OpenData

CASE STUDY: POWER CHAIN CAPACITY EXTENSION

Part of the Measurement Series™, by Modius

In this case study, Modius examines how its OpenData Data Center Infrastructure Management (DCIM) system allowed its client, a leading Californian technology company, to expand the IT capacity of its data center by 30% while at the same time improving the availability of its facility.

The company achieved these improvements by detecting and fixing current imbalances within its Power Distribution Units (PDUs). Fixing these imbalances allowed the company to grow its server capacity by as many as 540 new servers (on an inventory of 1,800) without placing undue stress on its PDUs. This improvement not only increased capacity, but also reduced the likelihood of equipment failure and harmful electrical harmonics that can cause overheating.

Data from the OpenData system played a key role in helping remediate these imbalances. OpenData captured performance data from many different points throughout the power chain, which included different types of devices from different vendors. The same data collection was also done at multiple sites simultaneously using the same software. This multi-site, multi-vendor data then allowed the company to implement a well-orchestrated rebalancing effort. The rebalancing effort occurred in two stages: The first phase involved a comprehensive physical rebalancing during a planned data center shut-down. The second phase involved the use of intelligent Add/Move/Changes after the shutdown, which allowed the company to incrementally improve the balance over time. Both stages depended on OpenData data to capture accurate balancing data across the phases.

The specific benefit of this initiative allowed the company to create more IT capacity within its power chain in order to continue adding servers (growing its business) without impacting equipment reliability by over-loading a single phase. Also, and perhaps most importantly, data from Modius' OpenData system allowed the company enough planning time to predict the approaching "capacity wall". This forewarning allowed the company sufficient time to plan a brief and well-organized facility shutdown while new power and cooling equipment were brought into the data center. By having enough time to upgrade the facility in this way, the company avoided a costly $13 million expenditure to build a new facility. During the planned shutdown, the company not only undertook the current rebalancing effort but also a host of other useful maintenance tasks.

TABLE OF CONTENTS

I. CASE INTRODUCTION

In this case study, the company uses OpenData, Modius' continuous and granular data collection system, to discover and correct imbalances in its three-phase power distribution chain. Three-phase systems perform best when the currents in the wires carrying each of the three phases are equal or "balanced." Unbalanced currents can reduce the effective capacity of the power chain, shorten the life of transformers and motors connected to the system, and reduce the reliability of the power infrastructure.

RETURN ON INVESTMENT

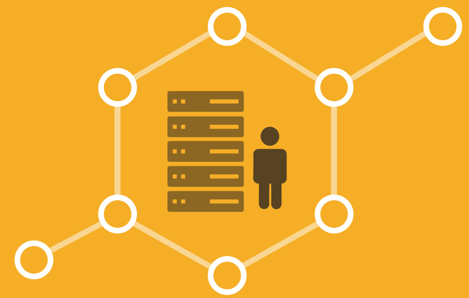
Once the imbalances in the 3-phase power distribution chain were corrected, the company experienced a number of benefits, including:

1: Increased server capacity of approximately 540 new servers, or 30% of its inventory
2: Increased transformer reliability from optimized performance of the devices
3: Ability to continue making incremental optimizations through intelligent Add/Move/Changes

The costs of the rebalancing initiative itself were relatively minor. The company was able to work the majority of the rebalancing effort into an already-planned data center shutdown, and then continue with incremental changes thereafter. The costs for rebalancing included (1) personnel costs to perform the task and (2) the costs of the OpenData monitoring software to capture the necessary data to perform and evaluate the rebalancing.

However, an even larger win for the company was the fact that the shutdown was properly planned. The company was able to plan the shutdown in part because trend data from OpenData enabled the company to predict upcoming power and cooling capacity limitations well in advance. This warning gave data center operators ample time to plan a brief, well-organized shutdown that would minimally impact business operations, enable upgrades to power and cooling, and permit a host of other useful maintenance tasks (including the rebalancing). To accomplish the same results without shutting down would have necessitated a further $13 million capital expenditure to build new data center facility alongside the old space.

ABOUT THE MEASUREMENT SERIES



This case study is part of Modius' Measurement Series, which examines the benefits of data center systems that provide detailed monitoring and trending of performance information. This case study was produced with the generous cooperation of our client, whose experience using Modius' OpenData system in its data center has been very valuable. The information in the case study comes from interviews with their data center personnel, and data collected from the OpenData software.

The company's data center houses about 1,800 servers in 16,000 square feet of raised floor area. The data center runs continuously 24 hours a day, 7 days a week, 365 days a year. The data center is part of a much larger office building of approximately 220,000 square feet. The data center space is separately metered for electricity, and it has dedicated chillers serving only the data center and some negligible laboratory area.[1]

1) Lab space can be very energy intensive, but the company's lab space requires only about 12 tons of cooling from the 240-ton chiller. Therefore, this case study ignores the lab's effect on data center cooling.

CONTEXT

At the start of the case study period, the company was very close to running out of power and cooling capacity in its data center. Although plenty of extra power was brought onto the site by the utility, and extra cooling units had been placed on the roof, there were insufficient wires and chilled water pipes to get this power and cooling into the data center where it was needed. The company was faced with a choice:

- One option was to spend about $13M to construct a new section of raised floor area into which this extra power and cooling could be brought. The new section would essentially be a separate data center (with its own generators) located next to the existing one. Although expensive, this new construction wouldn't interfere with the operation of the existing data center.
- The other option was to spend $2M and completely shut down the existing data center for 40 hours while construction personnel ran the necessary wires and chilled water lines into the raised floor area.

