THE CONSTANT VOLTAGE TRANSFORMER (CVT) FOR MITIGATING EFFECTS OF VOLTAGE SAGS ON INDUSTRIAL EQUIPMENT

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ABSTRACT

Electric power quality problems associated with interactions between distribution and industrial process control systems can be prevented. Surveys of large users that buy power at the transmission and distribution voltages turn up relatively few complaints about the quality of their incoming power, while surveys of small users connected at secondary voltages turn up numerous complaints about the quality of their incoming power. Three major changes in the characteristics of customer loads and power distribution systems have altered the nature of the power quality equation: (1) greater sensitivity of devices and equipment to electric power variations, (2) the interconnection of sensitive loads in extensive networks and automated processes, and (3) an increase in loads that use power electronics in some type of power conversion configuration [1][2]. This paper presents applications of the constant-voltage transformer (CVT) for mitigating the effects of electric service voltage sags on industrial equipment in an oil refinery. Unlike conventional transformers, the CVT or ferro-resonant transformer allows the core to become saturated with magnetic flux, which maintains a relatively constant output voltage during input voltage variations such as undervoltages, overvoltages, and harmonic distortion.

BACKGROUND

These above-stated changes have created an aggressive market for "externally" power conditioned and "internally" hardened equipment that can protect loads from the wide variety of power quality variations that may cause productivity problems. It will be shown that a CVT (see Figure 1) can maintain a relatively constant output voltage despite brief variations in input voltage. If properly sized, a CVT can regulate its output voltage during a voltage sag to sixty percent of nominal voltage for virtually any duration, as shown in Figure 2. However, they are not effective during momentary voltage interruptions or extremely deep voltage sags (generally below fifty percent of nominal). CVTs are often favored over other sag-mitigation devices because they are relatively maintenance-free, with no batteries to replace or moving parts to maintain [3]. The following paragraphs will describe what to look for to determine if a CVT application makes sense; how to size the CVT; a detailed case study of a refinery application that points out what benefits were derived; and how reliable the existing CVT retrofit applications have been.

SYMPTOMS OF POWER QUALITY PROBLEMS

There is a growing need to ensure electric service compatibility between end-user equipment and the utility power system. Nowadays, tiny electric supply disturbances can generate big headaches. Electric service transient phenomena, often less than a few milliseconds, are nothing new, but they rarely fazed older equipment. Today, delicate computer chips with microscopic wiring are less tolerant to electricity supply power quality problems. The results can be

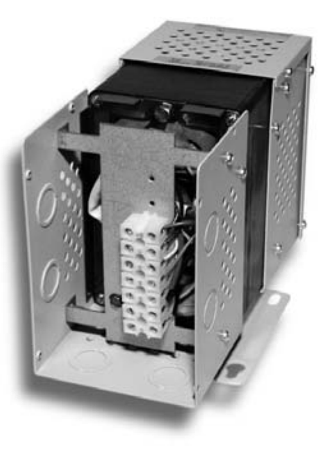

Figure 1. A constant voltage transformer, also called a ferro-resonant transformer, regulates its output voltage without switching to an alternate power source, such as batteries.

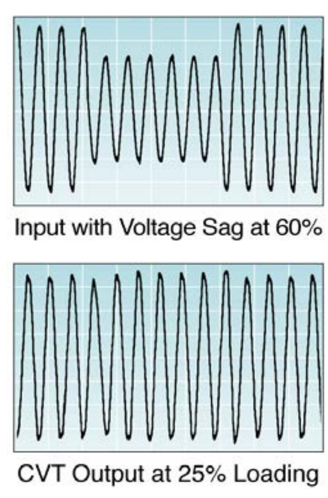

Figure 2. During a voltage sag to sixty percent of the nominal voltage, a properly sized CVT regulates its output voltage within the requirements of the connected loads.

burned-out equipment, scrambled data, and lost revenue. What is a *power quality problem*? It is any deviation of electricity applied to the equipment that results in damage or misoperation of electronic equipment or other electrical devices. Some common symptoms of power quality problems in facilities are:

- unexplained equipment trips or shutdowns
- occasional equipment damage or component failure
- erratic control of process performance
- random lockups and data errors
- power system component overheating

Power quality problems can be complicated, involving the facility wiring, natural phenomena such as lightning, interacting facility equipment, and equipment connections to the electric power system. Most commercial and industrial production machinery are typically designed to operate with flawless electricity from the electric utility; however, many things interfere with electricity as it travels from the utility to customer's equipment that produces revenue creating products and/or services. CVTs are particularly applicable to industrial-process control devices such as programmable logic controllers, motor starter coils, and the electronic control circuits of electrotechnologies. CVTs are often used to sustain the logic voltage or critical "hold-up" functions of these loads during voltage sags.

