	11.70	0.20	40.00	11.90
8.90	11.70	0.30	40.00	11.80
8.90	11.70	0.40	40.00	11.70
9.00	11.60	0.50	40.00	11.60
9.10	11.40	0.60	40.00	11.50
9.40	11.40	0.70	40.00	11.40
9.90	11.30	0.80	40.00	11.30
10.10	11.00	0.90	40.00	11.20
10.10	11.00	1.00	40.00	11.10
10.10	11.00	1.10	40.00	11.10
10.10	11.00	1.20	40.00	11.20
9.80	11.30	1.30	40.00	11.30
9.90	11.30	1.40	40.00	11.30
9.80	11.30	1.50	40.00	11.30
9.40	11.40	1.60	40.00	11.40
9.40	11.30	1.70	40.00	11.40
9.10	11.50	1.80	40.00	11.50
9.10	11.50	1.90	40.00	11.50
9.10	11.50	2.00	40.00	11.50

Figure 2.1: Distribution Set Points Data [3]

The highlighted row shows a total line minimum load of 11.1 MW with storage energy and power capacities of 40 MWh and 1 MW, respectively. With these results, Figure 2.2 [3] shows how much load leveling is attained.

It can be seen that the attempt at load leveling is an improvement over the primary load, but it could be better. The reason for this shortcoming is due to the fact that the storage power capacity of 1 MW for this storage system is a constant and too low for the system to efficiently maintain a constant feeder line load. With this constant storage capacity, it is practically and theoretically impossible to obtain an ideal load-leveling result, regardless of the size of the storage energy capacity or the variations in setpoints.

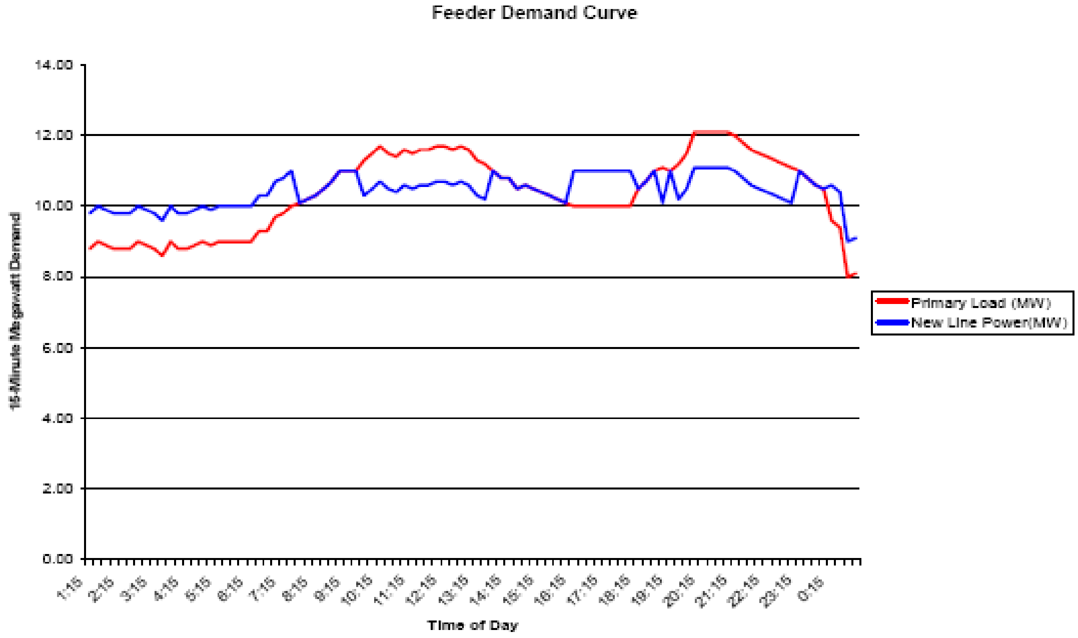


Figure 2.2: Minimum Line Load of 40 MWh Storage Capacity [3]

This paper rectifies the problem by varying the power capacity, at which the unit charges or discharges energy, to reasonably accommodate charge or discharge mandates, with the goal of achieving a desirable degree of load leveling. Also, the percentage of the primary load profile for which load leveling is achieved is shown.

The aim of this research was to achieve a load-leveling technique with the potential of providing perfect load-leveling results, as shown in Figure 2.3.

2.1 Load leveling

Figure 2.3 shows the result of a perfect load leveling of the total line load with the storage unit connected. With storage energy and power capacity at their maximum (42.5 MWh and 2.5 MW), the charge and discharge setpoints were set at the average load value of the primary load profile.

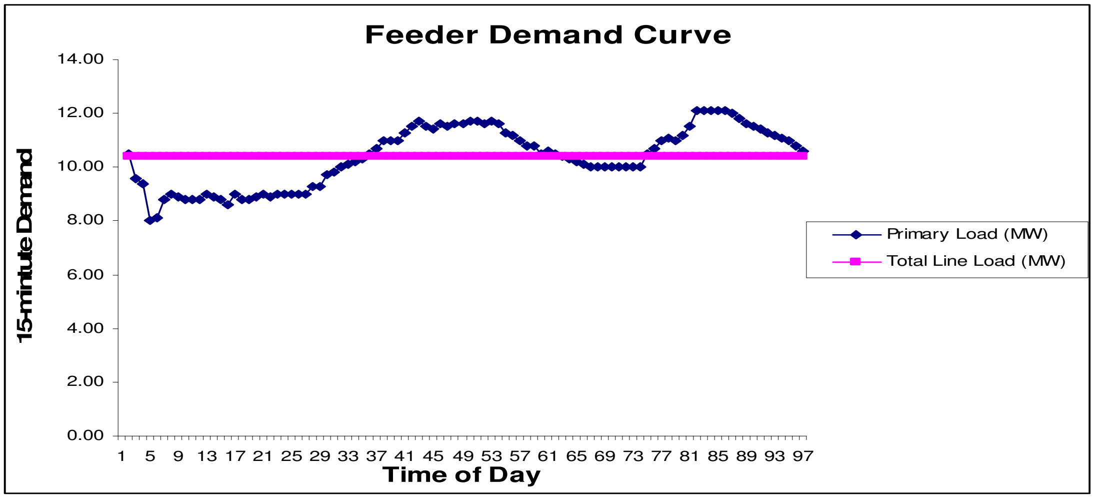


Figure 2.3: Perfect Load Leveling

Fortunately, there was enough energy stored whenever possible (primary load lower than average load) and in turn discharged whenever needed (primary load greater than average load) to compensate for the excess load demanded, which enabled compete load leveling of the primary load profile. Later in this report it is shown that the smaller the charge/discharge gap or bandwidth is from or around the average load, the better the load leveling capabilities of the storage unit.

CHAPTER 3

METHODOLOGY

Figure 3.1 [3] shows a substation connected to a load bus by a feeder. To the bus are connected the primary load with a load sensor, which registers the value of primary load, and an energy storage unit. Power from the substation flows through the feeder to the load bus with the intention of meeting an ever fluctuating primary load demand, such as that shown in Figure 2.2. Without the energy storage unit, the substation produces power by following the fluctuating primary load demand, which means that the substation fluctuates in its power production. One major aspect of the storage unit is to eliminate this fluctuation in power production by maintaining a constant line load on the feeder that the substation 'sees'. By achieving this objective, the substation no longer has to supply peak load since the needed capacity of transformers, lines, and equipment is lowered with a flat-load profile. This aspect of the storage unit is known as load leveling.

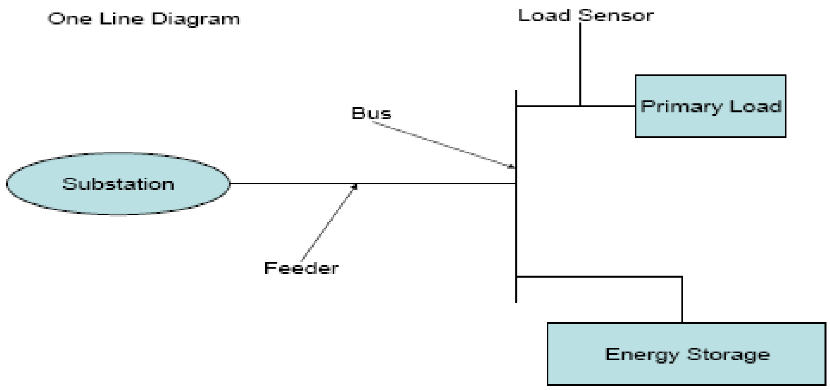


Figure 3.1: One Line Diagram [3]

The controller, as shown in Figure 3.2 [3], manages the functions of the storage unit to make it efficient and reliable in achieving its load-leveling objective. Using the inputs from the load sensor and charge-discharge setpoints, it controls how and when the storage unit stores energy, when the primary load is low, and discharges energy, when the primary load is at peak levels, to the feeder to keep it at a constant load, and as a result, enables the substation to produce constant power. When the primary load demand is low, part of the power capacity of the substation and line go unused, and during this period, the storage unit charges itself with the unused capacity. During peak demand, power from the substation is lower than demanded, and during this time that the storage unit discharges the previously stored energy to compensate for the excess power demanded, thereby keeping the total load on the feeder at a constant.

