The Modern Hospital/Health Care Environment & Harmonics

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Hospitals and other Health Care facilities have many of the non-linear, harmonic generating equipment that exists in all modern commercial and institutional buildings today. They also require the use of expensive diagnostic and other state-of-the-art medical equipment that can be sensitive to power quality issues, such as harmonic distortion. Control of harmonics therefore, has become extremely important to ensure trouble-free operation in these critical environments.

Although, medical equipment can often be a source of harmonics themselves, this paper is focused on other equipment in the facility that are known to introduce significant harmonic content in modern medical facilities. These include:

- Non-environmental system single phase non-linear loads, such as lighting/computer equipment and solid-state medical equipment.
- Environmental system single phase non-linear loads, such as exhaust and supply fans.
- Three phase non-linear loads associated with HVAC and other environmental control equipment.
  - Roof Top Air Handlers (RTAH)
  - Air Cooled Chillers (ACC)
  - Water Cooled Chillers (WCC)
  - Chilled Water (System) Pumps (CWP/CWSP)
  - Hot Water System Pumps (HWSP)
  - Others

Non-Environmental System
Single Phase Non-Linear Loads

These types of non-linear loads are typically 3rd order harmonic dominant. This form of harmonic can be easily controlled by planning your distribution system to utilize DOE-2016 compliant transformers that incorporate Harmonic Mitigation Technology like the Mirus International ULLTRA H1E and H2E transformer offerings. These transformers utilize low zero phase sequence and phase shifting strategies to control current harmonics upstream and voltage distortion throughout the distribution system. Deployment is fairly simple. Replace the standard distribution transformers from the "Big Box" supplier with the Mirus ULLTRA and designate the phase shift in either a 12-pulse pattern (0^o and -30^o Phase Shifts for H1E) or 24-pulse pattern (-30^o, -15^o, 0^o and +15^o for H2E). More information on application of these transformers can be found at www.mirusinternational.com.

Environmental System
Single Phase Non-Linear Loads

These do exist but tend to be small loads, typically in the fractional HP category. Even though the harmonic current can be a high percentage value, the actual current harmonic tends to be low and therefore, of little consequence. Requiring the use of a line reactor in front of the Single-Phase Drive can help. But unless the combined load value of these drives is significant, they can often be neglected within the harmonic evaluation. If desired, they can be mitigated effectively through the use of harmonic mitigating transformers as detailed for the non-environmental system non-linear loads mentioned above.

Three Phase Non-Linear HVAC and Other Environmental Control Equipment

Harmonics generated by these loads typically result from the extensive use of motors equipped with inverters. These can be conventional induction motors with AC variable speed drives (VFDs) or permanent magnet motors, such as those found in EC Fans (Electronically Commutated) and magnetic bearing chillers, which have built-in inverters. Recommended treatment for this equipment is the Mirus Lineator AUHF passive Wide Spectrum Harmonic Filter (WSHF). With 10's of thousands of these filters put into operation over nearly 20 years, these filters have proven to provide the best harmonic mitigation in a reliable, energy efficient and cost effective package.

- **Roof Top Air Handlers (RTAH):**

These are typically listed with the rated HP/Current ratings within the equipment listing. Table 1 provides an example of a typical schedule. These air handlers are packaged units consisting of multiple motors/VSDs and secondary modules which require sizing the passive harmonic filter to above the MCA (Minimum Circuit Ampacity) and coordinated with the Max Fuse ampacity. Due to the fact that there are often a mix of linear and non-linear loads within the assembly, the electrical single point connection data must be used. If a FLA (Full Load Amp) rating or an RLA (Run Load Amp) is listed, then that rating is to be used in sizing the filters. Understanding that these loads are typically variable torque in nature, it is best to get as close to the noted current rating as possible to avoid oversizing the harmonic mitigation. The Mirus Lineator AUHF Series filter is a constant torque rated filter, meaning it can handle a 50% overload for up to 1 minute every 10 minutes so oversizing is unnecessary. It should be noted that, in some applications, it might be more effective to have the harmonic mitigation built into the air handler itself. This would include units with a significant linear load component or ones where the trapezoidal nature of the output voltage of the filter could affect operation of certain internal equipment. This should be coordinated with the air handling equipment manufacturer.

Fig. 1: Rooftop Air Handler

At present, many manufacturers of these Air Handlers are including EC fan technologies, which offer significant energy savings due to their permanent magnet motors. The EC fan rectifier/ inverter electronics are integrated into the fan assembly and include a small DC bus capacitance to save money and space.

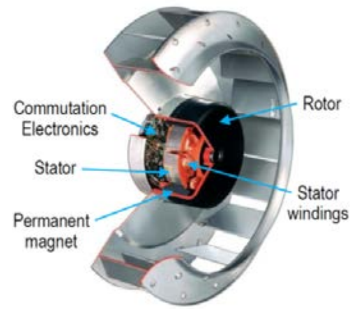


Fig. 2: Typical EC Fan Configuration *[Image Ref.: ebmpapst]*

They generate harmonics typical of a 6-Pulse rectifier so in order to take advantage of this energy saving potential, users of EC fan technology must take into consideration the effects of harmonics. This is difficult however, since the low DC bus capacitance of the EC fan shifts the resonant point of the circuit between the filter and the rectifier/inverter to a value above the prevalent harmonics being generated by the rectifier. The impedance of standard harmonic filters will tend to shift this resonant point down and into a region where the harmonics will be amplified creating instability, overheating, high DC bus voltage levels and even component fan failure. EC Fan manufacturers have come to recognize this challenge and Mirus has cooperated with them to develop a filter suitable for their application – the Lineator AUHF-HP2. This wide spectrum passive harmonic filter can be applied in one of two ways – (i) factory installed by the Air-Handler manufacturer or (ii) specified in the electrical contractor's scope of supply within the feeder circuit supplying the EC fans. In either approach, it is recommended that the EC fan filter supply only the EC fans and no other nonlinear or linear load.