IMPLEMENTATION PLAN

In the end, the company decided to shut down its data center and add the incremental infrastructure to the existing data center. Although no data center operator likes downtime, the company determined that a well-planned and executed outage was preferable to the expense of building a new facility.

In addition to adding infrastructure, the company used the shutdown as an opportunity to move server loads around on the different computer room circuits in order to better balance loads across the phases of the three-phase power distribution system. This redistribution of servers created 30% aggregate new capacity across the phases, which allowed the company to continue its IT growth well in the future without building a new facility.

II. CLIENT SYSTEM SET-UP

At the time of the upgrade, the company's data center had a central Uninterruptible Power Supply (UPS) system, which fed three-phase power to 11 power management modules (PMMs). Each power management module contained a transformer, which stepped down the voltage and provided three-phase power to the servers, storage, and networking equipment in the data center. Figure 1 on the following page shows a rough schematic.

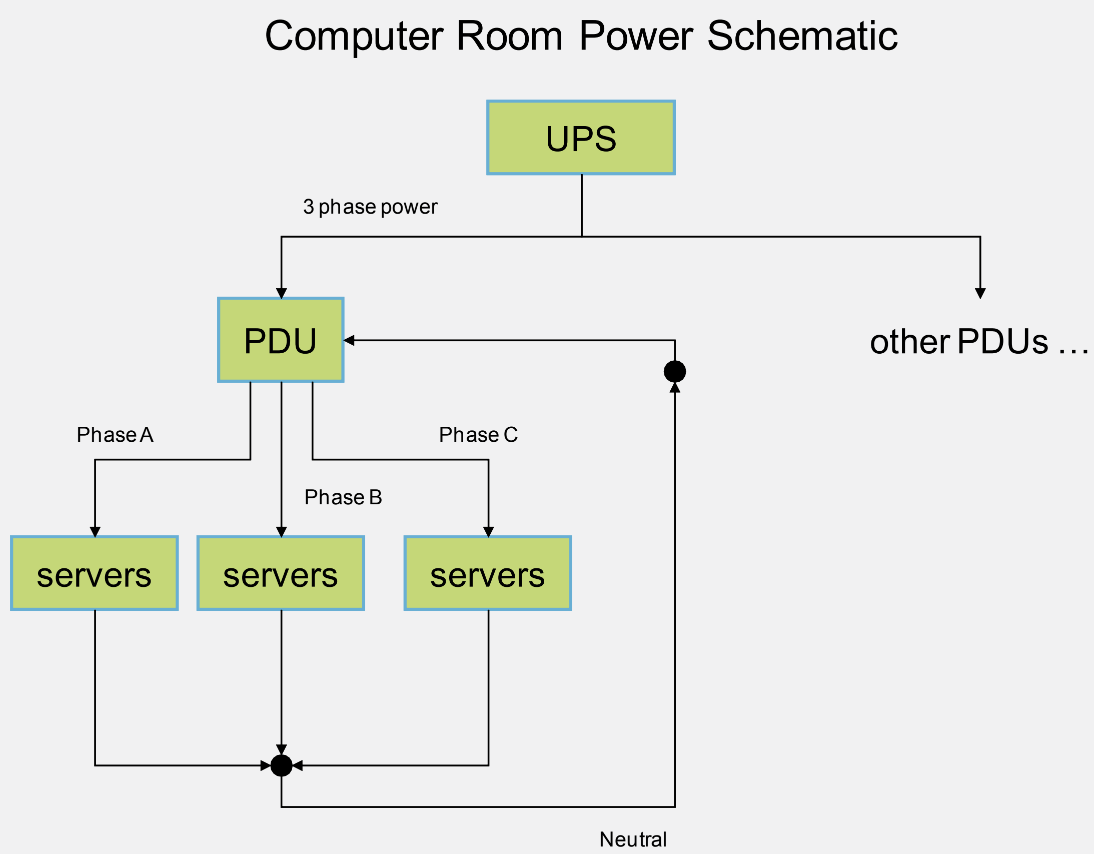


Figure 1 – Schematic of data center power distribution

When the currents in all three phases of power are perfectly balanced, they "cancel" each other out when they reconvene in the neutral wire that provides a common return path. If one phase draws more current than another, some of this canceling is prevented. Another source of current flow in the neutral wire is harmonics – alternating current that comes in multiples of the standard 60Hz frequency. Heat dissipated by harmonics in the neutral wire adds to any heat resulting from imbalanced currents.

III. CLIENT ACTION

The rebalancing occurred in two stages: the first included a shutdown stage during which major changes were made to bring the overall electrical phases into better alignment. The second was an operational stage after the shutdown that included incremental changes over time. The first stage involved a complete facility shutdown during which the company ungraded its overall site infrastructure. This upgrade included the laying of new electrical wiring to increase power density from 50 watts per square foot to approximately 60 watts per square foot. Determined to make the most of the upgrade, the company's data center team also carefully planned a host of other maintenance and improvement tasks that could be carried out in parallel with the power and cooling upgrade. Balancing the 3-phase currents on each PDU was only one of these tasks, but it is the primary focus of this paper.