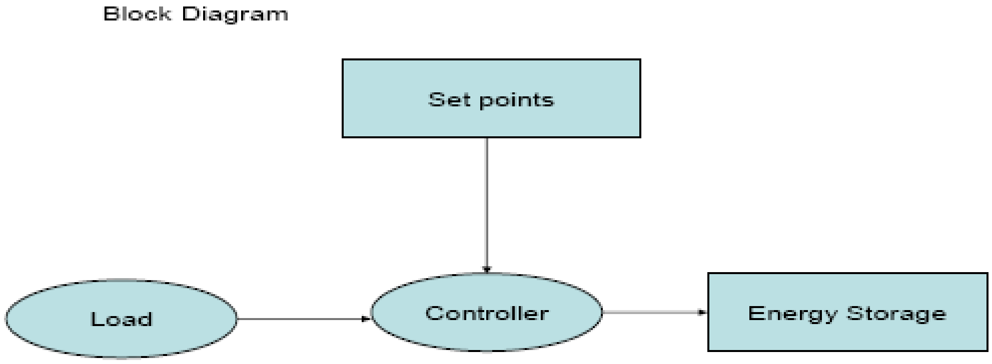


Figure 3.2: Block Diagram [3]

3.1 Simulation

The controller was simulated in a spreadsheet program, part of which is shown in Tables 3.1 and 3.2. The controller settings governing the operation of the storage unit are as follows:

Storage Energy Capacity

Storage energy capacity is the maximum amount of energy that can be stored by the storage unit beyond which there can be no further charging. After this energy capacity is reached, the storage unit goes ‘offline’ during instances where energy is available for charging and only comes ‘online’ when the circumstance demands energy discharge (i.e., when the primary load is above the average line load about which the charge-discharge bandwidth is set).

Storage Power Capacity

Storage power capacity is the maximum power at which the storage unit can charge or discharge at any given time time. This means that the storage unit can charge or discharge power equal to or less than this value at any time. For the case where the capacity available for charging is greater than this value, the unit only stores at the maximum capacity. In the case of a discharge, it only releases power at the maximum capacity, even when the power needed is more than its capacity.

Charge Setpoint

Charge setpoint is a preset load value, which sets the condition that controls when and how the storage unit stores energy from the feeder if there is storage space. When the primary load falls below this value, the storage unit goes into the charging mode and attempts to store energy by an amount equivalent to the difference between the average load and the primary load values. When the primary load is equal to or greater than this setpoint the storage unit leaves the charge mode. This is illustrated in Figure 3.3.

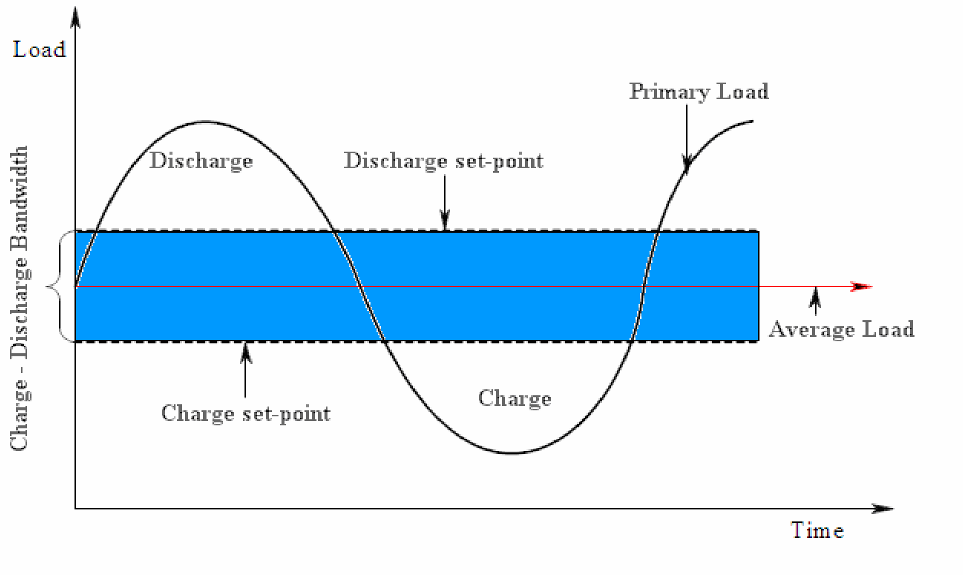


Figure 3.3: Storage Unit Operation

Discharge Setpoint

Discharge setpoint is a preset load value, which sets the condition that governs how and when the storage unit discharges energy to the feeder. When the primary load is greater than this value, the storage unit discharges energy to compensate for the excess energy demanded, which is the difference between the primary load and the average load. When the storage unit is depleted of energy before this instance, then the storage unit does nothing or goes ‘offline.’ Figure 3.3 illustrates this phenomenon.

3.2 Explanation of Data Columns in Spreadsheet

Table 1 shows an example of the spreadsheet used to run the simulations. The columns in Table 1 and 2 are explained.

Table 3.1: Spreadsheet Example

Column A	**Column B**	**Column C**	**Column D**	**Column E**	**Column F**
Load Timer (minutes)	Primary Load (MW)	Required Power Input (+) or Output (-) (MW)	Feasible Required Power Charged/Discharged (MW)	Actual Power Input (+) or Output (-) (MW)	Stored Energy (MW)
					0.10
0:00	10.50	-0.10	-0.10	-0.10	-0.10
0:15	9.60	0.80	0.50	0.50	0.40
0:30	9.40	1.00	0.50	0.50	0.90
0:45	8.00	2.40	0.50	0.50	1.40

Column A: Load timer (15-minute increments).

Column B: Primary Load. A 15-minute duration load on the feeder.

Column C: Required Power (MW) Input (+) or Output (-). The power available for charging, or required for discharge, to compensate for the excess energy demanded to maintain a constant total line load. It is the difference between the primary load and the charge or discharge setpoint. An IF statement checks if a primary load (B) is lower than the charge setpoint (B$4) and whether the amount of energy stored (F) in the storage unit is not up to full storage capacity (B$2). If both conditions are true, then (10.4 minus B) MW is available for storage. If either or both conditions are false, then the second statement is checked, the primary load (B) is checked against the discharge set-point (B$5) and the storage unit checked for available stored energy (F>0). If the primary load is greater than the discharge setpoint and there is available stored energy, then the amount of power needed to compensate for excess demand is (B minus 10.4). In the case where both conditions are false, the storage unit does nothing or goes 'offline'.

Column D: Feasible Required Power (MW) Charged/Discharged. The power that can be feasibly charged to the storage unit or discharged by it for load compensation. An IF statement checks the sign of the result of column C (C>0): a positive sign is an indication that the power is available for storage; otherwise it is the power needed for discharge to maintain constant total line load. Before charging, the available power is checked against the storage power capacity (B$3), and if it is lower, then storage is possible. Otherwise, power that is equivalent to the storage power capacity is stored. The same is true in the case of a power discharge.

Column E: Actual Power (MW) Input (+) or Output (-). The power that is charged to or discharged from the storage unit. (B$2 minus F) is the available storage space and is compared with the available feasible energy that can be stored. Should the feasible energy be more than the storage space then an amount of energy equal to that of the storage space is charged to the unit to its limit. If the feasible energy is less than the storage space, the unit stores the feasible energy. In the same way, if the energy needed to be discharged is greater than the residual energy (D), then the residual energy is discharged to the feeder for load compensation; but should the opposite be true, then the feasible energy required is discharged to help maintain a constant total line load.

Column F: Stored Energy (MW). This is the cumulative sum of the energy stored by the unit minus that which has been discharged to the feeder during the course of its operation so far.

Table 3.2: Spreadsheet Example (continued)

Column G	Column H	Column I	Column J	Column K
Excess Power (MW)	Total Line Load (MW)	Power Deviation (MW)	Power Deviation II (MW)	Load-Leveling Percentage (%)
0.00	10.40	0.00	0	42.3245614
0.30	10.10	-0.30	0.3	
0.50	9.90	-0.50	0.5	
1.90	8.50	-1.90	1.9	
1.80	8.60	-1.80	1.8	

Column G: Excess power (MW). In the case of charging, it is the difference between the amount of power available for storage and the actual amount of power stored by the unit. This excess power is unused capacity. For a discharge, it is the difference between the power demanded by the primary load to maintain a constant total line load at a preset average load and the actual power discharged by the storage unit.

Column H: Total Line Load (MW). The sum of all the loads on the feeder (i.e., the primary load and the energy stored by the unit).

Column I: Power Deviation (MW). A measure, in terms of power, of how far the total line load has strayed from the ideal result (as seen in Figure 2.3) and also shows the cause of the deviation. A positive value means that available energy on the feeder was not charged to the storage unit. A negative value means that energy demanded by the primary load, to maintain a constant total line load at a value of the average load, was not met. At the end of the column the cumulative sum is calculated which gives an idea of which of the two cases occurs most often.

Column J: Power Deviation II (MW). A measure of how far, in terms of power, the total line load has strayed from the ideal result (average load) for a particular primary load. The ideal result is to keep the total line load at a constant value of the preset average load.

Column K: Load-Leveling Percentage (%). This is the percentage of the primary load profile for which load leveling has been successfully achieved.

CHAPTER 4

LIMITATIONS OF PREVIOUS RESEARCH

One aspect of the objective of adding a storage unit to the line is to decrease the need for load following by the power source. By keeping the total line load constant through the process of charging and discharging the storage unit, the source can be made to supply constant power. To achieve this objective the storage unit will have to be designed with certain control capabilities and the research done to make this possible is what this thesis is about. The previous research made improvements in leveling the load of the total line but had problems achieving a complete load leveling of the primary load profile. The drawbacks are discussed next.

4.1 Drawbacks in previous work [3]

Storage Power Capacity

A notable problem in storage power capacity was that the storage power capacity was set to constant of 1 MW. This means that the storage unit only charged or discharged power at a constant value and this was often lower or higher than the required or available power. Therefore, getting the line load to stabilize around an average value was impossible. This is shown in one example from [3]. Using the control setpoints of Table 4.1, a simulation is ran which generate the result in Figure 4.1.