CVT APPLICATION CONSIDERATIONS AND SIZING GUIDELINES

Because the type of loads connected to a CVT may range widely, the startup and steady-state operational characteristics of each load must be well understood before deciding on the appropriate power rating of a CVT. Most industrial loads, whether a starter or contactor coil, a switch-mode power supply, or even a light bulb, will have an inrush current when it is first turned on or when it cycles on during normal process operation. If a CVT is sized without considering the inrush currents of all connected loads, the CVT output voltage may sag, causing other sensitive loads on the output to shut down.

The ability of a CVT to regulate its output is generally based upon two characteristics of the connected loads, both of which are related to current and both of which must be determined to properly size a CVT. First, you must determine the amount of steady-state current drawn by all connected loads during their normal operation. As shown in Figure 3, the lower the ratio between the actual current drawn by the connected loads and the rated current of the CVT, the better a CVT can regulate its output voltage. For example, a 1 kVA CVT loaded to 1 kVA will not mitigate voltage sags nearly as well as the same CVT loaded to 500 VA, and performance is even better if the same 1 kVA CVT is only loaded to 250 VA. Moreover, according to CVT laboratory testing [3], a CVT rated at less than 500 VA may not be able to handle even moderate inrush current. Therefore, a minimum CVT rating of 500 VA is seldom considered.

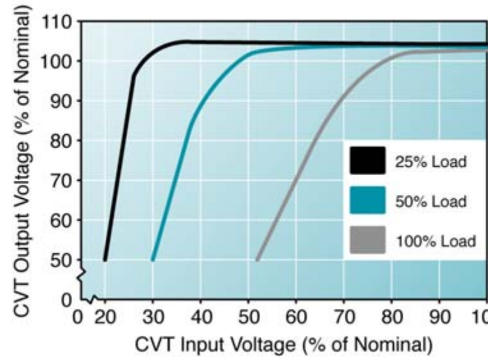

Figure 3. As the CVT load increases, the ability of the CVT to regulate its output voltage decreases.

The second characteristic of a CVT load is its inrush current. Values for inrush current and steady-state current of the connected loads will enable you to effectively size a CVT. Follow the procedure below to obtain the current characteristics of each circuit or load to be connected to the CVT.

HOW TO SIZE A CVT TO MITIGATE THE EFFECTS OF VOLTAGE SAGS

Step 1: Identify the Loads---Identify the circuit connections of each load to be connected to the CVT and locate an accessible point to measure load and circuit current.

Step 2: Select the Right Meter--- Because most of the equipment used in industrial control operations do not have easily obtainable nameplate data, a true RMS ammeter (or multimeter) is required to accurately estimate the current draw of loads to be connected to a CVT. Additionally, the meter must be able to capture transient peak current to measure inrush current [4]. However, avoid using RMS calibrated meters, which will result in erroneous readings for a load that draws non-sinusoidal currents [5].

Step 3: Measure the Maximum Steady-State Current---Set the meter to measure the maximum steady-state AC RMS current of each circuit to be connected to the CVT. Steady-state current is the current drawn by a load over a long period. For example, a programmable logic controller and a starter coil connected to the same circuit draw steady-state current any time they are on, but the starter coil may be on only a portion of the process cycle. Therefore, make sure that all loads in the circuit to be measured are in their normal operating state before measuring the circuit current. Steady-state current should not be measured when a load cycles (turns on or off automatically) or when it is first turned on and draws an inrush of current. If any loads on the circuit to be measured turn on or off automatically, then set the meter to record the maximum steady-state RMS current during a complete process cycle. Using either the current-probe method described in Figure 4 or by connecting your meter in series with the line conductor, measure the maximum steady-state current of each load. The sum of all steady-state currents you record should give you a clear steady-state current demand on the CVT.

Figure 4. To eliminate the need to break a circuit during current measurements, measure current with a clamp-on current probe attached to a true RMS meter by clamping onto the hot conductor of a load circuit.