To balance the phases, the company took the following steps:

1. Use OpenData software to look at the current imbalance on each power management module

Modius' OpenData data collection system provided readings on each of the three phases approximately every minute. The system recorded these measurements so that long-term chronic imbalances could be identified. In addition, the trend data also detected temporary imbalances. On some circuits, particular servers would idle most of the time and then only awaken for a scheduled periodic task. At these times, current on the circuit would increase rapidly and decline again once the servers finished the scheduled process. (These short-term imbalances were observed in the data by company personnel, but are too granular to be shown in the data subset used in this report.)

2. For unbalanced phases, measure each load with a hand-clamp

For each unbalanced phase, data center personnel used hand-clamps to capture supplemental measurements about the amount of current drawn by each piece of equipment on the circuit.

3. Make a plan for rebalancing

Once the power-hungry pieces of IT equipment on each phase had been identified, a plan was made for distributing the servers more evenly across the three phases at each PDU. The overall project was complex. First, entire breaker loads had to be moved from panel to panel. Second, the power supplies on the servers had to then be balanced on each leg of the circuit. This process involved unplugging the server from one outlet and plugging it into a different outlet on a different phase. (Figure 2 shows an example "before and after" picture.) The process was made even more complex because company personnel had to balance the redistribution evenly among two types of servers: those with continuous loads as well as those with transiently high peak loads.

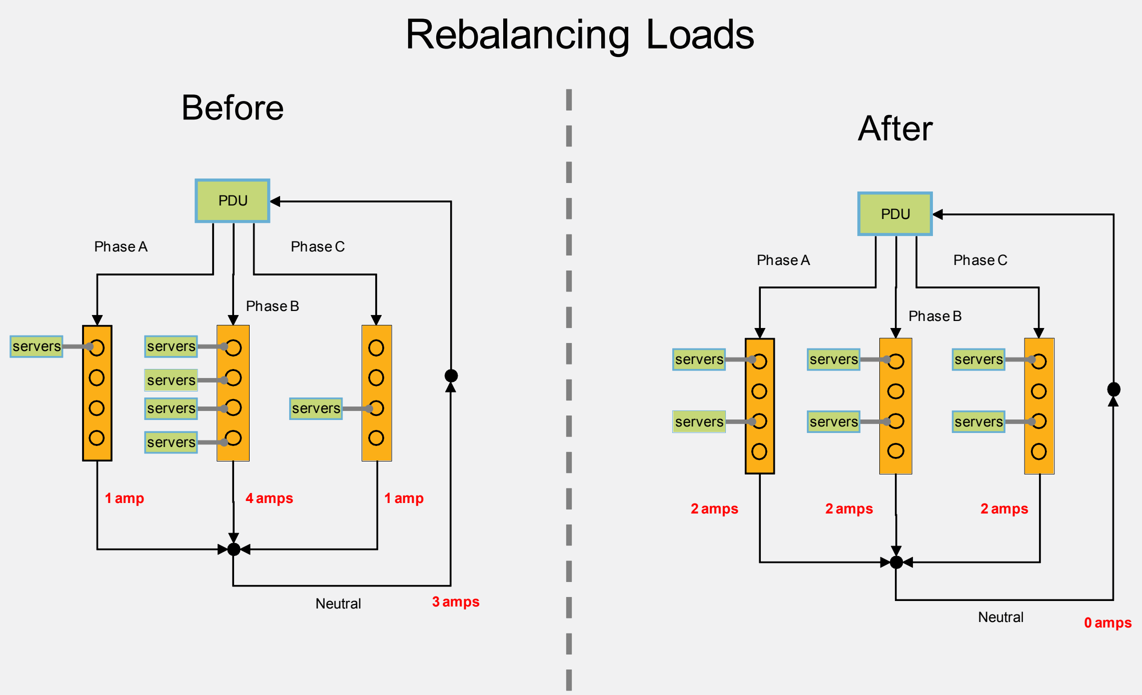


Figure 2 – Rebalancing server loads in the data center

4. Tape rebalancing instructions to the front of each server rack
After the plan was created, the data center personnel wrote down which servers needed to be unplugged and into which new outlets they should be plugged. They taped a piece of paper listing these changes to the front of each server rack, so the technicians could make the server-outlet changes quickly and easily in the frantic work pace during the shutdown.

5. Shut down the data center and perform the upgrade
The company took its data center offline for 42 hours, during which time they brought in the supplemental power/cooling infrastructure and performed many other maintenance tasks, including the phase balancing.

6. Bring the data center back online

7. Use OpenData to verify the improvement in the phase balances
After rebalancing, the company used OpenData to confirm the effects. Again, the company looked for balance in both continuous loads and transient loads.

IV. RESULTS AND CALCULATIONS - BEFORE AND AFTER REBALANCING

Modius case study authors quantified the results of the rebalancing procedure by examining current data over two months, as described below in Table 1:

DATA SET FOR THIS CASE STUDY	
DATA COLLECTION SYSTEM	OpenData, provided by Modius
DATA USED	Current in phases A, B, and C for all 11 PDUs [1]
TIME GRANULARITY	Data points approximately every minute
DATES INCLUDED IN THE "BEFORE REBALANCING" SET	2 weeks (1 Feb to 14 Feb)
DATES INCLUDED IN THE "AFTER REBALANCING" SET	4 weeks (1 Mar to 31 Mar)
NOTES:	
[1] The data set from OpenData also contained data for KF current, voltage, KF voltage, and active power, but these series were not used in the analysis.	