Table 1: Rooftop Air Handling Unit Schedule – Chilled Water

ROOFTOP UNIT AIR HANDLING UNITS SCHEDULE – CHILLED WATER													
UNIT NO.	LOCATION	SERVICE	SUPPLY FAN/MOTOR DATA						PREHEAT COIL MODULE DATA	UV	ELECTRICAL (SGL. POINT CONN.)		
			n-1 AIRFLOW CFM	#	HP (TOTAL)	HP (EACH)	VOLTS	PH/HZ	KW	LIGHTS	ELECTRIC SERVICE	M.C.A.	MAX. FUSE
RTU-1	ROOF	PATIENT CLINIC	25,850	4	80	20	480	3/60	-	YES	480/3/60	102	125
RTU-2	ROOF	EMERGENCY	12,250	4	40	10	480	3/60	40	YES	480/3/60	155.3	175
RTU-3	ROOF	DIAGNOSTIC SERVICES	19,050	4	80	20	480	3/60	-	YES	480/3/60	97.8	110
RTU-4	ROOF	SURGERY	11,300	4	40	10	480	3/60	-	YES	480/3/60	50.2	60
RTU-5A,5B	ROOF	OPERATING ROOMS	8,500	4	30	7.5	480	3/60	-	YES	480/3/60	37.2	45
RTU-6	ROOF	MAINTENANCE/KITCHEN	17,850	4	40	10	480	3/60	-	YES	480/3/60	50.2	60
RTU-7	ROOF	MOB	12,750	4	30	7.5	480	3/60	-	YES	480/3/60	38.3	45
RTU-8	ROOF	MOB	14,150	4	30	7.5	480	3/60	-	YES	480/3/60	38.3	45

Table 2: Air Cooled Chiller Schedule

AIR COOLED CHILLER SCHEDULE													
UNIT NO.	NOMINAL CAPACITY TONS	ACTUAL CAPACITY TONS	CONDENSER SECTION			COMPRESSOR SECTION		UNIT ELEC. DATA (SINGLE PT.) – VFD STARTER					
			NO. FANS	FANS FLA (EACH)	FAN MOTOR POWER (KW)	COMPRESSOR 1A RLA/AFD INPUT (A)	COMPRESSOR 2A RLA/AFD INPUT (A)	VOLTS	PH/HZ	FLA	MCA	MOCP	LINE SIZE LUGS
ACC-1,2,3	200	202.44	12	4	80	168	168	480	3/60	-	417	500	(2) 2/0-500MCM

- **<u>Air Cooled Chillers (ACC) / Water Cooled Chillers (WCC):</u>**

ACCs or WCCs tend to be the largest load structures relative to HVAC/EC and have the greatest consequence to the harmonic condition. The VSD driven compressor loads are large and the current harmonic contribution significant. Below is a typical ACC Schedule. For these loads, the unit electrical data information should once again, be used to size the WSHF. It is optimum to size to the units FLA/RLA rating (Full Load Amps/ Rated Load Amps) but during the bid stage of a project, this may not be available (note that the FLA/RLA column is blank above). Once a Chiller manufacturer is selected, this information is easy to obtain. MOCP (Maximum Over Current Protection), or MOP as it is sometimes known, is a value that should be used in conjunction with MCA (Minimum Current Ampacity) to size the Wide Spectrum Harmonic Filter, if FLA/RLA is not available.

Again, there is often a mix of linear and non-linear loads within the assembly, so you must size the WSHF to handle both the linear and non-linear loads. A useful explanation of ACC's current ratings can be found at:

https://www.titus-hvac.com/softwares/MOPulator/pdf/howwecalculate.pdf

on the Titus HVAC website or on the Mirus website https://www.mirusinternational.com/downloads/howwecalculate.pdf. Also, the same notation on Constant Torque and Variable Torque applies.

Some Chiller Package Manufacturers utilize 12 or 18 multi-pulse drives and even Active Front End Drives within their assemblies. Care must be taken in accepting these harmonic solutions, since the performance may be compromised by pre-existing power conditions (ie. voltage distortion and voltage imbalance) or the injection of high frequency harmonics from the active components. Multipulse Drives are dependent upon the electrical source having low levels of voltage distortion (typically < 2%) and near balanced source voltage (typically < 1%). These two assumptions are often exceeded due to heavy system non-linear loading and system unbalanced single phase loading. Active Front End Drives (AFE Drives) should also be avoided since they shift the predominant current harmonic above the 50^{th} (above 3 kHz) where it is difficult to measure and can have damaging effects on other solid-state loads within the overall system. More information on this can be found in the paper – 'Active Harmonic

Mitigation – What the Manufacturers Don't Tell You'. The cost effective and practical solution is to specify passive Wide Spectrum Harmonic Filters (WSHF). For more on the concerns with multi-pulse and Active Front End harmonic mitigation solutions, see Appendix A.

- **<u>Chill Water Pumps (CWP), Chilled Water System Pumps (CWSP) & Hot Water System Pumps (HWSP):</u>**

These are simple to isolate and size. Typically, they are single Motor/VSD units with clearly stated motor HP's (Table 3). Simply size the Passive Filter to the motor HP, and place it in line with the device and downstream of the circuit breaker protection, following NEC codes for Line of Sight rules.