Step 4: Measure the Inrush Current--- Make sure that all loads to be connected to the CVT are turned off and have been in the off position for at least one minute. This will ensure that any power-supply capacitors, which may hold energy for a short time after a load is turned off, have discharged. Set the meter to record maximum peak AC current over a one-millisecond period, not over a 100 millisecond period. With the meter set in a "record and hold" mode, manually turn on and off each circuit to be connected to the CVT at least eight times, leaving the load off for one minute in between each measurement. Such repeated measurements are necessary to increase the chances of capturing the highest inrush current of the load, which occurs close to the peak of the input-voltage sine wave. Turning on and off some loads may be difficult, but this step is critical to properly sizing a CVT. Enter the highest recorded peak current measurement for each load into a CVT Sizing Worksheet similar to that shown in Table 1.

Step 5: Size the CVT--- Add together all the steady-state currents in the worksheet and then multiply the resulting value by the circuit voltage to get the combined steady-state VA of all CVT loads. Then select the highest peak inrush current measurement and multiply this value by the circuit voltage to get the worst-case inrush VA for all loads. For optimum regulation during input-voltage sags, the VA rating of the CVT should be at least 2.5 times the steady-state VA calculated in the Worksheet. For example, if the steady-state VA calculation is 490 VA, then the recommended size of the CVT would be 1225 VA or more. For good sag regulation of the CVT output voltage during load starting or cycling, the VA rating of the CVT should be at least half of the maximum inrush VA calculated in the Worksheet. For example, if the maximum inrush VA is 3.49 kVA, then the optimum size of the CVT would be 1.75 kVA or more. A typical CVT Sizing Worksheet with measured data and calculations is shown in Table 1. Size the CVT based upon the larger of the two VA-rating calculations in the Worksheet (steady-state load VA or inrush load VA). A CVT can be specified and ordered by either a VA rating or a current rating.

Table 1. Typical CVT Sizing Worksheet
(Recommended Minimum Size:500 VA)

CVT Circuit or Load	Measured Steady-State RMS Current	Measured Peak Inrush Current (AMPS, 1msec)
Programmable Logic Controller	0.16	14.8
Programmable Logic Controller	0.36	10.8
±5-Volt, 12-Volt Power Supply	1.57	29.1
24-Volt Power Supply	1.29	14.4
NEMA Size 3 Motor Starter	0.43	9.9
NEMA Size 0 Motor Starter	0.13	3.1
Ice Cube Relay	0.05	0.2
Master Control Relay	0.09	1.8

Sum of Steady-State RMS Currents		4.08	
Circuit Voltage	x	120	
Steady-State Load VA	=	490	x 2.5 = 1225
Highest Peak Inrush Current		29.1	Use the larger of these values
Circuit Voltage	x	120	
Inrush Load VA	=	3492	x 0.5 = 1746

Step 6: Verify CVT Performance--- After installing the CVT, verify its performance by powering all connected loads and running a complete process operation. If the CVT has been correctly sized for steady-state and inrush currents, the process will continuously operate. The size of the CVT determined by using the CVT Sizing Worksheet may seem rather large compared to the VA rating of the connected loads. However, the enhanced sag tolerance of process control devices will likely pay for the cost of the CVT over time by reducing downtime, loss of production, and scrapped material otherwise caused by voltage sags.

CASE STUDY

Project Motivation--- The initial motivation for the Pennzoil Products Company, Shreveport, Louisiana, refinery CVT application was based on the fact that Louisiana is in the second highest lightning strike area in the U.S. (second only to Florida). For quite a while it had been recognized by refinery operators that power "blips" caused by lightning strikes and the resultant utility reclosure operations were causing significant downtime. Often, the disturbance would be less than 0.5 seconds in duration but would cause the shutdown of a significant potion of refinery electrical equipment. As more sensitive electronic equipment such as variable frequency drives and PLCs had been added, the impact grew in severity.