Table 1. – The data used in this analysis

DATA COLLECTION

The actual data center shutdown was approximately 42 hours, although the “hole” in the data set lasted for a few hours longer (the monitoring software was one of the last services restored, after the business-critical parts of the data center were back online.) In order to avoid catching transient effects from shutting down and re-starting the data center, Modius case authors used data from 1-14 February for the calculations of imbalance before the shutdown, and data from 1-31 March for calculations of imbalance after the shutdown.

Table 2 below shows the change in imbalance in all 11 PDUs.

PDU DATA BEFORE AND AFTER THE BALANCING PROJECT

	IMBALANCE BEFORE (%)	IMBALANCE AFTER (%)	CHANGE (%)
1	16	7	-9
2	16	3	-13
3	28	5	-23
4	16	13	-4
5	32	31	-1
6	14	17	+3
7	16	8	-8
8	13	16	+3
9	16	14	-2
10	27	29	+1
11	33	19	-13
OVERALL [1]	21	13	-8

NOTES:

[1] To calculate overall values, the imbalance percentages for each PDU are averaged together, weighting by each PDU’s respective total current output.

Table 2 – Before & after PDU data

IMPACT

In the majority of the data center PDUs (8 of the 11 devices), the imbalance in the three phases decreased significantly. PDU 3 showed the largest reduction in imbalance. The other PDUs (5, 6, 8 & 10) showed only slight changes in imbalance. Whereas 8% overall may not seem significant, the large improvements in 8 of the 11 PDUs opened up significant amounts of new capacity (which is calculated in detail below).

Imbalance among the three phase currents was calculated using the formula below.

$$\text{IMBALANCE} = \frac{\text{MAXIMUM DEVIATION FROM AVERAGE CURRENT}}{\text{AVERAGE CURRENT}}$$

Figure 3, Figure 4, and Figure 5 show time series data for three of the PDUs. Table 5 in the appendix shows more detailed numerical data for all the PDUs.

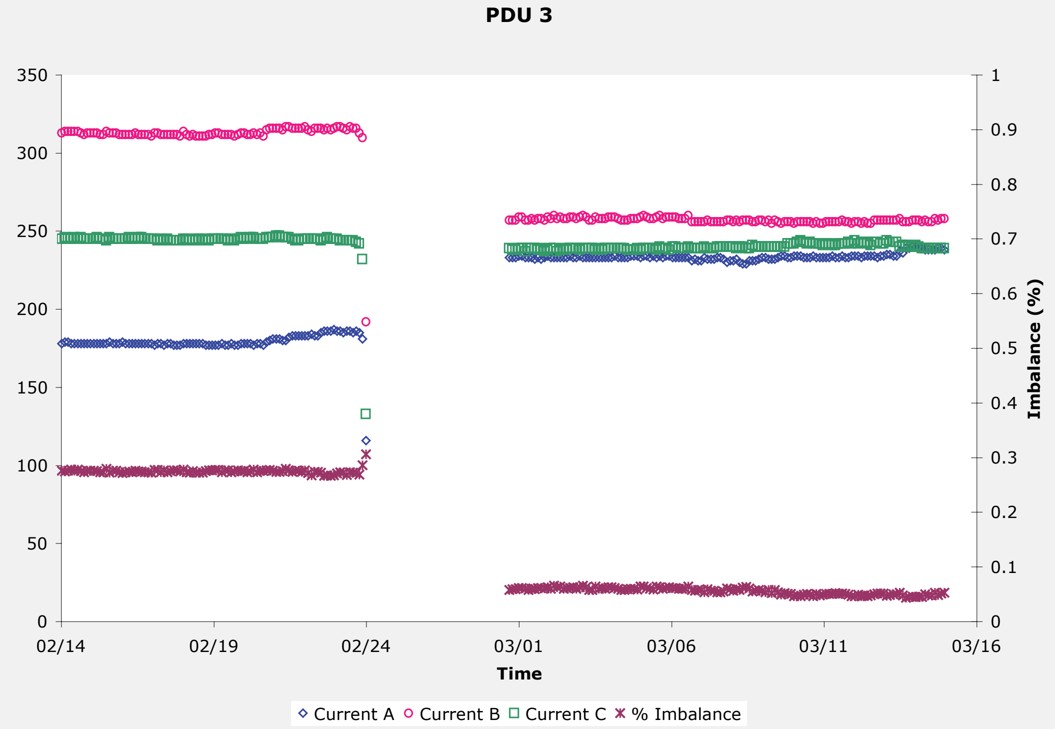


Figure 3 – The three phase currents and calculated imbalance in PDU #3, before and after the rebalancing procedure. PDU 3 showed the greatest decrease in current imbalance. Note the "hole" in the data during the time that the data center was shut down.