Table 3: Pump Schedule

PUMP SCHEDULE			
MARK	SERVICE	HP	ELECTRICAL
CWP-1	CHILLER PUMPS, ACC-1	7.5	480/3/60
CWP-2	CHILLER PUMPS, ACC-2	7.5	480/3/60
CWP-3	CHILLER PUMPS, ACC-3	7.5	480/3/60
CWSP-1,2	CHILLED WATER SYSTEM PUMPS	40	480/3/60
HWSP-1,2	HOTWATER SYSTEM PUMPS	20	480/3/60

<u>Sizing/Installation Example for an ACC:</u>

Fig. 3 shows a typical filter installation connection diagram. In the case of a packaged system like an ACC or RTU, the noted VSD load would be the entire ACC or RTU. As shown, the filter is series connected near the non-linear load, the VSD, where it can control the harmonics as close to their source as possible. This will reduce the overall voltage distortion in the system by lowering the current harmonic injection into the system impedance.

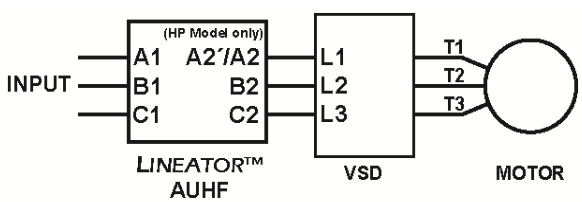


Fig. 3: Typical VSD System with Lineator

But from a practical point of view, we must know where the visible disconnect is and follow NEC code for the installation. Where the disconnect device is contained within the ACC or assembly and no other visible disconnect/isolation device is within line of sight upstream, connect the filter between the MCB or fuse and the downstream loads (Fig. 4A). This will provide isolation and overcurrent protection for the filter. If there is a line of sight isolation and OC protective device, then a more conventional installation is possible (Fig. 4b).

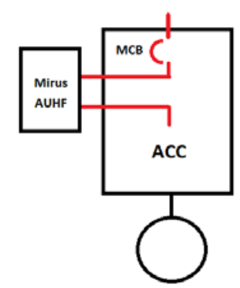


Fig. 4a: Installation without Line-of-Site Upstream Disconnect

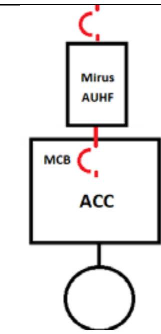


Fig. 4b: Installation with Line-of-Site Upstream Disconnect

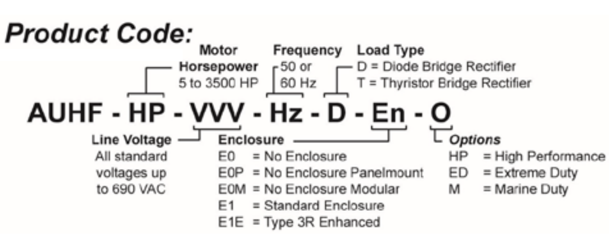
Using data from Table 2, sizing the filter can be determined. Each ACC has an MCA of 417A and a MOCP of 500A but no FLA or RLA is noted. If the FLA or RLA value for the input to the ACC Chiller is known, then it is suggested to size to this ampacity, which can allow for the most optimal filter selection. Since the total ACC FLA or RLA value is not available, the MCA rating should be used as the target current rating for the filter. Then from the filter rating schedule (Table 4), the closest output current rating can be found at the appropriate voltage (480V in this case) that meets or exceeds the ampacity. The correct selection would then be a 350HP (250kW) which has an output current rating of 419A at 480V. Mirus standard Lineators are constant torque rated so can handle 50% overload for up to one minute without compromising the filter. Optimal filter performance is achieved when matched closely to the load so selecting the next size up, 400HP unit, would not be recommended.

Table 4: Lineator AUHF Sizing Schedule

Motor Size		Lineator Rating (3-Phase)								480V (60Hz)			
		Current Rating (Amps)								Standard Enclosure		Enhanced Enclosure	
HP	kW	460/480V 60Hz		575/600V 60Hz		660/690V 50/60Hz		Output		Case	Weight	Case	Weight
		Input	Output	Input	Output	Input	Output	kVA	kW	Style	lbs [kg][1]	Style	lbs [kg][1]
5	4	7	7	5	5	5	5	6	4.5	SU1	58 [26]	SU1-E	68 [31]
7.5	5.5	9	10	7	7	6	6	8	6.3		67 [30]		77 [35]
10	7.5	12	13	10	11	8	8	10	8.5		78 [35]		88 [40]
15	11	17	18	14	15	12	13	14	13		90 [41]		100 [45]
20	15	23	24	18	19	16	17	19	17	SU2	118 [54]	SU2-E	128 [58]
25	18.5	29	31	23	24	20	21	25	21		130 [59]		140 [64]
30	22	34	36	28	30	24	25	29	25		142 [65]		152 [69]
40	30	46	49	37	39	32	34	39	34		154 [70]		164 [74]
50	37.5	57	60	45	48	40	42	48	42		186 [84]	SU3-E	196 [89]
60	45	69	73	55	58	48	51	58	51	SU3	218 [99]		228 [103]
75	55	85	90	68	72	59	63	72	63		304 [138]		314 [142]
100	75	113	120	90	95	79	84	96	84		323 [147]		333 [151]
125	90	141	149	112	119	98	104	119	104		345 [156]	SU4-E	419 [191]
150	110	169	179	135	143	118	125	143	125	SU4	365 [166]		439 [200]
200	150	226	240	180	191	158	167	191	168		415 [189]	MT3-E	489 [222]
250	185	281	298	225	239	196	208	237	209	MT3	578 [262]		640 [290]
300	200	337	357	270	286	235	249	284	251		585 [266]	MT4-E	695 [316]
350	250	395	419	315	334	275	292	334	292	MT4	800 [363]		1006 [456]
400	315	470	498	375	398	325	345	397	349		825 [374]	LT1-E	1031 [467]
500	400	595	631	475	504	415	440	503	443		915 [415]		1121 [508]

Building the Product Code:

The appropriate product code can be determined from the description below.