Teaming with Allies to Understand the Power Quality Issues---Awareness of the impact of electric power disturbances grew as tracking mechanisms were put into effect. It became apparent from the site-data collected that the impact was millions of dollars. In 1998, more than five major refinery disruptions lead to significant lost product opportunity and increased direct costs. The local utility, arranged for contacts within the Electric Power Research Institute's PEAC (Power Electronics Applications Center) to investigate and to identify what were the specific electric power quality issues. The PEAC does system compatibility and electronics equipment research on the problem of electric power "upsets." They have significant experience in working on practical equipment interconnection issues with over 200 electronic equipment manufacturers and 80 different utilities. Building on PEAC's ongoing insights to understand, solve, and eventually prevent power quality problems, they shared their know-how on "riding-through" the disruptions and offered their services to help with the problem. Refinery management jumped at the opportunity to solve the problem or at least get an idea of the cost to solve the power "blip" problem. An EPRI PEAC team was contracted to do a ride through survey and report. The report identified the "blips" as electric service voltage sags due to distribution system normal reclosure operations and the PEAC recommended the use of CVT's and other technologies to ameliorate the impact of these voltage sags. Within one month of receiving the initial report and cost estimate, funding was approved for the first phase of what has become known at Pennzoil as the " ride-through" project.

Convincing Management to Proceed--- EPRI estimated that with the proper technologies installed, CVT's being the primary technology, the refinery could "ride-through" five out of six electric service voltage sag events. The initial estimates showed that investments of thousands of dollars could save hundreds of thousands of dollars. It was clear that the simple payback was less than one year. Management felt the proposed project was a sound investment to improve process equipment "uptime" during less than ideal weather conditions.

Elements of the Preliminary Economic Evaluation--- The first essential element was to develop a "ride- through" goal or electric service voltage envelop that Pennzoil wanted the refinery equipment to perform without "tripping." With the help of the local utility, data was collected on the depth (in percent) and duration (in time) of the electric service voltage sags. From this data, and the EPRI PEAC belief that we should be able to ride-through five out of six voltage sag events, a Pennzoil goal of being able to ride-through an event duration of up to one half second down to 30 percent depth (that would be 70 percent below the nominal line-voltage) was established. The second element was to identify appropriate technologies. Third, was to determine a precise equipment specification. From these elements, one unit of the refinery was chosen and a detailed cost estimate was prepared. An installed cost of about $5,000 per CVT was estimated.

Results to Date--- About eight (8) CVT's were initially installed. The CVT installations ranged from 1 kVA to 3.5 kVA, with 120Vac to 120Vac or with 480Vac to 480Vac primary and secondary voltage ratios. These CVT voltage ratios were chosen to minimize changes to existing motor controller equipment. In four (4) other motor applications (less than 30 HP), a solid-state "coil-hold-in-device", designed to insure that any time low voltage is present, was used to protect the ac contactor coil from dropping out due to deep electric service voltage sags. At least two electrical events have occurred since the installation with all twelve (12) pieces of protected equipment achieving the goal of surviving an electric service voltage sag of up to a half second and down to 30 percent voltage. It is difficult to determine cost savings, but the protected equipment performed to expectations and improved onstream time was achieved. Perhaps the best testimony was from operations personnel who were very impressed with the improved “ride-through” capability and asked when the next units would be completed.

CVT INSTALLATION, ASSEMBLY AND TEST EFFORTS

North Texas Electric, Inc. generated the working drawings showing major components and wiring details necessary to construct the CVT system bill of materials used for purchasing. Detailed shop drawings with each component's mounting dimensions and wiring identification numbers were included for the CVT system enclosure with its related fuse protection, cooling fan, ground bar assembly, pilot light modules, and control transformer.

In most Pennzoil applications, multiple CVTs were used in an enclosure with components located on the enclosure's back panel. Figures 5 and 6 show a typical CVT enclosure front panel and internal arrangement housing the CVTs for two hydrogen compressors and one induced draft fan "ride-through" system.

Figure 5. CVT enclosure front panel tags for two hydrogen compressors and one induced draft fan ride-through systems.

Figure 6. CVT enclosure internal components i.e. CVTs, fans, fuses, and termination blocks.

As can be viewed in Figure 6, all external interface wiring connections are located on terminal blocks. Terminal blocks are also wired to each CVT's primary with fuse blocks and each CVT secondary with fuse blocks. If a control power transformer is used, the secondary is wired to the fan fuse block, and the fan fuse block is then wired to the fan. If a control power transformer is not used, the fan fuse block is fed from the customer terminal block.

