Impact of Small Horse-Power Adjustable-Speed Drives, as a Significant Part of the Plant Load

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Abstract

For filter application and harmonic simulation it is important to understand how loads interact with each other. This paper describes how the harmonics of small Pulse Width Modulated (PWM) drives combine when fed from a common bus. Effects on the power system at the local bus and throughout the plant are discussed.

Background

The information in the paper is based on the study of a large industrial plant in Ireland. Voltage at the point of common coupling with the utility is 110kV, plant distribution is 10kV, and utilization voltages are 3.3kV and 400V. The plant has a capacity of 60MVA and operates between 25 and 30MVA. Sixteen utilization buses are supplied from double-ended substations, each operating at 50% of capacity. The PWM drives are located at six of the 400V buses, representing up to 85% of the bus load, and 20% of the plant load.

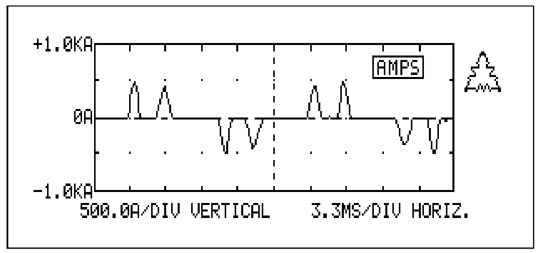
This paper will concentrate on a single 2000kVA step-down transformer from 10kV to 400V. The 14 PWM drives represent 100% of the load for the field measurements. The drives are set at a constant speed, but at various loads. Three bus ducts connect the drives to the low voltage bus. Measurements were taken at VM1, AM1, AM2, and AM3 as shown in Figure 3. These represent the low voltage bus, a single bus duct, and a single drive respectively.

Significance of PWM Drives

When modeling power electronic devices (e.g. variable speed drives) using SCR bridge rectifiers, the harmonic content of several drives in parallel would be less than that of a similar large drive. This is due to the cancellation between harmonics. The cancellation is a result of harmonic currents having different phase angles, due to the SCR's having different control firing angles. Because PWM technology utilizes diodes to rectify the AC power, the fundamental voltage is the control for all of the rectifiers. With this in mind, one would expect that the current spectra from ten PWM drives would be virtually the same as that of one, but with ten times the magnitude. This paper will show that this is only true if the drives are in close proximity to each other.

Input Chokes

As can be seen in Figure 1 below, the current distortion from a PWM drive can be quite severe. This is caused by the capacitor on the



PHASE A CURRENT SPECTRUM 11:49:06 AM
Fundamental amps: 103.8 A rms
Fundamental freq: 60.0 Hz

HARM	PCT	SINE PHASE	HARM	PCT	SINE PHASE
FUND	100.0%	10°	2nd	1.1%	78°
3rd	3.9%	-122°	4th	0.5%	167°
5th	82.8%	-125°	6th	1.7%	-56°
7th	77.5%	79°	8th	1.2%	131°
9th	7.6%	-80°	10th	0.7%	112°
11th	46.3%	-52°	12th	1.0%	-48°
13th	41.2%	149°	14th		
15th	5.7%	-26°	16th	0.3%	172°
17th	14.2%	19°	18th	0.4%	78°
19th	9.7%	-145°	20th	0.4%	-138°
21st	2.3%	19°	22nd	0.5%	-14°
23rd	1.5%	-148°	24th	0.5%	89°
25th	2.5%	108°	26th	0.7%	-135°
27th	0.9%	-29°	28th	0.3%	9°
29th	2.0%	-29°	30th	0.2%	55°
31st	2.0%	169°	32nd	0.3%	149°
33rd	0.5%	-19°	34th	0.4%	-61°
35th	0.3%	-147°	36th	0.1%	25°
37th	0.8%	75°	38th	0.3%	148°
39th	0.5%	-58°	40th		
41st	0.6%	-100°	42nd		
43rd	0.7%	114°	44th	0.1%	113°
45th	0.4%	-59°	46th	0.1%	-32°
47th	0.2%	165°	48th		
49th	0.4%	44°	50th	0.3%	144°
ODD	130.9%		EVEN	3.0%	
THD:	130.9%				

Figure 1

DC bus taking in energy from the power system four times per cycle resulting in the double hump wave form. A common resolution to this problem is in the form of an input choke as seen in Figure 2. The inductance reduces the rate at which the capacitor