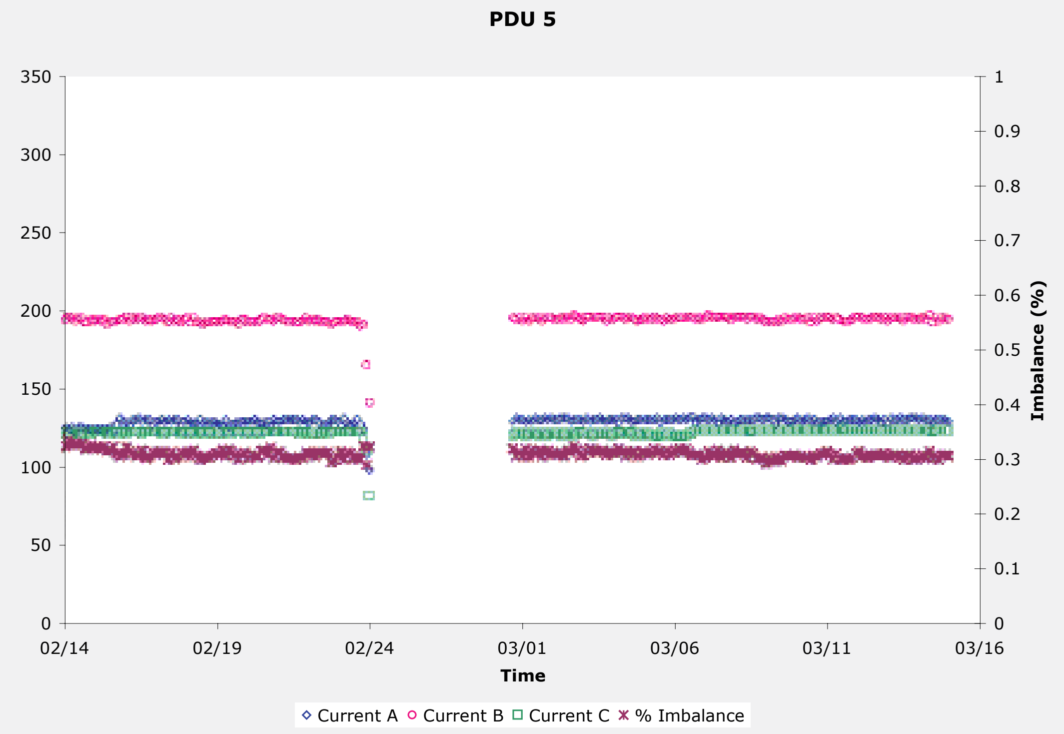


Figure 4 – The three phase currents and calculated imbalance in PDU #5, before and after the rebalancing procedure. PDU 5 showed an small decrease in current imbalance.

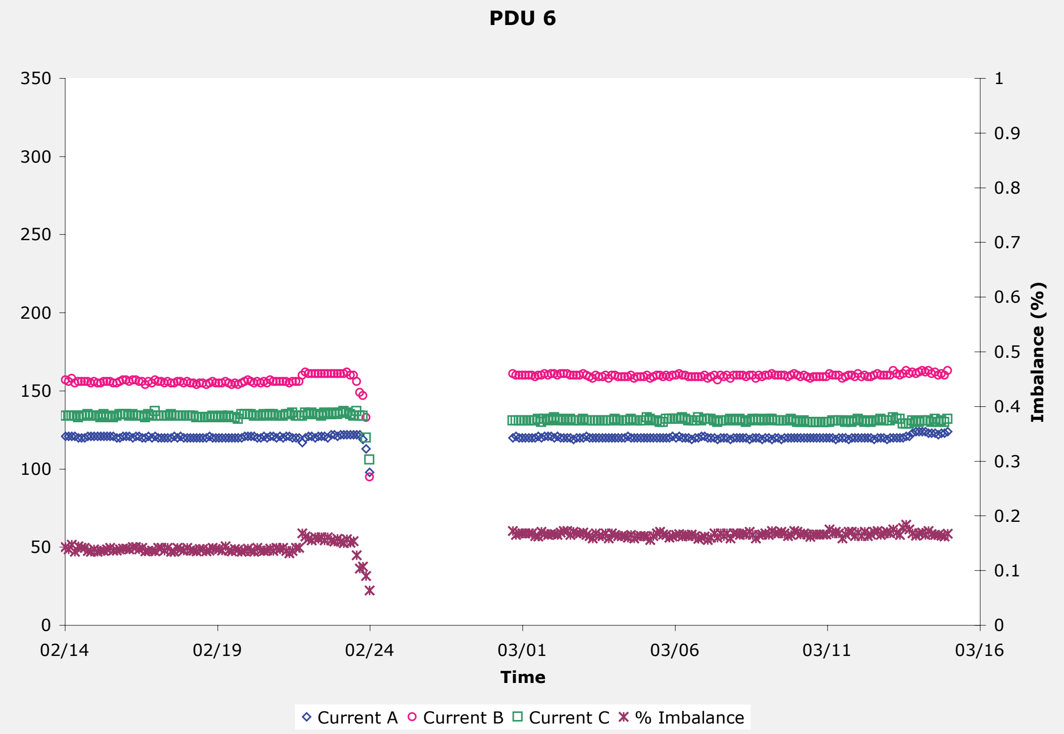


Figure 5 – The three phase currents and calculated imbalance in PDU #6, before and after the rebalancing procedure. PDU 6 showed a slight increase in current imbalance.

V. THE OPERATIONAL BENEFITS OF OPENDATA MEASUREMENT AND MONITORING

To what extent did the data center's OpenData software help the company to measure and monitor the PDUs? To a limited extent, alternative methods for collecting performance data already existed. The company could have spotted the unbalanced phases by manually tracking the faceplate displays on the power management modules (each PDU has a display showing the currents in all three phases). Data center personnel could have walked through periodically and written down spot measurements of the currents for each PDU. This could have detected imbalances among continuously running loads.