Table 4.1: Set-Points of Previous Work [3]

Storage Energy Capacity (MWh)	30
Storage Power Capacity (MW)	1.00
Charge Setpoint (MW)	9.00
Discharge Setpoint (MW)	11.00

The total line load, leveled by storage, shown in Figure 4.1 follows the primary load most of the time with little exceptions at the 7-22 and 41-53 minute gaps where load leveling seem to be achieved. This is because the Storage Unit charges or discharges at a constant capacity of 1 MW. This means that even when more than 1 MW of charge/discharge is needed, 1 MW is still provided. When a charge or discharge lesser than 1 MW is needed, the unit goes ‘offline’ or does nothing. This results in the uneven nature of load leveling shown.

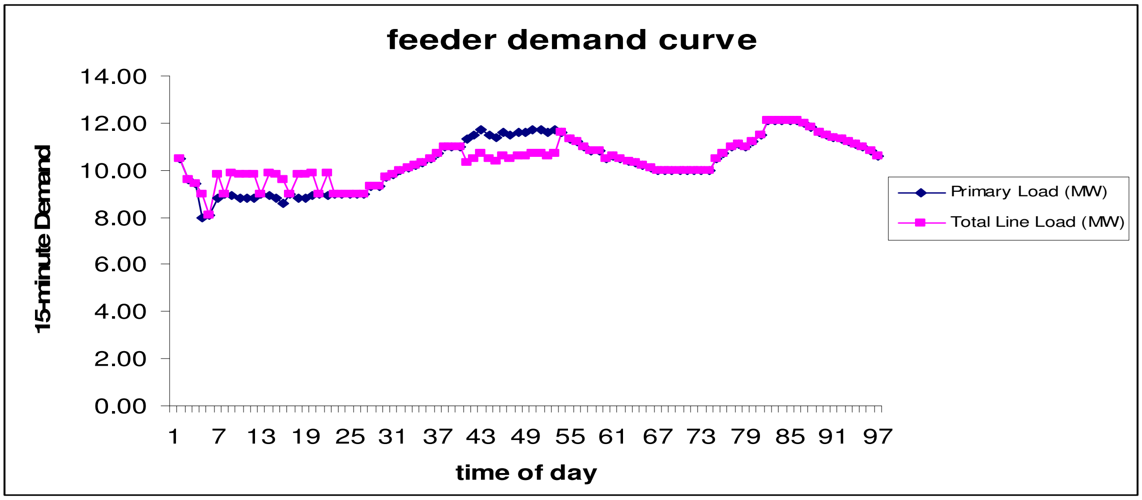


Figure 4.1: Load Leveling of Previous Work [3]

4.2 Modifications to Previous Work

The first modification was to make an allowance that enabled the storage unit to vary its charge or discharge rate in discrete increments of 0.1 MW. The plot of Figure 4.2 shows the result. As can be seen, the total line load is leveled around the average primary demand of 10.4 MW, except for the 22-37 and 85-97 minute intervals, where it follows the primary load. The reason for this is that the storage energy capacity was reached and therefore additional charging was impossible for the 22-37 minute interval. The storage unit was completely depleted of energy and therefore no discharge was possible to enable load leveling for the 85-97 minute interval.

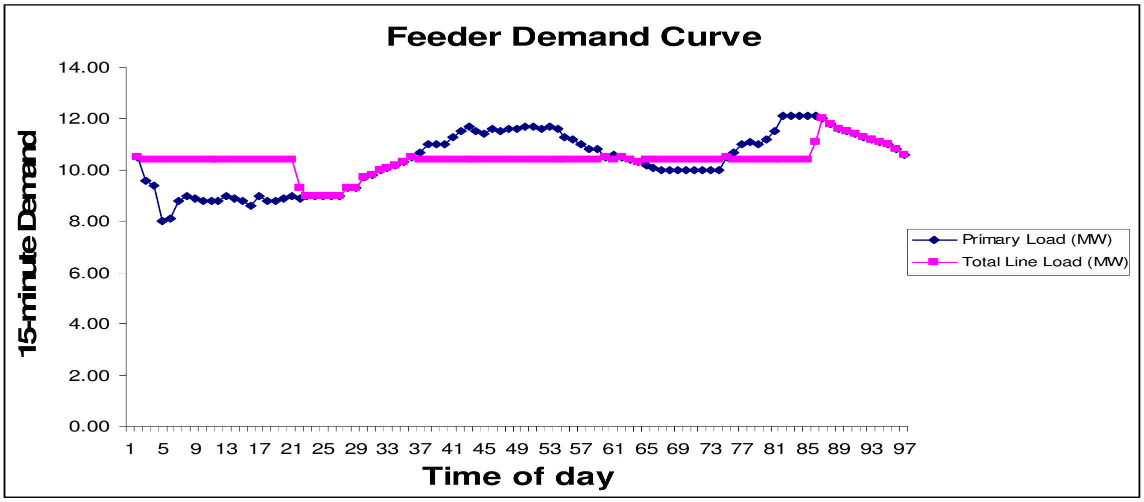


Figure 4.2: Load Leveling at Maximum Power Capacity

Therefore, the next step was to increase the storage energy capacity to a higher value. The plot of Figure 4.3 shows that it is possible to keep the line load constant. The load leveling of the total line load looks almost perfect, except for a few disparities at 35-36, 60-64 and 75 minute intervals. This was due to the charge-discharge setpoint bandwidth. For every primary load that falls within this bandwidth, the storage unit is 'offline,' and the total line load follows the primary load during the time interval of that particular primary load. Load leveling is ineffective during such an instant.

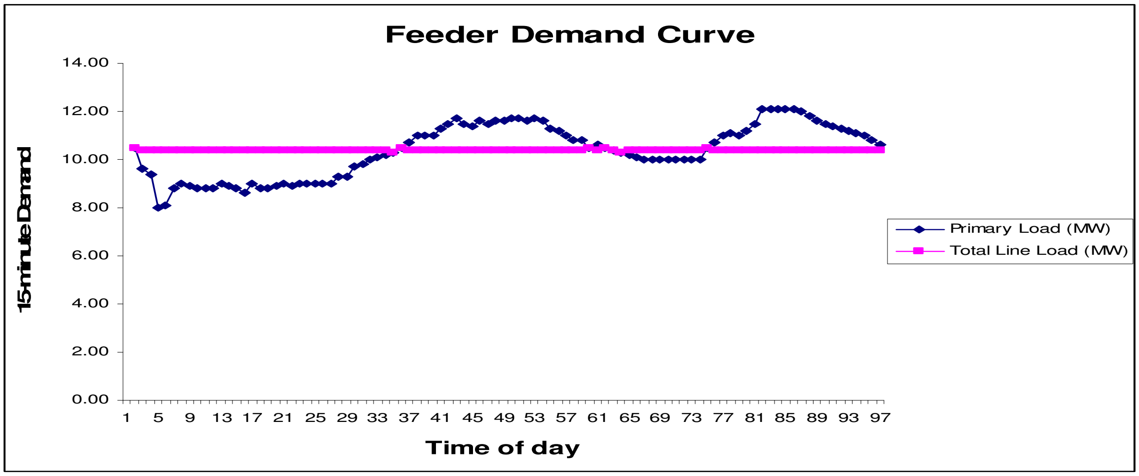


Figure 4.3: Load Leveling with Increased Storage Energy Capacity

With no bandwidth we get a perfect total load line that is leveled at average primary load as is seen in Figure 2.3.

Chapter 5 discusses the effects of varying the control variable setpoints.

CHAPTER 5

EFFECTS OF VARYING CONTROL VARIABLES

To make this concept the most economically viable, energy and power capacities were kept to a minimum in lieu of the main objective – load leveling. To help achieve this, each control variable wad varied while simultaneously keeping the others constant, and the effects were analyzed with the goal of finding some *referenced values* that would give desirable load leveling capabilities with low storage system capacities.

Optimal Variables

These are the control variable settings that produce the ideal result of a constant total line load or perfect load leveling (see Figure 2.3) are as follows:

Storage Energy Capacity (MWh): 42.50

Storage Power Capacity (MW): 2.40

Charge Setpoint (MW): 10.40

Discharge Setpoint (MW): 10.40

With these control values, load leveling was shown to be 100 percent both from Figure 2.3 and the spreadsheet. Also, there was 0 MW power deviation II from the ideal result, as shown by the spreadsheet.

5.1 Varying Charge and Discharge Setpoints

Keeping everything else constant, the charge and discharge setpoints were initially varied by a difference of 0.2 MW (this increased the bandwidth by a margin of 0.4 MW) to see how results were affected.

Charge Setpoint (MW): 10.20 and Discharge Setpoint (MW): 10.60

There were very small disparities as shown in Figure 5.1, at 2, 34-36, 60-65, 75 and 97 minute periods where there was no load following or the storage unit was ‘offline’. The primary load values at these periods fall within the charge/discharge bandwidth. Within the bandwidth, they are neither higher than the discharge setpoint nor lower than the charge setpoint and so nothing happens with the storage unit and is coined ‘offline’. There is 1.5 MW power deviation II from the ideal case and 98.4 percent load leveling.