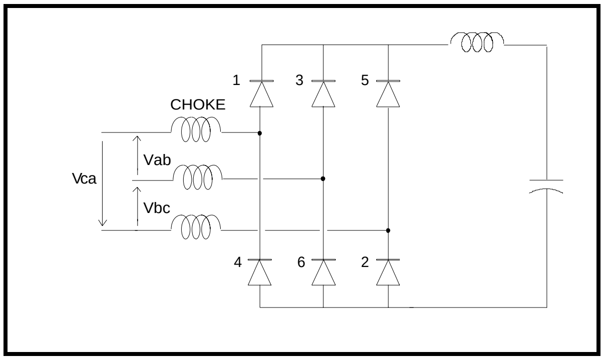


Figure 2

may be charged and results in a less distorted wave form. Typically chokes are sized as three or four percent impedance based on the drive rating. In this case:

10HP, 380V, 3% input choke

$$X_{BASE} = \frac{V^2}{MVA_{DRIVE}}$$

$$X_{CHOKE} = X_{BASE} \cdot \frac{\%Choke}{100\%}$$

$$X_{CHOKE} = \frac{0.38^2}{0.01} \cdot 0.03 = 0.43\Omega$$

$$L_{CHOKE} = \frac{0.43\Omega}{2\pi \cdot 50Hz} = 1.38mH$$

In contrast to this, a single 200HP drive with a 3% choke would have one-twentieth the inductance. If the drives acted independent of each other, each drive would require 1.38mH to limit its harmonic distortion. Table 1 shows the impact that different impedances have when placed at the input of a single 10HP PWM drive. The terminal impedance is shown as a percent of the base impedance for a 10HP drive, this is the base impedance shown above. Harmonic currents are shown in percent of the fundamental, and were calculated using the Electromagnetic Transient Program (EMTP).

Table 1

Condition	%Z	5th	7th	11th	13th
System Only	0.08	87	79	58	47
Bus Reactor (200HP)	0.24	79	65	35	23
3% Choke	3.00	34	14	7	5
4% Choke	4.00	30	11	7	5

The table shows that a single choke sized for ten drives on a bus, the second condition in the table, has little affect on the current distortion from a single drive. When several small PWM drives are in close proximity to each other, they will appear to be one large drive. This is because the drives see a similar voltage and their capacitors charge at about the same time. So the bus reactor would be effective, if it fed 20 10HP drives. If the number of drives became a significant percent of the transformer rating, the system impedance would appear to be a choke to the combined drives. For instance, a 2000kVA transformer with 6% impedance with 1000kVA of drive load would look like a 3% choke to the combined drives. This is in contrast to condition number one, where this same impedance looks like a 0.08% choke to a single 10HP drive.

Measurements

In Figure 3, a one-line diagram of the measured bus is shown. From the bus ducts, the drives are fed from AWG #8 cables that vary in length between 20 and 40 feet. Bus duct feeders vary in length from 200 to 500 feet and are AWG #3/0. Each of the bus ducts have four to five drives that were running at a fixed speed for the duration of the test. Measurements at bus S2A were made with the tie breaker open and closed. Minimal load was connected at bus S2B while the tie was closed. Measurements at AM2 and AM3 were only made while the tie breaker was open. Pertinent data is shown in table 2.

The triplen currents measured at all the locations are larger than what would be expected for steady-state measurements. Typically, these would be less than 1% of the fundamental for a three-phase PWM drive. This indicates that either the drives being measured were in transition or that a large load, at another location in the plant, was switched causing a slight change in voltage. Because the triplen currents were seen in all of the measurements, it is suspected that