However, the automated and granular design of the OpenData monitoring software provided several important functions that made the data collection both more practical and accurate given limited personnel and time:

CONTINUOUS TRACKING TO IDENTIFY CHRONIC IMBALANCES

First, if loads in the data center were fluctuating over time, a chronic current imbalance might not have been noticed if it happened to have subsided during the particular times when the PDU displays were read. OpenData showed complete trends to see what was happening over the course of any given day or week. The company places much more trust in documented trends than in snapshots.

GRANULAR TRACKING TO IDENTIFY TEMPORARY IMBALANCES

Second, the company suspected that even on circuits where there was little or no chronic imbalance, the ramping up and down of certain pieces of equipment in response to daily load/task variation could have caused temporary imbalances. OpenData's high resolution and granular (in time) data collection allowed the company to check for this condition.

AUTOMATED DATA COLLECTION

Third, taking spot measurements for all 11 PDUs, even periodically, would have been cumbersome for busy staff members. This tracking would have been especially cumbersome to maintain efficiently over a time span long enough to generate meaningful 1/2 year or 1 year trends. OpenData allowed the company to track current and voltage trends at approximately 1-minute resolution for all 11 PDUs from a central location.

REMOTE DATA COLLECTION

Fourth, the company also wished to track similar power trends at its disaster recovery site hundreds of miles away. This remote site has no electricians on-site, so no manual measurements would have been possible. OpenData can be used to collect this data at the remote site and automatically send it to the central application database.

TREND ANALYSIS

Fifth, the trend data generated by OpenData allowed the facility's personnel to be confident that current imbalances were significant long-term issues worthy of addressing during the data center shutdown.

VI. THE STRATEGIC BENEFITS OF OPENDATA MEASUREMENT AND MONITORING

PREDICTING FUTURE CAPACITY LIMITS

First and foremost, trend data from OpenData enabled the company to predict that the data center would soon run out of IT capacity. With this knowledge, supported by trend data and graphs from OpenData, data center personnel made a credible case to management and the IT group that some kind of facility upgrade would be needed in the near future.

This granular trend analysis gave the company adequate time to consider its options and conduct a well-planned upgrade. If “the capacity wall” had not been noticed in time, the company may have been forced down a path that was much more costly and/or disruptive to business operations.

ABILITY TO CONTINUE SERVER GROWTH BEFORE IMPACTING RELIABILITY

More importantly, rebalancing allowed the company to continue adding servers (i.e., growing their business) within their existing facility without negatively impacting transformer life or reliability. As shown below, the combination of rebalancing combined with using OpenData to ensure balanced growth of new servers in the future enabled the company to increase their server stock by approximately 30% within the existing facility.

Because the company’s business is growing, new IT loads will be added to the PDUs over time. If the current imbalance among the three phases stayed the same (as the supplied current grows), then each PDU would reach their optimal capacity (347 amps per phase) prematurely, as well as causing stress on the devices themselves from unbalanced harmonics. However, if the phases are brought closer into balance and then OpenData software is used to ensure new servers are added to the right phase in order to maintain the overall balance, then aggregate capacity is dramatically increased.

Table 3 on the following page shows how this capacity increase is calculated.

CALCULATED EXTRA SERVER CAPACITY SUPPORTED BY BALANCED GROWTH SCENARIO		
	Units	Amount
TOTAL AMPS SUPPORTED UNDER UNBALANCED GROWTH	Amps	9,671
MAXIMUM AMPS SUPPORT UNDER BALANCED GROWTH	Amps	11,451
ADDITIONAL AMPS SUPPORTED BY BALANCED CASE	Amps	1,780
DISTRIBUTION VOLTAGE [1]	Volts	120
POWER FACTOR [2]	%	0.95
TOTAL EXTRA WATTS SUPPORTED BY BALANCED CASE	Watts	20,296
WATTS PER SERVER	Watts/server	300
EXTRA SERVERS SUPPORTED AT 80% PDU LOAD [3]	#	**541**
NOTES:		
[1] Some of the company's IT equipment uses power at 208 volts instead of 120 volts. Using higher voltage levels in this calculation would increase the calculated number of additional servers.		
[2] Modius case authors assume power factor of 0.95%.		
[3] To preserve safety margin, the company's policy is to only load PDUs to 80% of design rating. This calculation assumes both balanced and unbalanced growth cases only hit 80% of PDU design rating.		

Table 3 – Number of extra servers supported by balanced growth scenario

Note that if the company increases IT load through unbalanced server growth, then it can only support 9,671 amps of IT capacity in its data center. However, if it achieves balanced growth (through a combination of rebalancing and better managed growth after rebalancing) then it can support a total of 11,451 amps, which represents approximately 18% more capacity in amps.

However, the extra amp capacity translates to even greater server growth. After making adjustments for the distribution voltage and the power factor in the power chain, the extra capacity created by the balanced growth equates to over 20,000 watts. At 300 watts per server, this capacity growth equals approximately 540 new servers, depending on what load the company chooses to run its PDUs, which is a 30% expansion in the number of servers.

By alleviating these phase imbalances before they became a significant limit to PDU capacity, the company will be able to accommodate further IT growth across the entire power chain for the foreseeable future. These power distribution improvements helped the company expand IT capacity in order to accommodate further server growth for a long enough period that they could avoid a near-term incremental $13 M capital expenditure on a new facility.