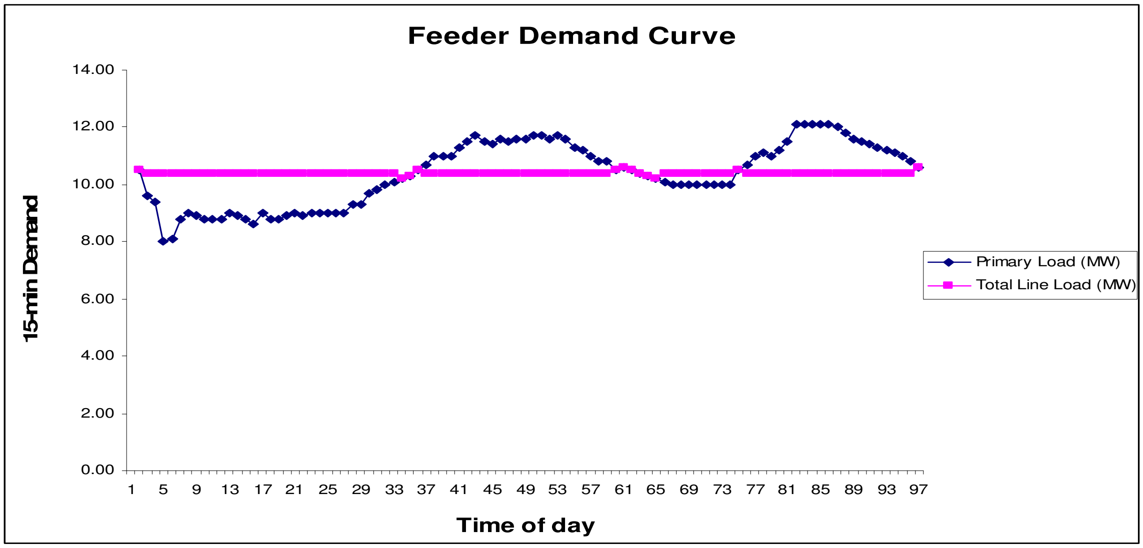


Figure 5.1: Load Leveling at 0.4 MW Charge-Discharge Bandwidth

Charge Setpoint (MW): 10.00 and Discharge Setpoint (MW): 10.80

The levels of disparities increased in Figure 5.2, compared to Figure 5.1, at 32-37, 58-76, and 95-97 minute intervals. With a larger bandwidth, more of the primary load values fell into this gap that puts the storage unit ‘offline,’ and therefore no load leveling occurred at these periods. This caused an increasing level of periods where there was no load leveling. There was 8 MW power deviation II from the ideal case resulting in a 91.2 percent load leveling.

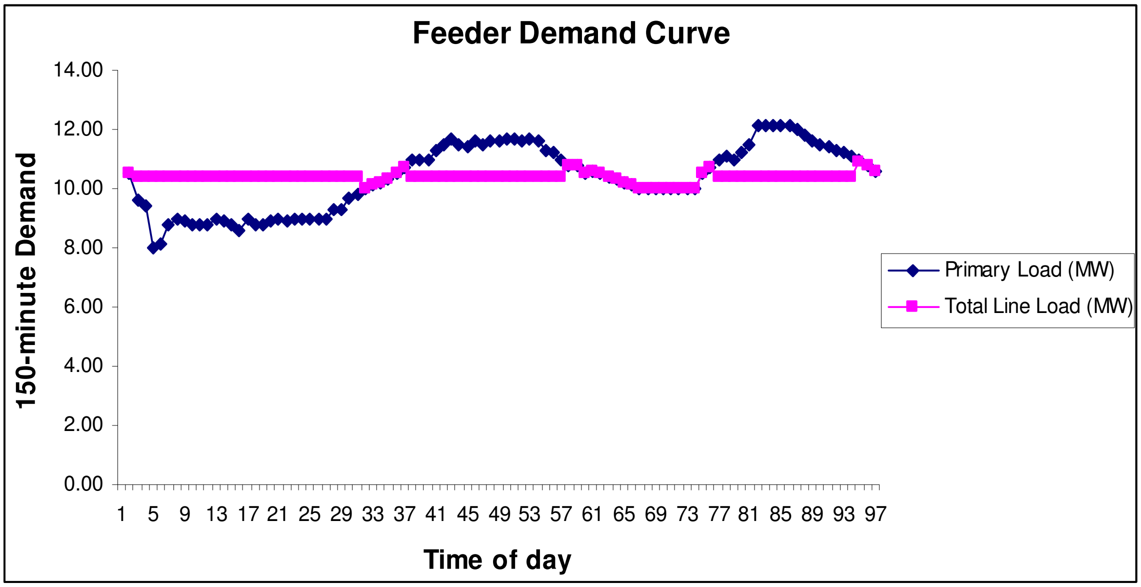


Figure 5.2: Load Leveling at 0.8 MW Charge-Discharge Bandwidth

Charge Setpoint (MW): 9.8 and Discharge Setpoint (MW): 11.00

The areas or periods of no load leveling, as shown in Figure 5.3, increased with storage unit 'offline' gaps at 31-40, 57-80, and 95-97 minutes. The degree of load leveling decreased and the storage unit was utilized less. There was 12.3 MW power deviation II and 86.5 percent load leveling.

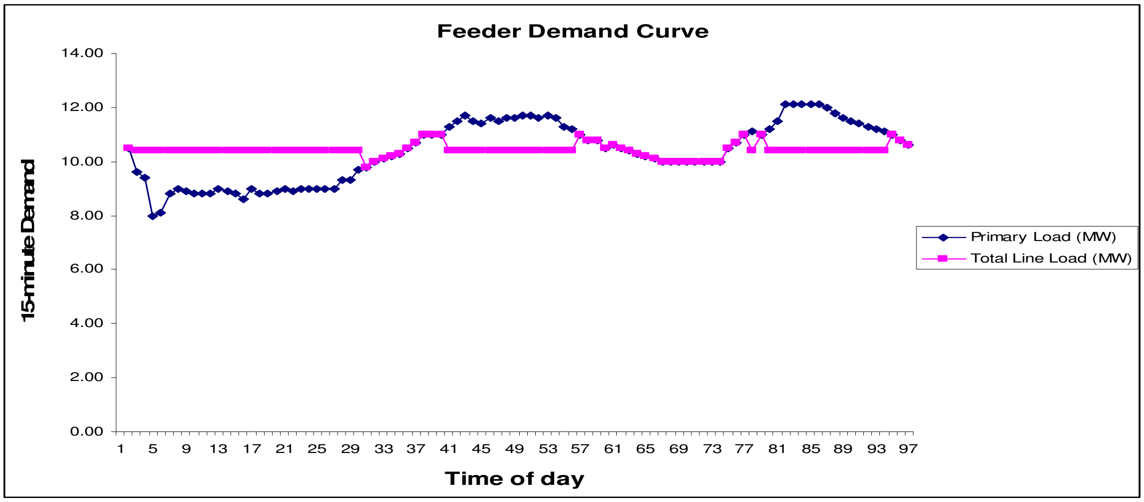


Figure 5.3: Load Leveling at 1.2 MW Charge-Discharge Bandwidth

Charge Setpoint (MW): 9.5 and Discharge Setpoint (MW): 11.30

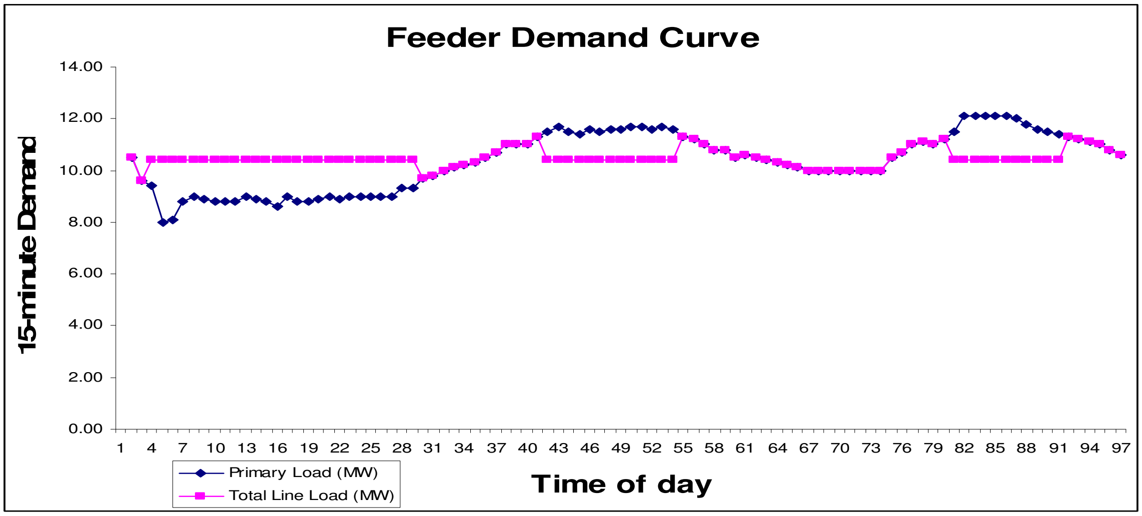


Figure 5.4: Load Leveling at 1.8 MW Charge-Discharge Bandwidth

The trend of an increase in ‘offline’ gaps in Figure 5.4, increased as the charge-discharge bandwidth was increased resulting in a decreasing level of load leveling. There was 77.7 percent load leveling with an accompanying 20.3 MW power deviation II.

Charge Setpoint (MW): 8.00 and Discharge Setpoint (MW): 12.10

After setting the charge and discharge setpoints to extreme limits in Figure 5.5, it can be seen that the storage was totally ‘offline’. There was no charge or discharge by the storage unit.

