Design, development, and testing of a voltage ride-through solution for variable speed drives in oil field applications

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Abstract

ChevronTexaco initiated a plan in 1996 to develop the Boscan Oil Field just west of Maracaibo, Venezuela, that included the expansion and reconditioning of the existing 24 kV distribution system in order to ensure reliable service for the new and existing wells. About 75 percent of the southern field production uses electrical submersible pumps (ESP) while the remainder uses beam pumps and progressive cavity pumps (PCP). All ESPs and PCPs and some beam pumps are driven by variable speed drives (VSDs). About 255 km of overhead lines results in high exposure to lightning events and subsequent sags and interruptions that cause well-site VSDs to trip, severely impacting production goals.

A strategy was developed to combine VSD ride-through with a recloser system so that most disturbances would have no effect on production. This paper describes the successful development, building, and testing of a VSD ride-through prototype for the PCP drives, and the strategy of providing ride-through for the PCP drives in conjunction with a recloser system. This paper also provides the results of a technical literature survey and evaluation of possible solutions for Boscan Field, in addition to target specifications for a prototype ride-through unit along with development plans and testing requirements.

Based on this analysis, a prototype ride-through module for the PCP drives was built using power electronic components and ultra-capacitors. This paper describes the design, development, and testing of the ride-through modules for the VSDs and how this solution applies to the overall industry.

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Introduction

With more than 255 km of exposed 24 kV overhead lines, ChevronTexaco had a high exposure to faults on the power distribution system feeding their well pumps in the Boscan Field near Maricaibo, Venezuela. Historically, most of the faults on this power system were temporary in nature, and were due to faults initiated by lightning because this part of Venezuela has a very high incidence rate of lightning strikes. During these temporary faults, wells fed from the faulted line experienced very low voltage or zero volts, depending on the fault location. Wells on adjacent feeders fed from the same substation experienced voltage sags with a depth dependent on the electrical distance from the fault to the common substation, and the duration depended on the fault-clearing device (breaker, fuse, or recloser). In order to minimize the effects of these temporary faults, a system of reclosers was installed to minimize the duration of the interruptions and sag events.

Voltage sags and short (recloser) interruptions are a well-known and understood problem for power electronic loads. Most electronic loads have some inherent "ride-through" based on DC bus capacitance in the equipment, but the tolerance is typically not enough to ride-through many of these events. Variable speed drives (VSD), for example, have a DC bus capacitance that allows for very short interruption protection (approximately 1 cycle) and minor sag compensation (for example, 5 cycle sags at 70 percent retained voltage). However, when voltage sags are deep or the voltage is completely interrupted during a recloser operation, the VSDs typically trip as the DC bus voltage reduces below its undervoltage protection setting.

By addressing temporary faults with reclosers, field operations was able to minimize the affected area and duration of the events, but the resulting effect was that many of the well pump drives would trip on undervoltage during these faults. Some of the well pumps, specifically the PCP pumps, required approximately 8 hours to return to full production following the drive trip. Therefore, a choice was made to investigate ride-through options for the well pump drives. Ultimately, the hope was that with the reclosers and ride-through on the drives, Chevron would be able to eliminate the effects of any temporary fault on the power distribution system.

The focus of this analysis was to:

- Review the state of technology and investigate potential solutions
- Create a specification for the drive ride-through solution
- Build a prototype
- Test the proposed solution and demonstrate the performance
- Install six beta units in the field

Constraints were cost-per-drive and time (one month to develop and test).

Available technologies and solutions

Solution alternatives

Many different alternatives were evaluated including modifications to existing drives, add on ride-through modules, and sag compensation/isolation equipment. The following are general categories of the types of equipment that were evaluated during this investigation.

- *Kinetic buffering* makes use of the stored energy in the rotating masses to support the DC bus voltage. When the DC bus voltage falls below a threshold, the kinetic buffering becomes active. During kinetic buffering, the VSD slows down, regenerates the stored energy into the DC bus, and prevents or minimizes the DC bus voltage decay. This is often referred to as "catch a spinning motor," and is a setting or firmware modification to a drive
- *Boost converter* maintains the DC bus voltage to a set point during the sag. The boost converter can be connected to the DC bus of the VSD, but more commonly is connected in parallel to the VSD. It uses the remaining voltage during a sag to supply the DC bus. Boost converters can be retrofitted in the field
- *Active front end* is selected to provide four-quadrant power flow and minimal harmonic distortion on the line-side of the VSD. In addition, the active front end can provide a boost function, which controls the DC bus voltage during a line-side disturbance. DC capacitance provides additional energy storage to that of the DC capacitor internal to the VSD. The DC capacitor is sized to maintain an acceptable DC voltage and power to the pump during the sag or interruption for a specific period of time. These capacitors may be either standard electrolytic or high density ultra-capacitors. Modifying existing drives is a difficult solution. Simply increasing the capacitor size in a drive (e.g., adding more electrolytic capacitors) is not a simple solution and may create problems with the drive rectifier or pre-charging circuit. This solution would be drive-dependent and each drive manufacturer would have to coordinate the addition of capacitors to their DC bus
- *Sag correction* is also called Sag Ride-Through (SRT) or Dynamic Voltage Restorer (DVR), and is an AC-to-AC converter that uses a series injection transformer to recreate the missing voltage during a voltage sag to raise the voltage above the required level for the affected equipment (acts like an offline UPS without batteries). This device can typically compensate for 40 to 60 percent of nominal voltage for single-, two-, or three-phase voltage sags but has no energy storage for full interruptions
- *Oversizing the drive* would inherently offer some additional ride through in the drive because the DC capacitor size varies linearly with the hp of the drive, so increasing the size of the drive increases the size of the capacitors and the ride-through. Unfortunately, this would be an expensive solution and would require changing out of all existing drives without guaranteed success