- The 'D' designation is used since the drives feature an AC diode bridge front end. Type 'T' would be selected for a DC Drive with thyristor front end.
- The 'HP' option should be chosen if the target current harmonic is < 5% versus < 8%. If IEEE Std 519-1992 is specified, the requirement is < 3% VTHD for hospital applications, so the HP option would then be considered.
- The 'ED' Option is used for extremely high source background voltage distortion (Vd_{bkg}) of 8% or greater, the nominal ambient is 50°C or higher, or for altitude deration above 1000m. This is not a configuration normally used for HVAC or other commercial loading structures but may be relevant in high altitude applications.
- The MD Option is used for Marine and Offshore Installation (MOS), and not relevant for these applications.

From this selection guide, the appropriate product code would be either:

- AUHF-350-480-60-D-E1 for Indoor Standard Duty
- AUHF-350-480-60-D-E1-HP for Indoor High-Performance Construction
- AUHF-350-480-60-D-E1E for Outdoor Standard Duty

- AUHF-350-480-60-D-E1E-HP for Outdoor High-Performance Construction

Sizing/Installation Example for an RTU:

Using data from Table 1, sizing a filter for an RTU can be determined. Per the schedule, RTU-2 has four (4) 10 HP motors and a preheat circuit rated at 40 kW, so the total MCA is 155.3 Amps at 480V. Using the Mirus sizing guide in Table 4, the 150HP (110kW), 179A output current rated filter would be the best match for the application as it is above the 155A MCA requirement. The product code selection procedure described previously should then be followed to select the appropriate filter.

What Non-Linear Loads should be filtered and which ones can just have line reactors?

This is a great question and one that requires a rudimentary harmonic analysis to determine. Often, if the larger sources of harmonic pollution are filtered, thereby turning them into more linear load structures, the smaller non-linear loads can be simply treated with line reactors.

The information given in Tables 1, 2 and 3 were taken from an actual medical center application so can be used for this analysis. Fig. 5 shows a one-line created in Mirus' SOLV computer simulation software from this data. For simplicity, the VSD's are combined into single non-linear load structures in each branch circuit. No harmonic mitigation has been applied.

Without harmonic mitigation, the current harmonics are high (> 28%) resulting in voltage distortion that is very high (> 10%). This is predictable since current harmonics passing through the impedance of the power system will produce voltage harmonics. The impact to the medical equipment can be profound and when switched to a higher impedance emergency Generator source, the voltage distortion levels will be even more severe.

Fig. 6 shows the IEEE Std 519 Compliance Report created by the simulation program. The report shows the limits for voltage and current harmonics for the 2014 version of the standard and the stricter 1992 version. As can be seen, the application fails on all aspects of current and voltage harmonics for both standards.