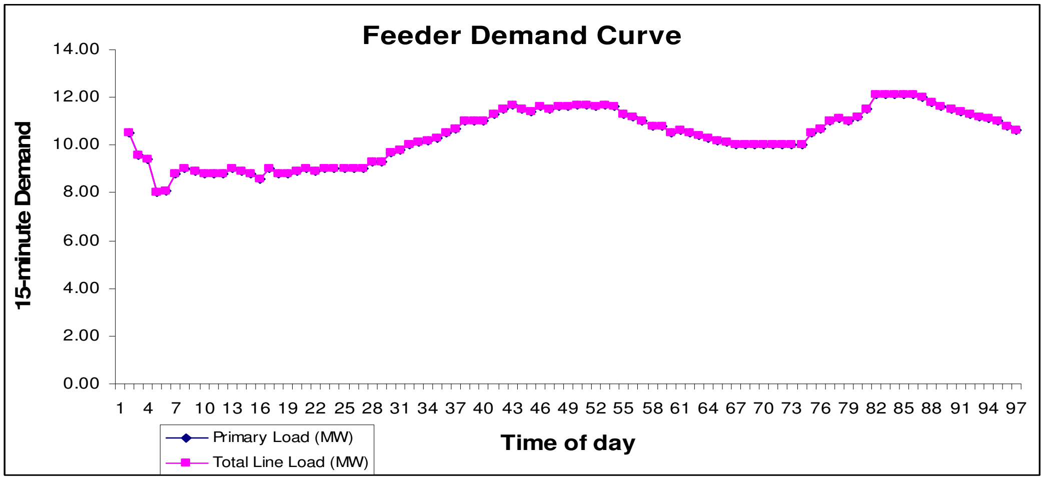


Figure 5.5: Load Leveling at 4.10 MW Charge-Discharge Bandwidth

It can be seen that the total line load completely followed the entire primary load profile. There was no load leveling. Evidently there was 0 percent load leveling and a power deviation II of 91.2 MW from the ideal scenario.

Conclusion

Under the condition that optimal storage energy (42.5 MWh) and optimal power capacity (2.50MW) are held constant, the following conclusions can be made about the effects of varying charge and discharge setpoints.

For a given load profile, increasing the charge-discharge setpoint bandwidth will cause the storage unit to do the following;

A. Store less power because the amount of the load profile falling below the charge setpoint decreases.

B. Discharge less power because the amount of the load profile falling above the discharge setpoint decreases.

For a favorable degree of load leveling, the charge-discharge bandwidth must be kept relatively small about the load value around which leveling is to be done. As can be inferred from the results above, the degree of utilizing the storage unit can be decreased or increased by increasing or decreasing the charge-discharge bandwidth respectively.

Whenever load leveling capabilities are completely lost, the total line load follows the primary load profile.

5.2. Varying Energy Storage Capacity

Keeping other control variables constant, the energy storage capacity was varied and the effects analyzed. The charge and discharge setpoints were at 10.4 MW which provided no bandwidth.

Storage Energy Capacity (MWh): 40.0

It can be seen in Figure 6.1 that reducing the storage energy capacity had adverse effects on load leveling at the 29-35 and 95-97 minute intervals. During the 29-35 minute interval, the storage unit was fully charged at the new storage capacity of 40 MWh and the excess energy resulting from the primary load being lesser than the average demand load stays on the line. At this point, the storage unit went 'offline' and there was no load-leveling attempt; therefore the total line load followed the primary load until the load profile went above the discharge setpoint and the storage unit began to discharge. For the case of the 95-97 minute interval, the total line load followed the primary load as a result of the storage unit being completely discharged. The storage unit was unable to compensate any excess load demanded with the primary load being greater than the average load demand. This storage energy capacity of 40 MW gave 96.3 percent of load leveling and a 3.4 MW power deviation II.

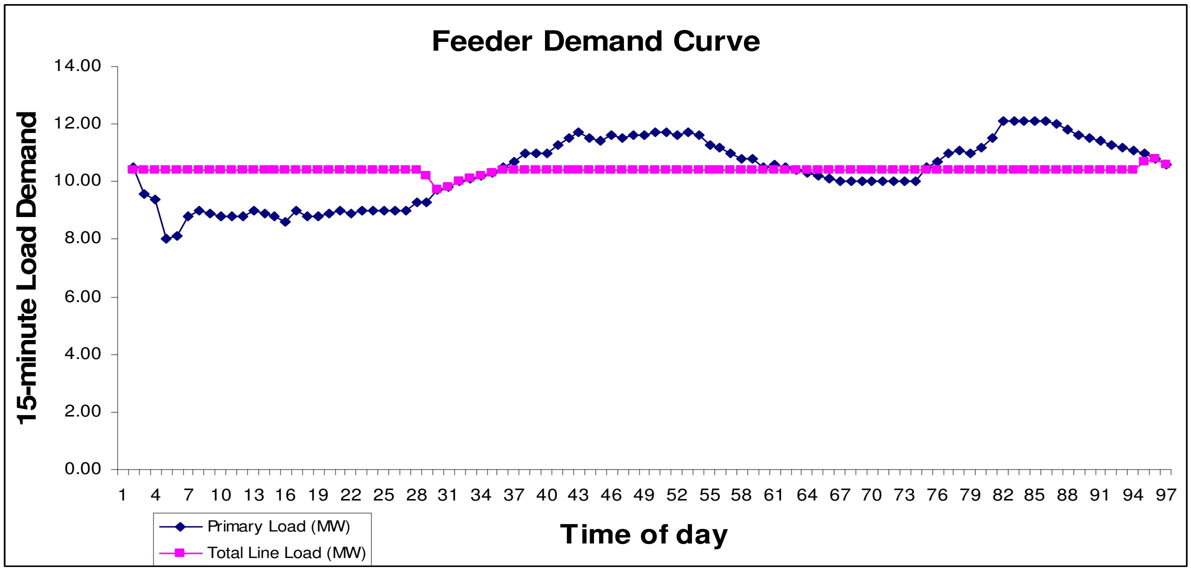


Figure 6.1: Load Leveling at 40 MWh Storage Energy Capacity

Storage Energy Capacity (MWh): 38.0

With the storage energy capacity further reduced, as shown in Figure 6.2, a minute increase in 'offline' mode was noticed from 28th-39th minute interval as a result of the storage unit being fully charged. There was also a three-minute increase in 'offline' mode at 92-97 minute interval due to complete depletion of the storage unit. Load leveling was adversely affected. This resulted in a 91.9 percent of load leveling coupled with 7.4 MW of power deviation II.

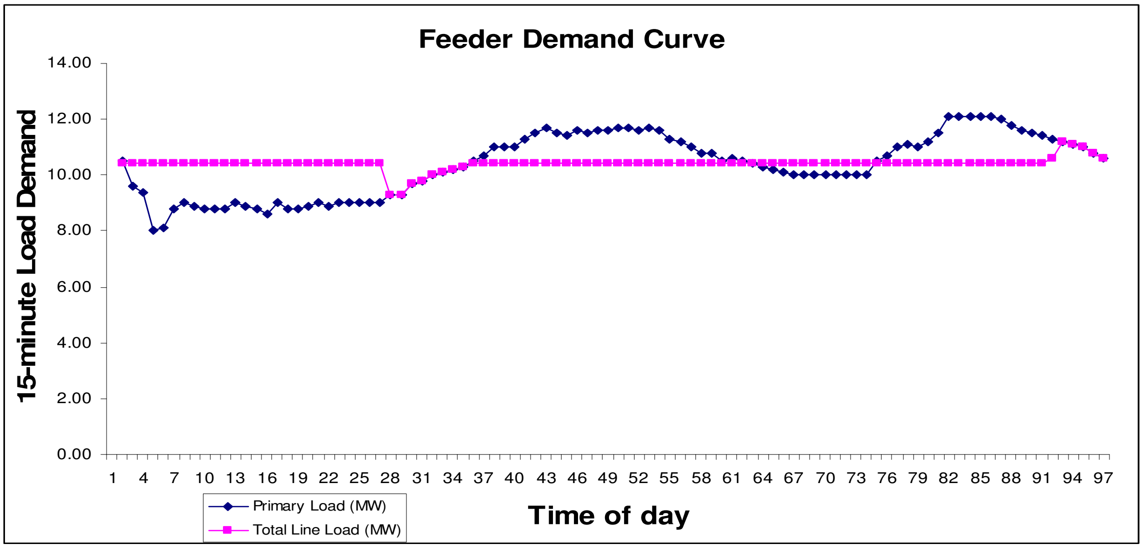


Figure 6.2: Load Leveling at 38 MWh Storage Energy Capacity

Storage Energy Capacity [MWh]: 35.0

With the storage energy capacity further decreased, as shown in Fig 6.3, the storage unit reached its maximum energy capacity limit much faster and went 'offline' during the 25-35 minute interval since it could not be charged anymore. The excess energy available for storage stayed on the feeder, and load leveling during this period was not achieved. Also the storage unit was depleted faster, compared to that shown in Figure 6.2, and could not compensate for excess energy demanded by the primary load during the 89-97 minute interval because it was 'offline,' and there was no load leveling. Load leveling was 85.3percent as a result of 13.4 MW of power deviation II from the ideal case.