VII. OTHER BENEFITS OF REBALANCING

Beyond extending the useful life of the data center, the rebalancing initiative had many benefits for the company. These benefits are listed in the following sections:

INCREASED TRANSFORMER RELIABILITY FROM REDUCED THERMAL AGING OF INSULATION

Another key benefit of the rebalancing project is the resultant increase in transformer reliability, according to data center personnel. Typically, a transformer's probability of failure in any given year increases over time as the unit ages. After a period of "infant mortality" (in which a new unit may fail due to some initial defect), a transformer enters into a period of stable operation with a relatively low per-year failure rate.

Table 4 below describes the key characteristics of the PDUs used in the data center.

PDU SPECIFICATIONS [1]	
MANUFACTURER	MGE
MODEL NUMBER	PMN 168-42-125-F
TYPE	Dry Type [2]
RATED CAPACITY	125 kVA
INPUT VOLTAGE	480 V
OUTPUT VOLTAGE	120 V / 208 V
RATED OUTPUT CURRENT (EACH PHASE)	347 Amps
WINDING TEMPERATURE RISE [3]	150° C
TYPICAL SERVICE LIFE	20 Years
NOTES:	
[1] Data from client and manufacturer correspondence.	
[2] "Dry type" indicates that the transformer is not filled with mineral oil, as are many large power transformers.	
[3] Winding temperature rise is the maximum increase in temperature above ambient.	

Table 4 – Chiller operating characteristics

As age begins to take its toll, the per-year failure rate starts to increase again. Thus, a transformer is more likely to fail in the 17th year of its life than the 10th. This failure rate pattern is commonly referred to as the "bathtub curve."[3]

3: See *Wilkins* (references) for a general introduction to the bathtub curve. *Kurtz et al* discusses the bathtub curve in reference to electric power transformers specifically.

Much of the transformer's degradation over time is driven by the thermal aging of its insulation, and the hottest-running winding will be the first to fail. By distributing currents more evenly in the transformer, rebalancing currents across allow the three sets of windings to better share the heat, slowing down the thermal aging process in the hottest winding. This means that for any given year, the effective age of the insulation will be less in a balanced transformer than in an imbalanced one, leading to a reliability improvement.

ABILITY TO MAKE INCREMENTAL IMPROVEMENTS THROUGH INTELLIGENT ADD/MOVE/CHANGES IN THE DATA CENTER

After the initial rebalancing was completed during the first phase of the project, company personnel could continue to make incremental improvements to their overall balancing efforts by using OpenData data to be intelligent about the destination where they would add, move or change new servers. As new servers were added to the facility as a result of the capacity expansion, company personnel had granular data with which to choose the most appropriate racks within the facility to place the new servers. Moreover, as the new servers were inserted into the facility, data center personnel could collect detailed performance information over time about their load levels that enables them to make further modifications if required.

Because these changes are on-going after the initial capacity expansion effort, they can be included as a second stage to the overall rebalancing effort. When the next major upgrade to the data center facility occurs (perhaps further upgrading the power density of the facility), then another cycle of major changes followed by incremental changes will attempt to again improve the facility's phase balance.

REDUCED RISK OF NEUTRAL WIRE OVERHEATING FROM HARMONICS

Another reliability benefit to the rebalancing initiative was the reduced risk of overheating in the neutral wire from harmonics. As mentioned earlier, harmonics are electric current waveforms at multiples of the basic 60 Hz power frequency. There are harmonics at 120 Hz, 180 Hz, 240 Hz, etc., with 3rd harmonics being particularly problematic. As mentioned earlier, the neutral wire is the wire acting as the common return path for currents delivered to equipment on all three phases that a PDU supplies.

Harmonics are introduced into the neutral wire by the loads being served. Many older PCs have inexpensive power supplies that simply "dump" harmonics into the neutral wire. Even newer pieces of equipment typically only include a capacitor in the power supply to suppress harmonics. Such capacitors often wear out and fail, allowing the equipment to become part of the harmonics problem. Harmonics create resistive losses and heat in the wire, just like "regular" 60 Hz current. Even worse, while the three phases of 60 Hz current can partially cancel each other out when combined in the neutral wire, certain harmonics add together, becoming more problematic. Excessive harmonics can cause the neutral wire to overheat, possibly resulting in a data center fire.

Balancing currents in the PDUs does not reduce harmonics directly. However, when currents are balanced, the 60 Hz waveforms can partially or completely cancel each other out in the neutral wire. This gives the harmonics on the wire extra “room” to generate heat on the neutral wire without causing it to get too hot.

Quantifying the actual reduction in neutral currents throughout the data center is difficult. The amount of neutral current in each PDU is highly depended on the mix of 120 V and 208 V loads plugged into a PDU’s circuits. For circuits with only 120 V loads, the neutral current is dependent on how well balanced the three phase currents are. Neutral current is not affected by 208 V loads, regardless of balance, because they do not connect to the neutral wire.