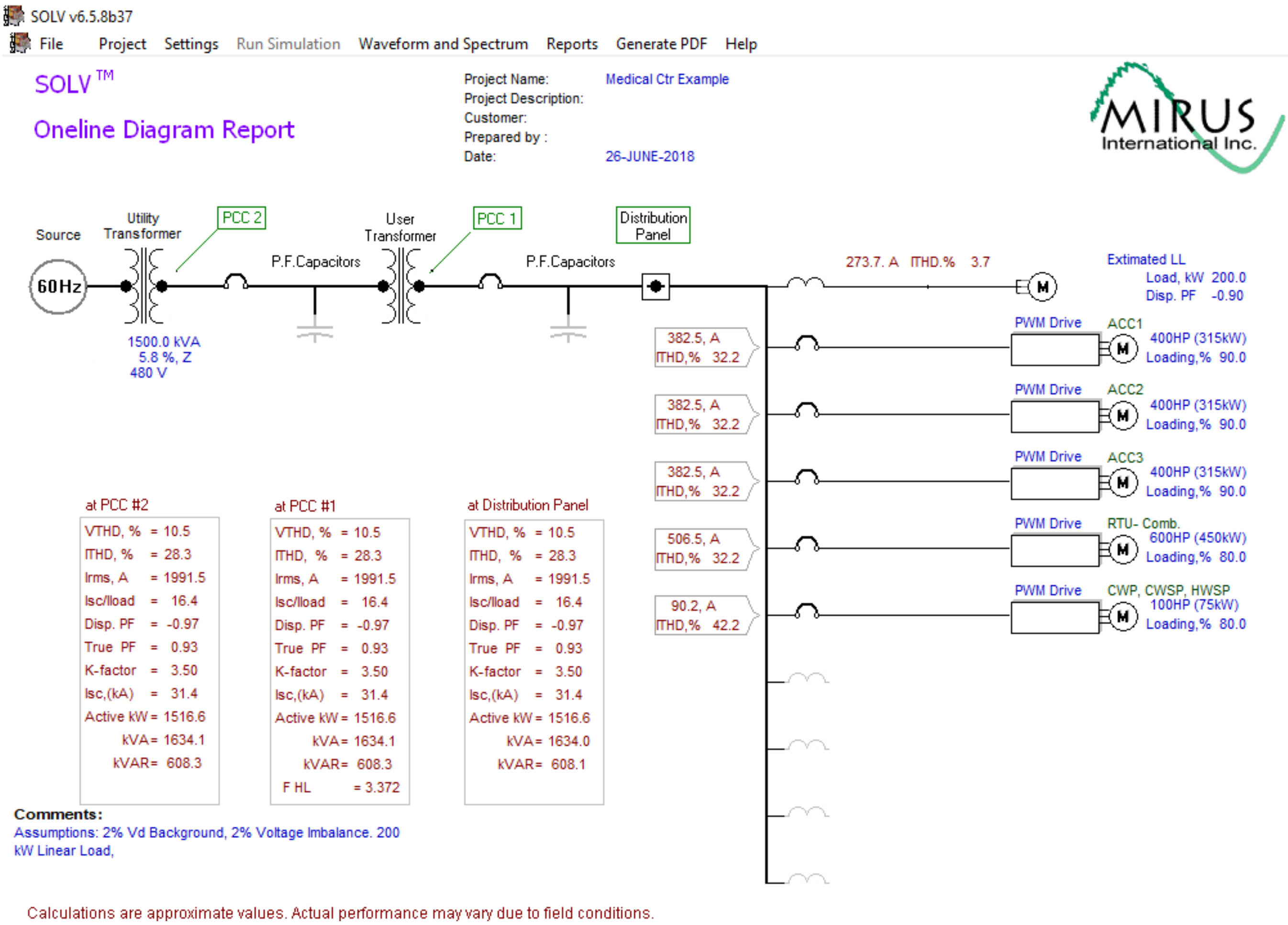


Fig. 5: Computer Simulation 1-Line for Medical Center with No Harmonic Mitigation

Project Name: **Medical Ctr Example**
Point of Coupling: **PCC #2**
Bus voltage at PCC: 480 V
Short-circuit ratio: 16.4

Summary of Compliance with IEEE Std 519:1992 and IEEE Std 519:2014 Harmonic Limits:

		Calculated Value, [%]	IEEE-519:1992 Limit, [%]		IEEE-519:2014 Limit, [%]	
Voltage Total Harmonic Distortion	(VTHD)	10.5	5.0	FAIL	8.0	FAIL
Max.Individual Voltage Harmonic		8.3 { 5}	3.0	FAIL	5.0	FAIL
Current Total Demand Distortion	(iTDD)	28.3	5.0	FAIL	5.0	FAIL
Max.Individual current harmonic	<11	26.6 { 5}	4.0	FAIL	4.0	FAIL
	11 to 16	5.0 {11}	2.0	FAIL	2.0	FAIL
	17 to 22	1.6 {17}	1.5	FAIL	1.5	FAIL
	23 to 34	0.7 {25}	0.6	FAIL	0.6	FAIL
	>35	0.4 {35}	0.3	FAIL	0.3	FAIL

Fig. 6: Computer Simulation IEEE Std 519 Compliance Report for Medical Center with No Harmonic Mitigation

Now adding Mirus High Performance Lineators to just the ACC's (Fig. 7), the results show a vast improvement, but not quite up to the IEEE Std 519 requirements yet.

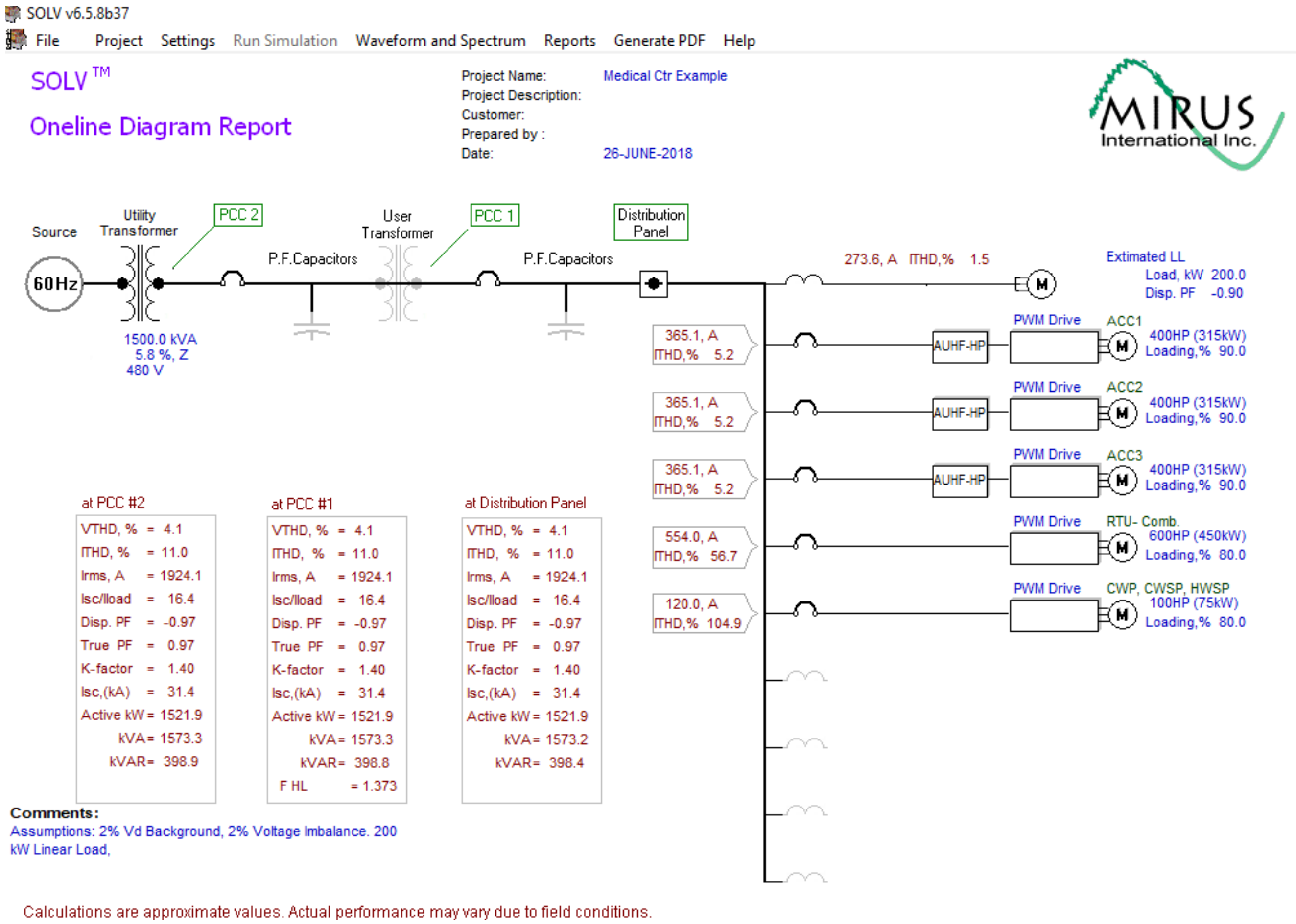


Fig. 7: Computer Simulation 1-Line for Medical Center with Harmonic Mitigation on ACC units only