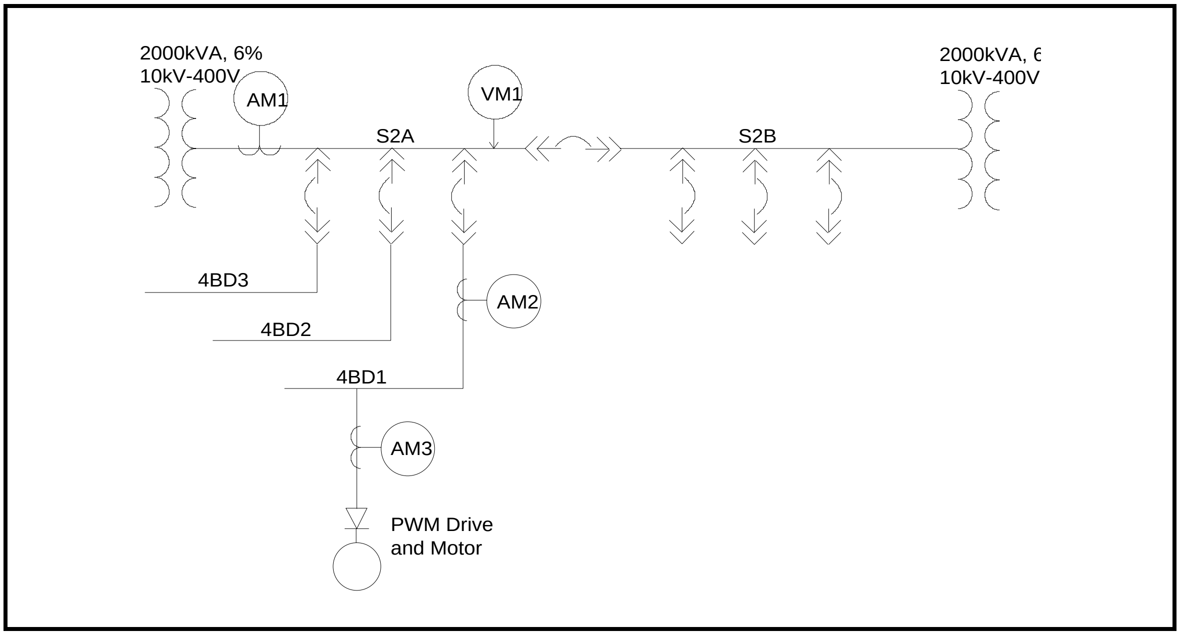


Figure 3

the drive loads were varying. Because the drives were operating fan motors at a constant speed setting, the changes in load are assumed to have been small.

Analysis

From Table 2, it is seen that voltage distortion decreases with the tie breaker closed, but the current distortion increases. The decrease in voltage distortion can be attributed to the system impedance being halved by the two transformers in parallel with each other. The measurements in Table 2, also show that the current flowing through AM1 is reduced by about half with the tie closed. In other words, the voltage distortion decreases because the transformers are sharing the distorted current being supplied by the drives. The THD doesn't decrease by 50% because part of the voltage distortion is due to other loads in the plant and on the utility system. With the tie closed, there is a 1.35% increase in the bus voltage. This will increase the ΔV between the drives rectifier output and the D.C. bus allowing an increase in charging current. With a combination of increased charging current and the reduced system impedance, the capacitors of the PWM drives charge quicker, resulting in the current being more distorted.

Comparing the measured data at AM2 and AM3, it is seen that the relative distortion is fairly consistent in magnitude at all harmonics except the triplens. This suggests that the currents of all the drives on bus duct 4BD1 add together. A combination of short feeders with little fundamental current allow the drives to see the same voltage and look like one large drive drawing 40.0 Amps. Slight variations in magnitude and phase angle are attributed to the drives operating at slightly different speeds.

The significant decrease in current distortion at bus S2A is due to a phase shift between harmonic currents from the three bus ducts. The effect of this is shown in Figure 4.

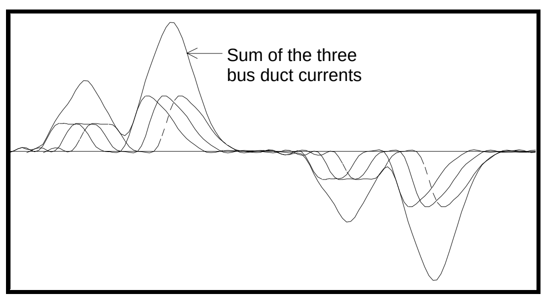


Figure 4

From the measured data, it was determined that the current measured at AM2 was 27^{o} wider per half-cycle than that measured at AM3. This means that the combination of the drives fed from bus S2A conducted charging current longer than that of the four drives at bus duct 4BD1. With the use of a computer simulation, the measured current at AM2

Table 2

Condition	Location	Fund. A | Deg	Harmonics, (%Fund. | Deg) 3rd	5th	7th	9th	11th	13th	THD
Tie Closed	AM1	67.2 | 083	5.8 | 143	42.5 | 305	25.9 | 134	2.6 | 161	6.7 | 025	5.6 | 284	51.1
Tie Open	AM1	142 | 096	12.6 | 174	34.6 | 320	15.6 | 173	2.3 | 055	6.1 | 120	3.6 | 359	40.8
Tie Open	AM2	40.0 | 082	30.9 | 187	63.3 | 294	44.5 | 106	10.6 | 283	7.0 | 028	9.2 | 205	85.9
Tie Open	AM3	12.7 | 081	7.8 | 125	69.9 | 266	38.0 | 098	19.1 | 004	10.7 | 176	7.1 | 222	85.2
Tie Open	VM1	229.3 | 086	0.1 | 097	3.2 | 044	2.5 | 258	0.3 | 142	1.0 | 201	0.7 | 083	4.4
Tie Closed	VM1	232.4 | 087	0.6 | 091	2.1 | 038	2.2 | 259	0.3 | 099	0.6 | 154	0.5 | 071	3.3

was reproduced. It was then copied again with phase shifts of 12.5º and 25.0º from the original snapshot. These three wave forms and there resulting sum are shown in figure 4. The resulting wave form is a close approximation of the current measured at AM1.