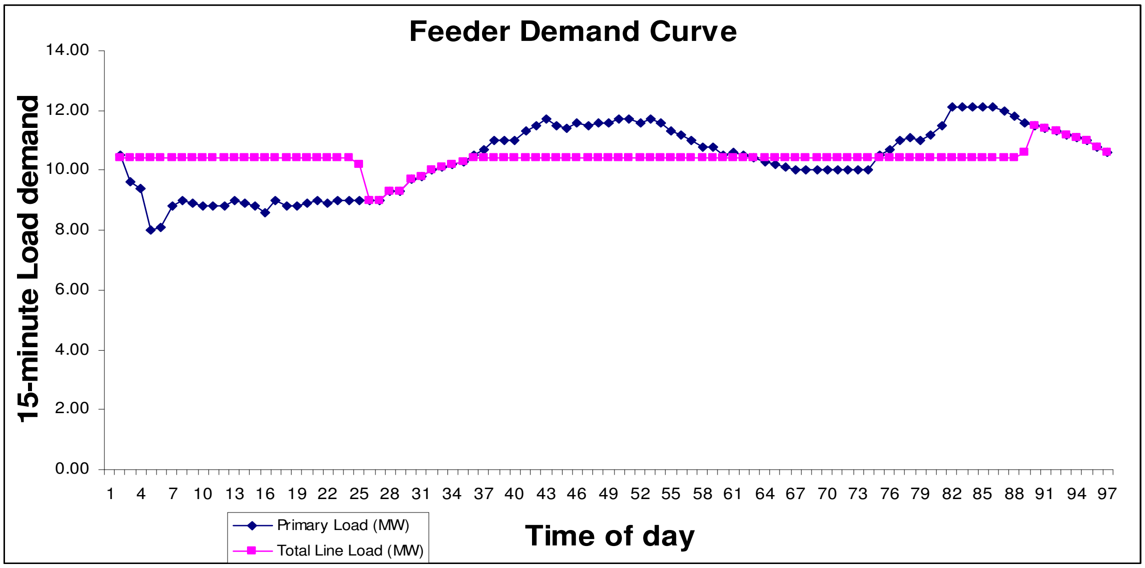


Figure 6.3: Load Leveling at 35 MWh Storage Energy Capacity

Storage Energy Capacity (MWh): 32.0

After the 22nd minute, as shown in Figure 6.4, the storage unit was fully charged and went 'offline' until the 35th minute when it began to discharge power. During the 22-35 minute interval period the primary load was lesser than the average load and there was available power that could not be stored. Therefore it remained on the feeder. After the 35th minute the primary load was greater than the average load and the storage unit went into compensating for the excess load demand by discharging power and load leveling was achieved. After the 85th minute, load leveling was lost since the storage was completed depleted of stored energy and could not compensate for the excess energy demanded by the primary load. The spreadsheet shows that 78.7 percent of load leveling occurred with 19.4 MW of power deviation II.

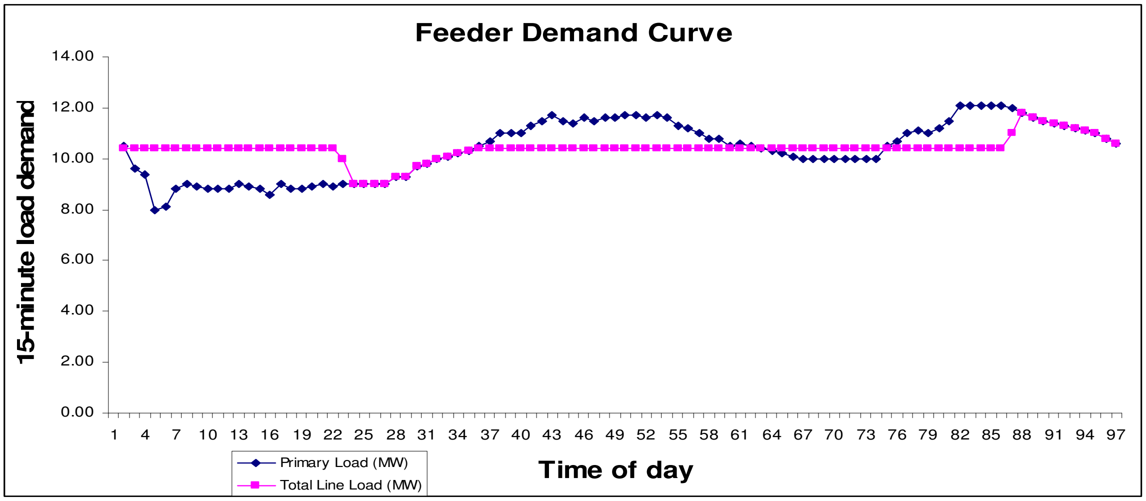


Figure 6.4: Load Leveling at 32 MWh Storage Energy Capacity

Storage Energy Capacity (MWh): 30.0

As shown in Figure 6.5, the storage unit was fully charged at the 21st minute and completely depleted of stored energy after the 86th minute. There was a power deviation II of 23.4 MW and 74.3 percent of load leveling.

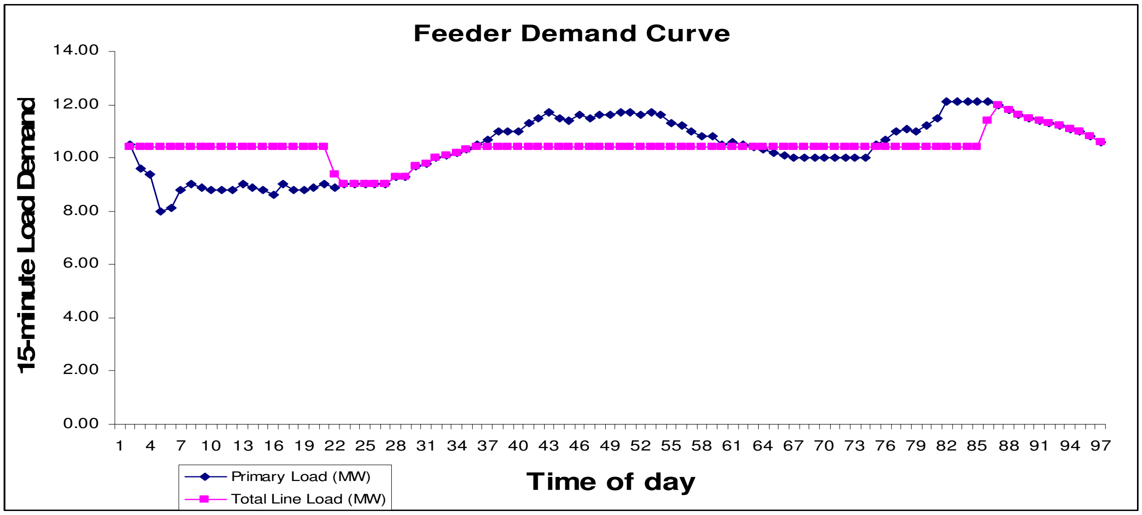


Figure 6.5: Load Leveling at 30 MWh Storage Energy Capacity

Storage Energy Capacity (MWh): 20.0

As the storage energy capacity was further decreased, as shown in Figure 6.6, the storage unit exhausted its storage energy capacity faster. This happened under the 14 minutes. Then excess energy available for storage went unused and load-leveling capability was lost until the 35th minute when the primary load profile became greater than the average load and caused the storage unit to discharge energy.

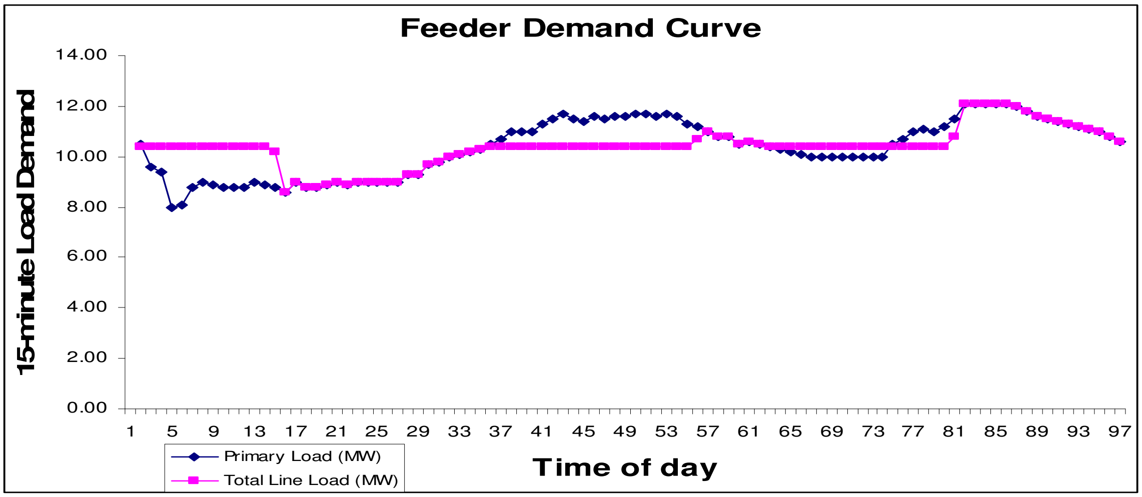


Figure 6.6: Load Leveling at 20 MWh Storage Energy Capacity

Since the amount of energy stored decreased with decreasing storage energy capacity, the time period of compensation for excess energy demanded by the primary was less compared to that shown in Figure 6.5. This is apparent as the storage unit went 'offline' after the 80th minute. It is interesting to note another 'offline' period at 56 – 62 minute interval. This is because, even though the unit depleted itself of stored energy by the 56th minute, it started storing energy at the 63-75 minute interval where the primary load profile was below the average load. The spreadsheet shows that 52.4 percent of load leveling occurred at 43.4 MW of power deviation II.

Conclusion

It appears advantageous to have the storage energy capacity be as large as possible, in order to avoid missing any opportunity to charge, and therefore useful for a future discharge. The tradeoff is that higher capacity costs more, so a better idea is to optimize storage capacity versus cost and the need to completely level the primary load profile.

5.3. Varying Storage Power Capacity

Keeping all other control variables constant, the storage power capacity was varied and the results analyzed.

Storage Power Capacity (MW): 2.20

Reducing the power capacity by 0.2 MW had almost no adverse effect on load leveling except at the 5th and 6th minute periods where the storage unit was charged by 0.2 MW and 0.1 MW less, respectively, than the power needed for complete load leveling. At 2.20 MW power capacity, the difference between Figure 7.1 and Figure 2.3 could be considered insignificant. There is 99.7 percent of load leveling and 0.3 MW of power deviation II.