Project Name: **Medical Ctr Example**
Point of Coupling: **PCC #2**
Bus voltage at PCC: 480 V
Short-circuit ratio: 16.4

Summary of Compliance with IEEE Std 519:1992 and IEEE Std 519:2014 Harmonic Limits:

		Calculated Value, [%]	IEEE-519:1992 Limit, [%]		IEEE-519:2014 Limit, [%]	
Voltage Total Harmonic Distortion	(VTHD)	4.1	5.0	PASS	8.0	PASS
Max.Individual Voltage Harmonic		3.1 { 5}	3.0	FAIL	5.0	PASS
Current Total Demand Distortion	(iTDD)	11.0	5.0	FAIL	5.0	FAIL
Max.Individual current harmonic	<11	10.0 { 5}	4.0	FAIL	4.0	FAIL
	11 to 16	2.0 {11}	2.0	PASS	2.0	PASS
	17 to 22	0.2 {17}	1.5	PASS	1.5	PASS
	23 to 34	0.2 {31}	0.6	PASS	0.6	PASS
	>35	0.2 {35}	0.3	PASS	0.3	PASS

Fig. 8: Computer Simulation IEEE Std 519 Compliance Report for Medical Center with Harmonic Mitigation on ACC units only

This indicates that the bulk of the harmonics are being injected from the ACC's, but additional filtration is required in some of the larger RTU's and other loads. Picking the RTU's with a HP rating above 50, we add Standard Duty filters to these loads and 3% line reactors to the drives that were less than 50HP.

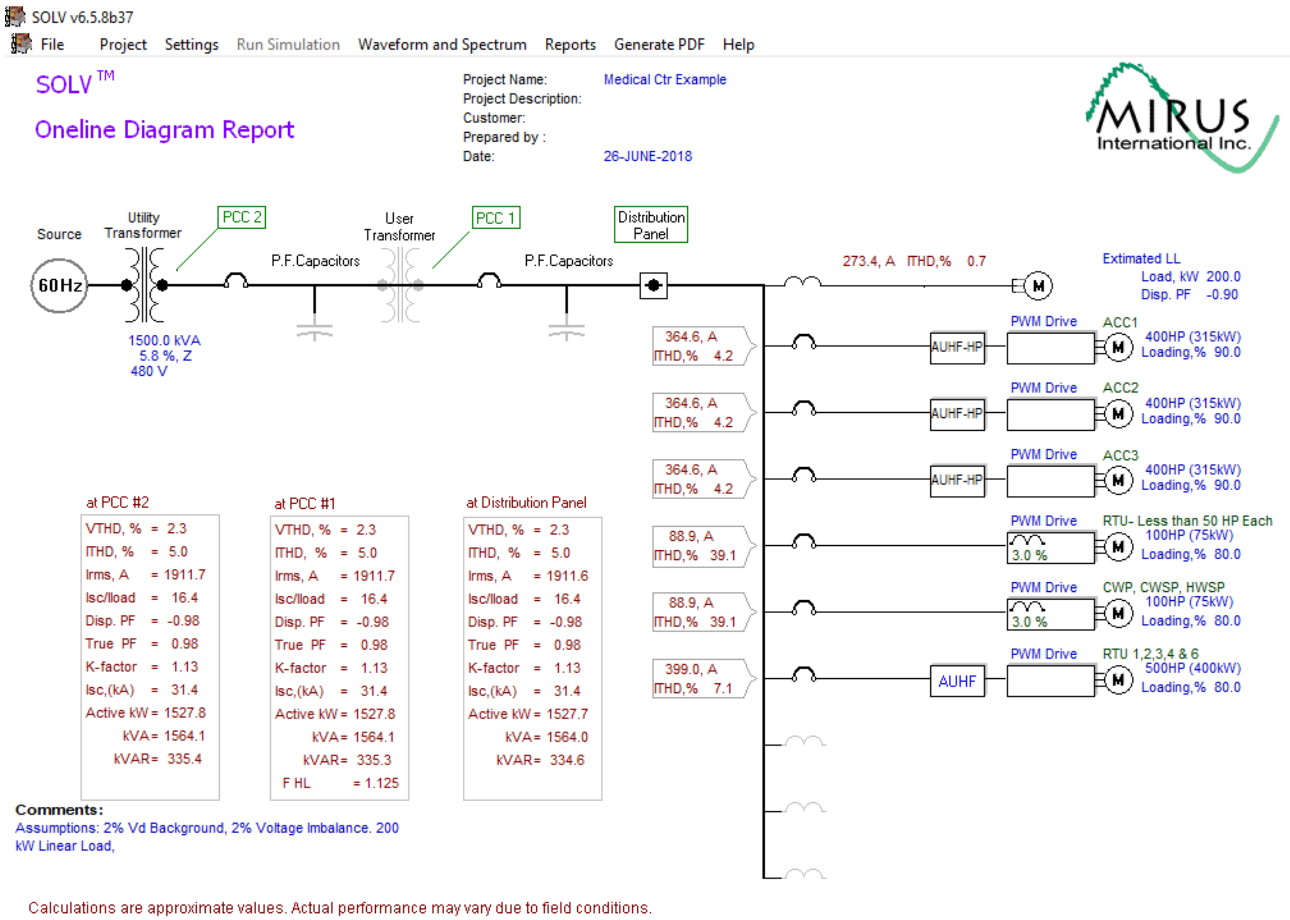


Fig. 9: Computer Simulation 1-Line for Medical Center with Harmonic Mitigation on ACC units and RTUs