The phase-shift in the three currents is attributed to two factors. The rate at which the drives at each bus duct take in energy to charge the drive capacitors and the randomness of load conditions for each drive. Voltage magnitude at the bus ducts and the inductance introduced by the feeder cables and step-down transformer affect the rate the capacitors will charge. Drive load will impact the amount of energy required during each conduction period.

It is not unreasonable to expect a 0.5 to 1.5% drop in voltage across the three bus duct feeders. A 0.5% drop in voltage was calculated for the longest feeder. As discussed in the beginning of this section, this is enough to impact the current distortion at the bus ducts by decreasing the capacitor charging current.

Secondly, the step-down transformer and bus duct feeders look like a choke to the combined load. From the calculations below, it is shown that the system appears to the drives as a weak choke one-fifth in size of that typically recommended. Along with the voltage drop across the cable, this limits the current THD to 85.9%, about 20% less than isolated drives of this type and size without chokes.

Impact of system impedance at bus duct 4BD1:

$$MVA_{Base} = 0.03\,MVA$$

$$X_{Base} = \frac{0.4^2}{0.03} = 5.33\Omega$$

$$X_{Trans} = \frac{0.4^2}{2.0} \cdot 0.06 = 0.0048\Omega$$

$$X_{Cable} = 0.026\Omega$$

$$\%Choke = \frac{0.026 + 0.0048}{5.33} \cdot 100\% = 0.6\%$$

It should be noted that no appreciable phase-shift between the S2A bus and 4BD1 bus duct voltages was suspected. Calculations for the feeder discussed above show less than 1º change in angle across the cable. For this reason, it is considered to play a small factor in the phase-shift of the bus duct currents.

Conclusions

Three points of interest have been presented. If several PWM drives see a similar voltage, in magnitude and phase relationship, the drives will add to look like one large drive. Second, the combined drive load can become large enough that the system impedance acts as a choke to that load. Finally, small differences in voltage magnitude will cause a change in the conduction period for a drive.

For the measurements presented in this paper, differences in length by 100 feet in bus duct feeder cables resulted in a decreased current distortion at the S2A bus. It is presented here that this is due to a shift in the conduction period for the drives at each bus duct. It was measured that the current at bus S2A conducted 1ms longer than the current at bus duct 4BD1. To the power system, this looked like a 12% increase in the conduction period. Because the system was allowed to supply energy to the drives over a longer period of time, the current distortion was less.

This reduction in distortion is important to the sizing of shunt filters. Based on the findings of this paper, it was possible to design filters for the plant half the size than if the drives were considered to add linearly. This assumes that the filters will be applied at bus S2A. There is a concern that the filter may alter the system impedance, allowing the current distortion to increase and possibly over load the filter. Placing chokes at individual drives would avoid this problem completely. The effects described in this paper would have been local to each drive resulting in a more predictable and lower distortion level than observed.

The key to accurate computer simulations is characterizing the loads. When this facility was first modeled, it was assumed that the PWM drive spectra added without cancellation. The result of the analysis was peculiar looking wave forms and rather large and expensive filters. Using the rationale outlined, we developed a reasonable spectrum to represent the drive load. This was later verified by the measurements presented.

[1] T.E. Grebe, and L. Tang, "Analysis of Harmonic and Transient Concerns for PWM Adjustable-Speed Drives Using the Electromagnetic Transients Program," Presented at the 5th International Conference on Harmonics in Power Systems, September 23-25, 1992, Atlanta.

[2] "Power Quality Considerations for ASD Applications," EPRI CU.3036, 1991.

Brian Prokuda was born in Detroit, Michigan on September 29, 1966. He received his BS degree in Electrical Engineering from Michigan Technological University in 1988 and a MS degree in Electric Power Engineering from Rensselaer Polytechnic Institute in 1992. Prior to joining Electrotek, Brian designed process control and drive systems for the Dow Chemical Company. Presently, he performs harmonic and transient studies along with managing the data collection process for the EPRI Distribution Power Quality project.