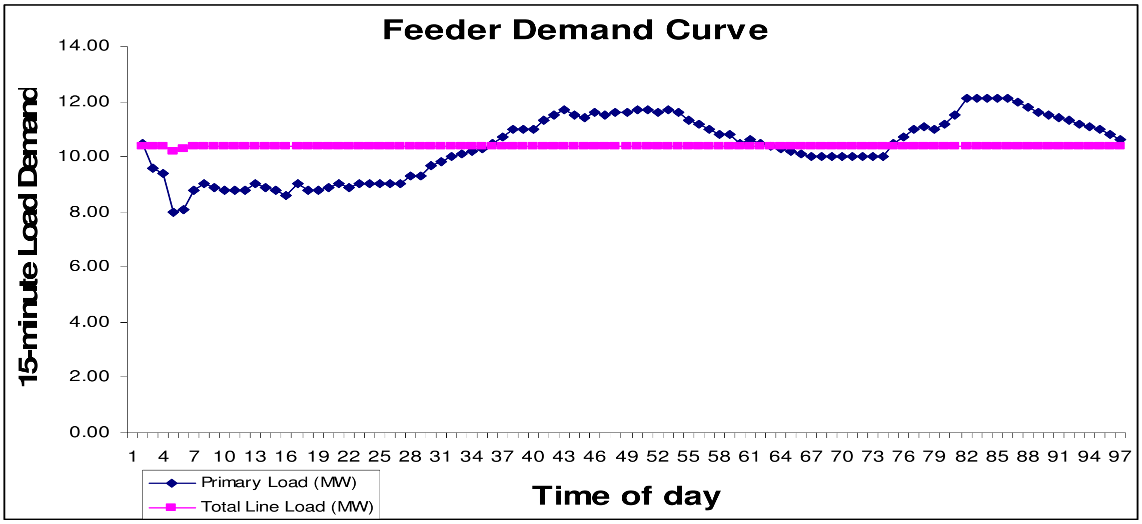


Figure 7.1: Load Leveling at 2.2 MW Storage Power Capacity

Storage Power Capacity (MW): 2.0

Results here were fairly similar to that of shown in Figure 7.1 except at the 5th and 6th minute periods where there was less charging since the power capacity was reduced. This explains why the 'dip' in the plot is bigger in Figure 7.2 compared to Figure 7.1. This power capacity gave a 99.2 percent of load leveling and 0.7 MW of power deviation II.

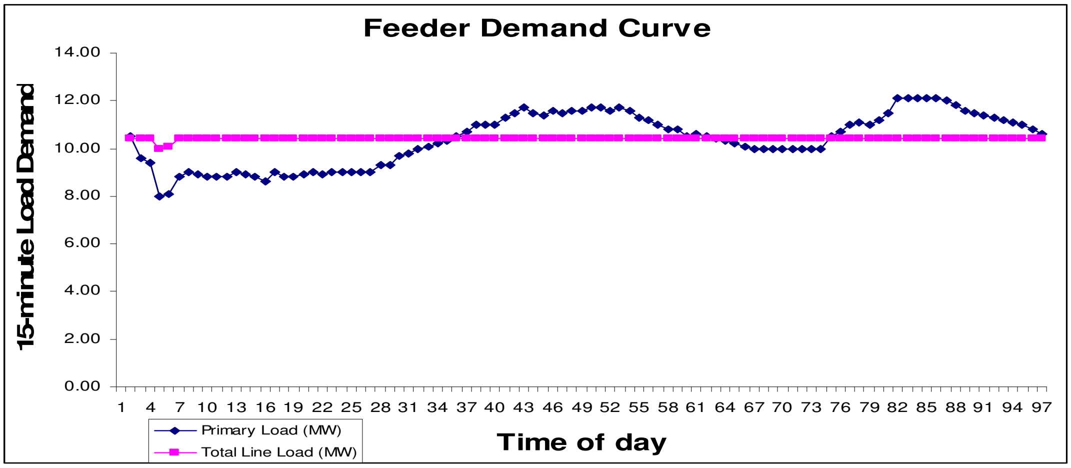


Figure 7.2: Load Leveling at 2.0 MW Storage Power Capacity

Storage Power Capacity (MW): 1.8

At a power capacity of 1.8 MW, the load profile generated similar results, with the 'dip' at the 5th and 6th minute periods slightly larger than that shown in Figure 7.2. There is a lower charge rate with reduced power capacity. A power capacity of 1.8 MW would be more economically viable since a lower power capacity might reduce cost. This resulted in a power deviation II from the ideal by 1.1 MW resulting in 98.8 percent load leveling.

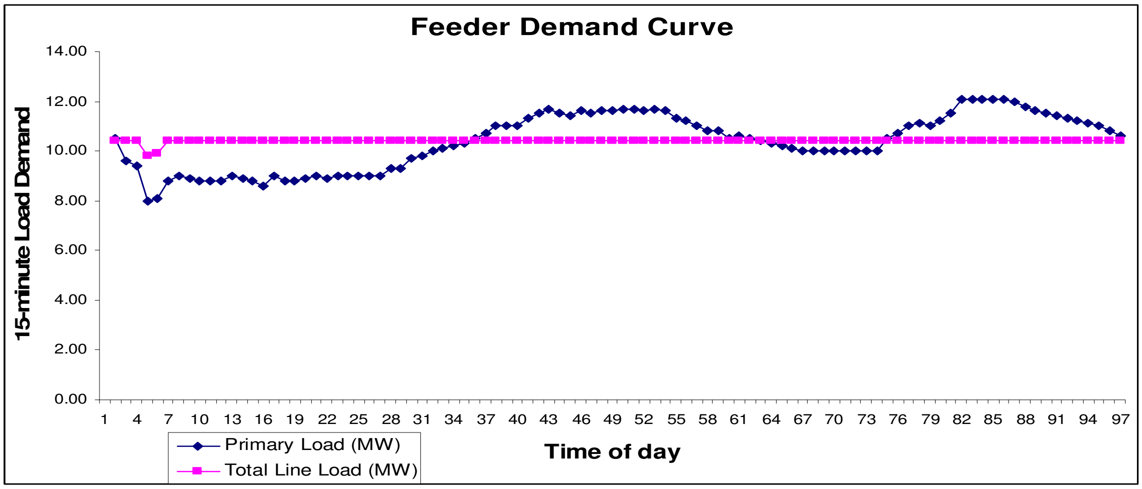


Figure 7.3: Load Leveling at 1.8 MW Storage Power Capacity

Storage Power Capacity (MW): 1.6

As the power capacity was further reduced, as shown in Figure 7.4, the less amount of power charged and the 'dip' at the 5th and 6th minute became larger. This plot is fairly similar to previous plots, except at the 16th minute and 82-86 minute interval where discharge power capacity was less than that required by the load profile. The level of load leveling was very high, with the total line kept constant at the average load throughout the entire load profile. As a result it could be considered, relative to cost, that a 1.6 MW power capacity would be a good control setpoint to work with in achieving a desirably high level of load leveling. This results in a 97.6 percent load leveling with 2.2 MW of power deviation II.

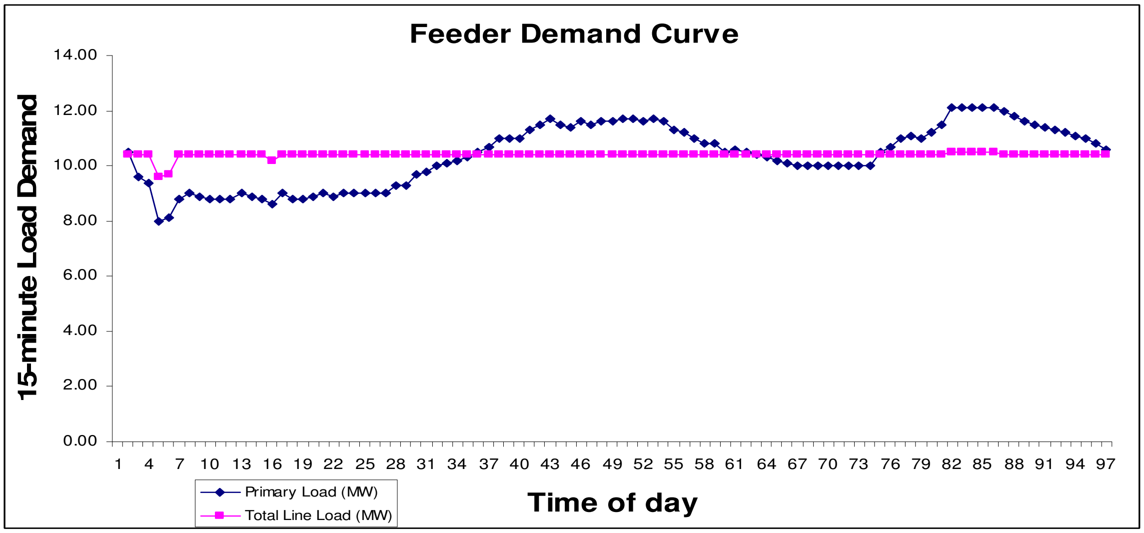


Figure 7.4: Load Leveling at 1.6 MW Storage Power Capacity

Storage Power Capacity (MW): 1.4

The plot for the total line load, as shown in Figure 7.5, became more distorted, most of which were very close to the average load, as the power capacity was further reduced. But on average, the total line load appears to be mostly controlled around the average load. There is a load leveling of 92.8 percent and a power deviation II of 6.6 MW.