In one fortunate case, it is possible to make an illustrative estimate; PDU #1 was serving only 120 V loads. Before rebalancing, the three phases of PDU 1 were carrying currents of 179, 148, and 205 amps, respectively, for a total current of 532 amps. However, during the rebalancing process, some of the loads on PDU 1 were removed entirely, so after rebalancing the total current on PDU 1 was only 502 amps. To properly count only the reduction in neutral current from rebalancing (and not count the reduction from lowering the total load), Modius case authors downward adjusted the pre-rebalancing currents in PDU 1 by the ratio 502/532, leaving the imbalance ratio the same. This results in adjusted pre-rebalancing currents of 169, 140, and 193 amps for PDU 1, with a total adjusted current of 502 amps. Using these three currents from PDU 1 before rebalancing, current in the neutral wire (return path) was found using the formula:

$$\text{NEUTRAL CURRENT} \quad \sqrt{A^2 + B^2 + C^2 - AB - AC - BC}$$

Where A, B, and C are the currents (in amps) in the respective phases A, B, and C.

Applying this formula to PDU 1 before rebalancing yields a calculated neutral current of 46 amps. After rebalancing, PDU 1 has phase currents of 179, 160, and 163 amps. The total current is still 502 amps, but the calculated neutral current is only 17 amps.

VIII. CONCLUSION

Using Modius’ OpenData, the company was able to improve data center reliability by identifying and correcting current imbalances within its PDUs. Fixing current imbalances:

- Allowed the company to increase server load by 540 servers, or 30% of existing capacity
- Extend the life of the transformers in each PDU
- Reduces the risk of transformer failure

Balancing currents allows the company to continue growing by adding IT loads and make the most of its PDUs without placing undue stress on any one set of transformer windings within a PDU.

Although it might have been possible to identify the current imbalances without a monitoring system like OpenData, doing so would have likely been labor intensive and error prone. The OpenData system allowed the company to automatically collect detailed information on the currents in each PDU, to examine trends to verify chronic imbalances worthy of corrective action, and to see just what effects the corrective actions produced.

Finally, it’s worth noting that the company performed the current rebalancing during a scheduled outage to expand power and cooling capacity at its data center. Trend data collected by OpenData helped the company know that it was running out of power and cooling capacity in the first place.

REFERENCES

Kurtz, Chris, et al. "Managing Aged Transformers." Transmission & Distribution World. Available at **studylib.net/doc/18526899/managing-aged-transformers**. Accessed 23 June 2017.

MGE. Personal correspondence. Respondent was a senior engineer at the company experienced with transformer issues. Respondent also sent equipment specifications.

Wilkins, Dennis J. "The Bathtub Curve and Product Failure Behavior (Part 1 of 2)". Reliability Hotwire (eMagazine). Available at **weibull.com/hotwire/issue21/hottopics21.htm**. Accessed 23 June 2017.

APPENDIX - ADDITIONAL DATA

SUMMARY DATA FOR ALL PDUS - BEFORE AND AFTER REBALANCING

TABLE 5-1: BEFORE REBALANCE

PDU #	CURRENT A	CURRENT B	CURRENT C	IMBALANCE	TOTAL CURRENT
	AMPS	AMPS	AMPS	%	AMPS
1	179	148	205	16 %	532
2	129	169	164	16 %	462
3	178	313	245	28 %	735
4	121	152	119	16 %	391
5	126	194	121	32 %	441
6	121	155	134	14 %	410
7	255	204	202	16 %	661
8	104	112	88	13 %	304
9	152	201	189	16 %	542
10	68	108	79	27 %	255
11	96	62	119	33 %	278

TABLE 5-2: AFTER REBALANCE					
PDU #	CURRENT A	CURRENT B	CURRENT C	IMBALANCE	TOTAL CURRENT
	AMPS	AMPS	AMPS	%	AMPS
1	179	160	163	7 %	502
2	148	142	150	3 %	440
3	240	257	240	5 %	737
4	123	150	127	13 %	400
5	130	195	123	31 %	447
6	120	160	131	17 %	411
7	195	204	178	8 %	577
8	99	115	84	16 %	298
9	140	166	185	14 %	491
10	72	119	86	29 %	278
11	101	79	113	19 %	292

TABLE 5-3: CHANGE (AFTER MINUS BEFORE)					
PDU #	CURRENT A	CURRENT B	CURRENT C	IMBALANCE	TOTAL CURRENT
	AMPS	AMPS	AMPS	%	AMPS
1	0	12	-42	-9 %	-30
2	19	-27	-14	-13 %	-22
3	61	-55	-5	-23%	1
4	2	-2	8	-4 %	8
5	4	0	1	-1 %	6
6	-1	5	-3	3 %	1
7	-60	0	-24	-8 %	-84
8	-5	3	-4	3 %	-6
9	-11	-35	-4	-2 %	-50
10	5	11	7	1 %	23
11	5	16	-6	-13 %	15

TECHNICAL SPECIFICATIONS

Modius OpenData is a software application that can be installed on-premise or hosted in the cloud. Some customers choose to run the application within VMWare ESX. Software platform requirements are as follows:

- **Windows Server** - 2008, 2008 R2, 2012

- **Database** - Express, Workgroup (Up to 2012) and MS SQL Server 2008 - 2016

CONTACT YOUR MODIUS REPRESENTATIVE FOR MORE INFORMATION ABOUT HOW OPENDATA CAN FREE UP TRAPPED CAPACITY IN YOUR DATA CENTER, SIGNIFICANTLY REDUCING OPERATING COSTS.

modius

71 Stevenson Street, Suite 400, San Francisco, CA 94105 USA
sales@modius.com   www.modius.com   (888) 323-0066