Project Name: Medical Ctr Example
Point of Coupling: PCC #2
Bus voltage at PCC: 480 V
Short-circuit ratio: 16.4

Summary of Compliance with IEEE Std 519:1992 and IEEE Std 519:2014 Harmonic Limits:

		Calculated Value, [%]	IEEE-519:1992 Limit, [%]		IEEE-519:2014 Limit, [%]	
Voltage Total Harmonic Distortion	(VTHD)	2.3	5.0	PASS	8.0	PASS
Max.Individual Voltage Harmonic		1.4 {7}	3.0	PASS	5.0	PASS
Current Total Demand Distortion	(iTDD)	5.0	5.0	PASS	5.0	PASS
Max.Individual current harmonic	<11	3.4 {7}	4.0	PASS	4.0	PASS
	11 to 16	1.7 {11}	2.0	PASS	2.0	PASS
	17 to 22	0.3 {17}	1.5	PASS	1.5	PASS
	23 to 34	0.2 {29}	0.6	PASS	0.6	PASS
	>35	0.1 {35}	0.3	PASS	0.3	PASS

Fig. 10: Computer Simulation IEEE Std 519 Compliance Report for Medical Center with Harmonic Mitigation on ACC units and RTUs

As can be seen, IEEE Std 519 requirements can be fully met with only partial filtering by focusing on the largest harmonic polluters and specifying 3% line reactors for the smaller VSD loads. Line reactors are not required for filtered VSDs and doing so would introduce additional voltage drop and losses compromising overall energy efficiency. Of course, if the VSDs come equipped with AC reactors or DC chokes, they can remain. This simulation has been done using real-world conditions with background voltage distortion and source voltage imbalance. Simulations that do not include these two factors, are simply analyzing laboratory conditions and are therefore, of limited value.

Summary:

Eliminating harmonic distortion in a Hospital or other Medical Facility need not be a difficult task. Simple to apply and very effective solutions are available to reduce the harmonic current distortion introduced by the many non-linear loads found in these facilities. For assistance in designing your harmonic mitigation strategy, please feel free to contact Mirus directly, using the information found in the footer.

1-888-TO MIRUS (1-888-866-4787) | Tel: 905-494-1120 | Fax: 905-494-1140 | Email: mirus@mirusinternational.com

Appendix A: Concerns Related to Multipulse and Active Harmonic Mitigation Solutions

The ability of multipulse VSD configurations, such as 12 or 18 pulse, to mitigate harmonics is greatly dependent upon the level of background voltage distortion and source voltage imbalance in the system. In a nutshell, the greater the Source/Background Voltage Distortion (Vd_{bkg}) and Source Voltage Imbalance (V_{imb}), the greater the impediment to the harmonic cancellation of the phase shifted transformer due to flux and load imbalances. The practical limit on 18 pulse deployment is less than 1% Vd_{bkg} and 1% V_{imb} but all circuits have their own challenges. A graphical representation of the vulnerability of an 18 Pulse drive to Vd_{bkg} and V_{imb} is shown below.

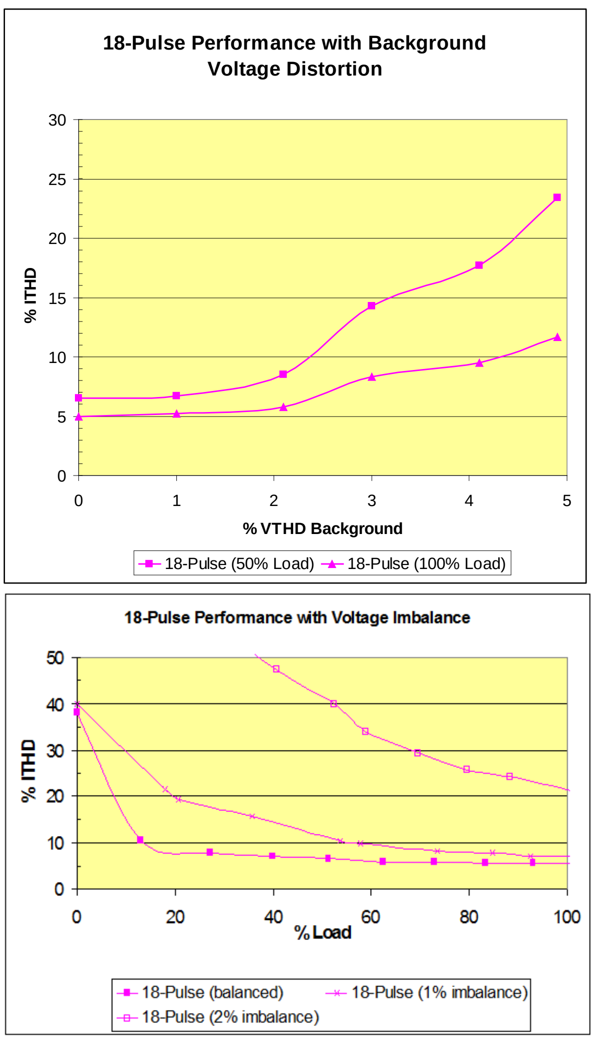
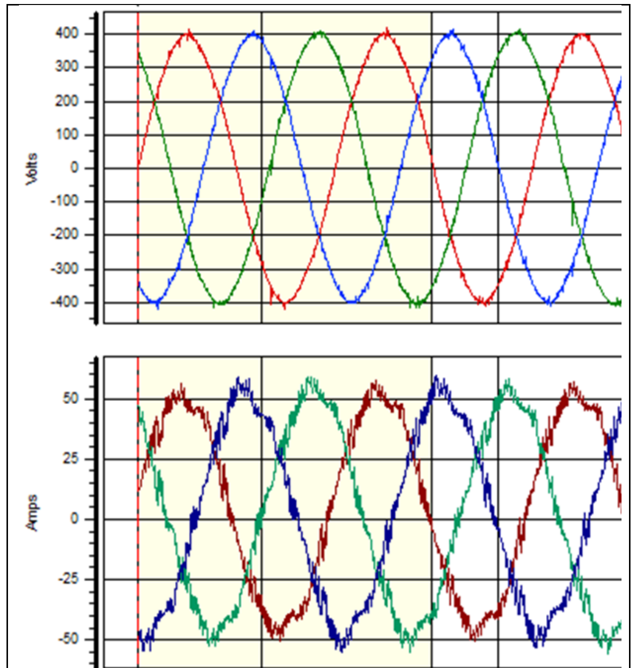