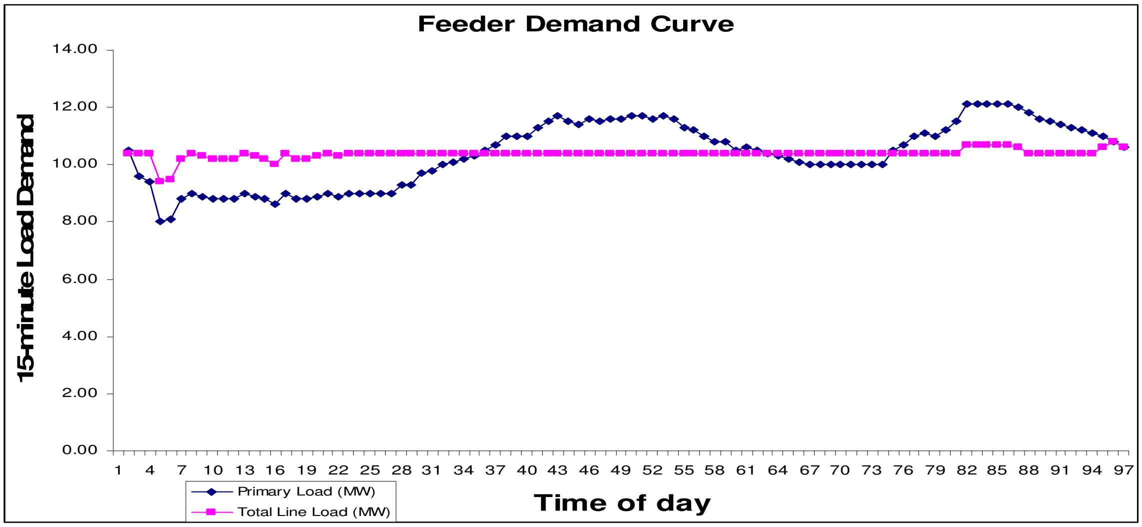


Figure 7.5: Load Leveling at 1.4 MW Storage Power Capacity

Storage Power Capacity (MW): 1.0

The distortions, shown in Figure 7.5, were becoming significant at 1.0 MW power capacity and load leveling was adversely affected. With this power capacity, the power deviation II is 25.4 MW, resulting in 72.1 percent load leveling. The deviation was quite large with this capacity.

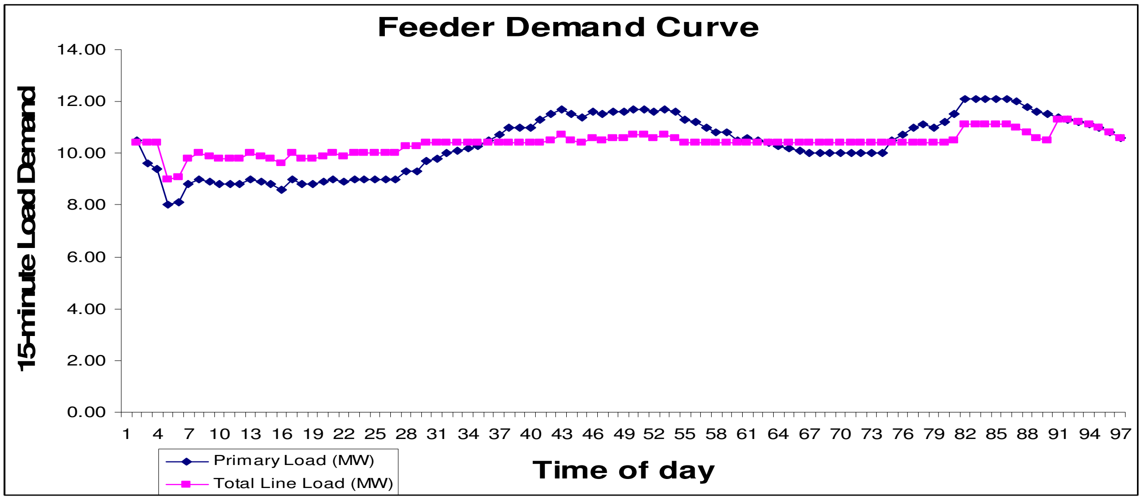


Figure 7.6: Load Leveling at 1.0 MW Storage Power Capacity

Storage Power Capacity (MW): 0.5

At a capacity of 0.5 MW, the total line load practically followed the primary load, as shown in Figure 7.7. The power capacity was so low that energy stored was not enough to compensate for excess load demanded when the primary load profile was greater than the average load. As a result the degree of load leveling became undesirably low. With such a low power capacity, the power deviation II became 52.6 MW giving a load leveling of 42.3 percent.

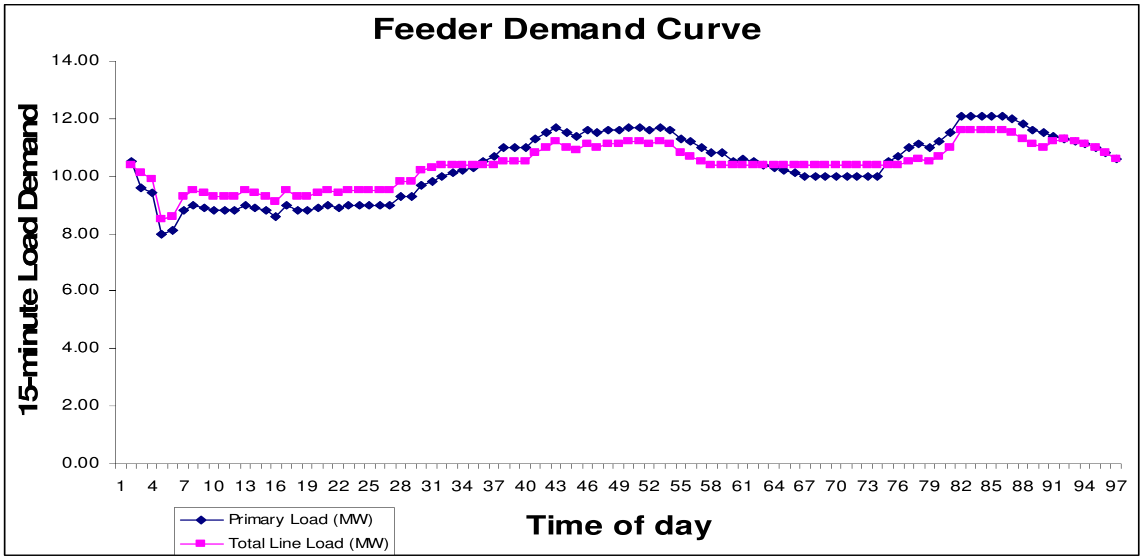


Figure 7.7: Load Leveling at 0.5 MW Storage Power Capacity

Conclusion

A larger power capacity enables a greater amount of charging. This better meets demands for discharge later in the day and hence provides better line load leveling. Lower power capacity creates less charging, which is less likely to meet future discharge demands. In this case, line load leveling becomes poor.

CHAPTER 6

SENSITIVITY ANALYSIS

This chapter interprets the deviations from perfect load leveling of Figure 2.3 when control setpoints are varied.

Deviation I

A negative value is an indication of failure to charge the storage unit, and a positive value indicates failure to discharge the storage unit, when needed, to level the load. The magnitude is the difference between the total line load and its ideal level value.

Deviation II

Deviation II is the absolute value of Deviation I, and the magnitude is the difference between the actual total line load and its ideal level value.

Question to Consider

How are the previous and new techniques affected by different load profiles?

Previous Technique [3]

This technique, which has a constant power capacity of 1 MW, works well with load profiles that are closely crowded around the charge-discharge bandwidth such that the difference with any primary load point above or below is not greater than 1 MW. Other than that then the technique works poorly as the difference increases.

New Technique

With this new technique, a charge-discharge bandwidth is formed about the average of any load profile and a proper storage power capacity chosen, such that it accommodates the largest of the differences between the bandwidth and any primary load. With a proper storage energy capacity and a reasonable bandwidth, the level of load leveling can be increased to desirable degrees. Also the ‘offline’ periods of the storage unit can be manipulated as desired (i.e. one can increase or decrease how much the energy storage unit is utilized).

CHAPTER 7

CONCLUSIONS

A control system for a distributed energy storage system designed in a previous project [3] was modified and its performance analyzed and compared with the previous design. The previous system allowed charging and discharging at a constant value only. The modified system allowed variable charge and discharge rates.

It was shown how each of the control setpoints affected the degree of load leveling; by decreasing the charge-discharge bandwidth load leveling is improved. This information can be used to increase or decrease how much the storage unit is utilized. It also determines the size of the storage system in terms of storage energy and power capacity.

In the case where storage energy and storage power capacities are already predetermined factors, a bigger bandwidth goes well with a system with low capacities and a smaller bandwidth with that of high capacities. This depends on how the primary load profile is distributed about the calculated average load where load leveling is done. Also, having larger storage energy and storage power capacities increase the percentage of load leveling of the load profile. While power capacity could be decreased significantly to 1.6 MW (64% of 2.4 MW) and yet produce very good load leveling results of 97.6 percent, the storage energy capacity was producing load leveling of 96.3 percent at 40 MWh, with an approximate 6 percent decrease in capacity. This shows that the storage system is more sensitive to changes in storage energy capacity than storage power capacity in regards to this primary load profile. The same can not be said for different primary load profiles until simulations are ran for them.

CHAPTER 8

FUTURE RESEARCH

This paper has clearly shown that achieving a 100 percentage load leveling with an energy storage system for any primary load profile is a possibility, yet as with most issues in the power industry, financial constraints limit its potential. This calls for techniques that enable the design of a storage system to reduce cost and yet produce very desirable load-leveling results. It has been clearly shown that the greater the storage energy and storage power capacities, the better the degree of load leveling but unfortunately, this makes the unit undesirably expensive. A storage system with smaller storage energy and storage power capacities is cheaper yet has less load-leveling capabilities with the new technique. Techniques that result in high load-leveling percentages with low storage energy and power capacities should be pursued, since this will reduce the cost of the storage system and greatly increase its desirability in the power industry.

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