After each CVT system was assembled, a testing phase was initiated with a visual inspection for overall general appearance, component labeling, wiring and terminal block numbering, and grounding of all components and the CVT system enclosure. Following the visual inspection, the CVT system was energized and the input and output voltages of each CVT were verified for proper operation and safety under sag voltage conditions.

MAIN CONCLUSIONS & SUMMARY

Relays, contactors, and motor starters are used extensively in industrial facilities to control process equipment. However, these devices often have a low tolerance to voltage sags, and are often diagnosed as weak links in automated processes. During a common voltage sag, the coils in these devices may de-energize long enough to cause the contacts to open and the connected equipment to shutdown. Recognizing this "Achilles" heel of the process industry, some manufacturers of power conditioners have invented hold-in devices that are marketed as improving the voltage-sag tolerance of relays, contactors, and motor starters. One such device is a properly sized CVT to maintain a relatively constant output voltage despite brief variations in input voltage.

It is noteworthy to point out that ongoing research [6] has demonstrated additional power quality attributes of CVTs that include filtering voltage distortion and notched waveforms. Figure 7 depicts a typical distorted input voltage versus the filtered CVT (ferro) output, and the CVT successfully filtering a notched voltage input waveform.

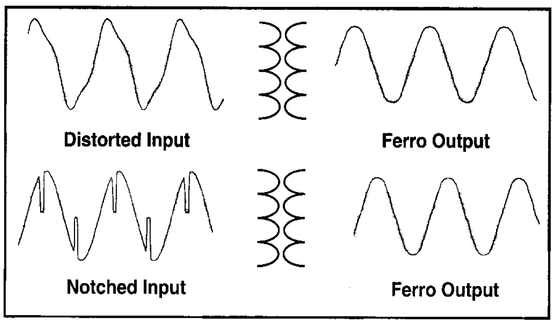

Figure 7. CVT output voltage with distorted and notched input voltages at full load.

Also, as shown in Figure 8, a CVT can practically eliminate oscillating transients caused by capacitor switching and can significantly dampen impulsive transients caused by lightning. To ensure full protection of sensitive electronic loads, CVTs may need to be coupled with other devices designed to mitigate dynamic disturbances.

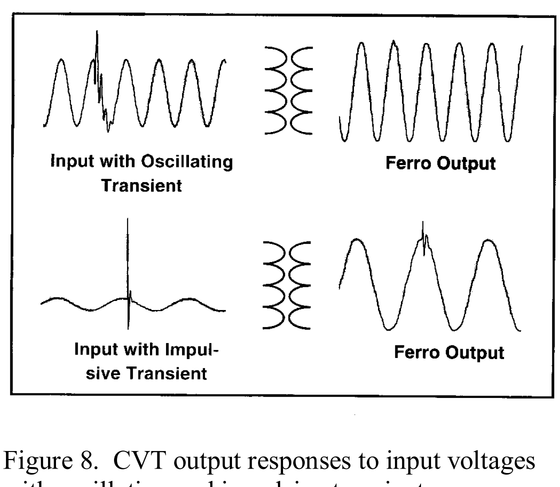

Figure 8. CVT output responses to input voltages with oscillating and impulsive transients.

End-users of industrial equipment have many options for increasing voltage sag and electronic equipment disturbance tolerance. This paper and case study results suggest that CVTs can be a reliable, cost effective and relatively maintenance-free voltage sag mitigation device compared to other expensive remedies for process shutdown problems caused by voltage sags.

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REFERENCES

1. R. Ferraro, 1990, *Electric Service Compatibility: Dealing with Realities,* Power Quality Magazine

2. A. Mansoor & R. Ferraro, 1997, *Characterizing Adjustable-Speed Drive (ASD) Power Quality Applications Issues,* PQA "97 Columbus, Ohio

3. EPRI PEAC, 1997, *Sizing Constant Voltage Transformers to Maximize Voltage Regulation for Process Control Devices.*

4. EPRI PEAC, 1997, *PQTN Application Brochure #10—Tutorial; Inrush Current Measurement*

5. Basic Measuring Instruments, Inc., Alex McEachem, power quality article comparing conversion techniques for AC measurements with true RMS, peak (RMS calibrated), and average (RMS calibrated) instruments.

6. EPRI PEAC Corporation, Knoxville, Tennessee, *System Compatibility Projects to Characterize Electronic Equipment Performance Under Varying Electric Service Supply Conditions.*