Fig. 11: 18 Pulse Performance

Active Front End Drives (AFE's) and Active Harmonic Filters (AHF's) introduce high order harmonics well above the 50^{th}. These can have disastrous effects on other solid-state equipment within the circuit, as well as, Emergency Generator Regulation Equipment. As stated, an IEEE published and peer reviewed paper is available for reference. Below are wave traces from this paper that highlight the issue.



Voltage and current waveforms at input of 40 HP (30 kW) AFE drive.

Fig. 12: Input waveform of AFE

As can be seen, there is a "fuzzy" current waveform present, a typical indication of the presence of high frequency current harmonics being created by the IGBT/MOSFET switching rectifier/front end. You will also see a high frequency noise on the associated voltage waveform due to the high frequency current injection.

The harmonic spectrum for the current waveform is shown on the following page and highlights the potential for introducing problems with higher order harmonics when using AFE or AHF devices within the circuit. Although not what the manufacturer promised (ie. < 5%), the Ithd below the 50th harmonic is quite reasonable at < 8% and meets IEEE Std 519-2014. But the real issue is when you measure out past the 50th harmonic. Measuring through to the 100th, the Ithd now exceeds IEEE-519 Standards and settles in between 8.9% and 9.9% and over 10% when measured to the 150th. This high frequency noise can have significant impact on your system integrity and the many sensitive equipment found in medical facilities.

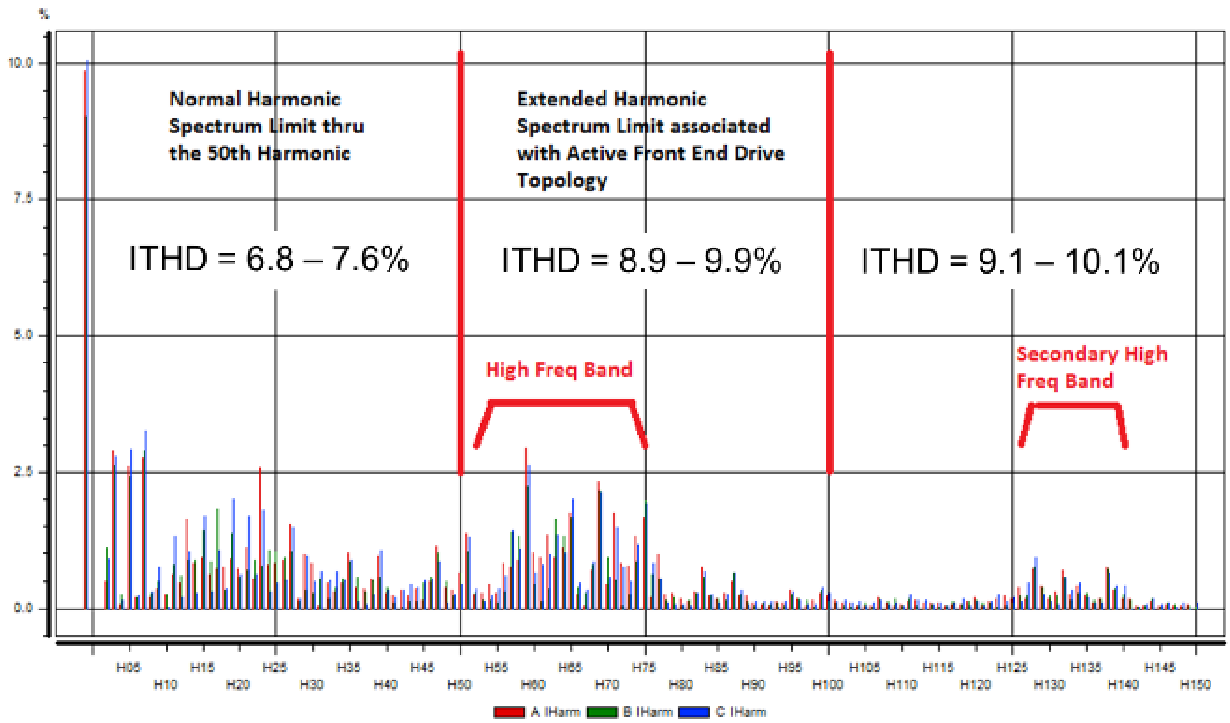


Fig. 13: AFE current harmonic spectrum measured up to the 150th harmonic.