Solution comparison

Table 1 presents a comparison of the available technologies. After evaluating all of the available solutions, it became apparent that the best technically feasible and cost-effective solution for this application would be additional DC bus capacitance using ultra-capacitors. Ultra-capacitors are unique in that they are a high density (farads versus micro-farads) capacitor in a small package. Ultra-caps can be charged and discharged many, many times, unlike an equivalent-sized battery.

There are two significant drawbacks in using ultra-capacitors for power applications: cost and voltage requirements. The cost of ultra-capacitors is high, but is decreasing as more applications arise, such as electric/hybrid vehicles. Regarding voltage, the nominal voltage for most ultra-capacitors is very low (for example, 5 V) and while this makes for a great energy storage device for a toy, it is less than ideal for power system applications because many have to be added in series to match a DC bus voltage of 300–700 V, for example, for a typical power application. However, the benefits of applying ultra-capacitors in this application far outweigh the design drawbacks, so they were selected. Packaged (assembled) higher voltage ultra-capacitors (300 V) were used for this application.

Table 1. Technology Comparison

Solution	Advantages	Disadvantages
Kinetic buffering	Firmware change on most drives	PCP pumps cannot withstand the significant speed change on the long shaft
Boost converter	No energy storage required	Cannot handle full interruption in voltage
Active front end	Opportunity for new drives	Expensive and cannot handle full interruption in voltage. In addition, would require changing out existing drives
DC capacitance (electrolytic or ultra-capacitors)	Can provide extended interruption protection. Ultra-caps are compact and can handle many charge/recharge cycles	Electrolytics require a lot of space and generally require manufacturer support. Ultra-caps are expensive. Both require additional charging circuits
Sag corrector	¼ cycle response. Works very well for voltage sags within its capability	Cannot handle full interruption in voltage. Is not cost-effective for a small single drive in remote applications
Over-size drive	Adds inherent ride-through to drive	Costly—requires replacement of existing drives with a significantly more expensive drive. Does not guarantee success

Equipment specifications (site specific)

The existing drives for the PCP wells are standard pulse-width modulated (PWM) type drives. These drives rectify the 480 V input to DC, and invert the output to high frequency pulses of voltage (PWM). The DC bus on these drives operates at a constant voltage dependent on the magnitude of the rectified AC input voltage, regardless of the output of the drive. The DC bus has an electrolytic capacitor(s) to filter the ripple on the DC bus. This DC capacitor can provide a very small amount of ride-through during voltage sags or interruptions on the AC input. The length of the ride-through is dependent on the size of the capacitor bank and the amount of load the drive is supplying. An undervoltage trip on a drive occurs when the input AC voltage falls low enough that the DC capacitors cannot support the DC bus to a high enough, predefined voltage level (for example, 85 percent of nominal). This setting (undervoltage) protects the power electronic components in the drive during an undervoltage condition.

All of the available solutions that could meet the criteria of cost and the required time constraints were investigated. Field operations wanted to install the first six prototypes prior to the next lightning season. This meant that the initial prototype had to be completed and tested within a month so that the additional units could be built within approximately three months. **Figure 1** is a simplified one-line diagram of a typical PCP well application showing the drive and typical load on the drive.

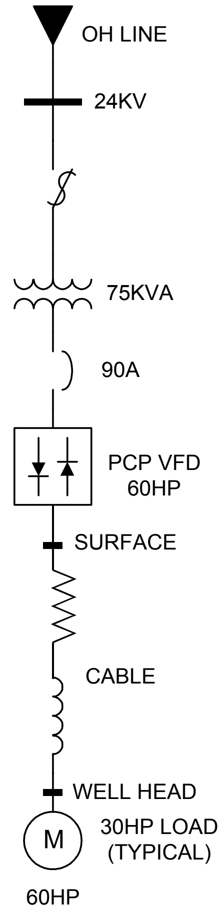

Figure 1. Simplified One-Line Diagram of PCP Application

The specifications, based on the site-specific requirements of this installation, are shown in **Table 2**.

Table 2. Technology Comparison

Specification	Target
Ride-through time	250 ms minimum ①
Minimum acceptable DC bus voltage	90% of nominal
Maximum power on 60 hp PCP drive	30 hp ②
Maximum voltage disturbance	Full interruption (0V)
Firmware adjustments to drives ③	None
Target cost per drive	$10,000
Enclosure	NEMA® 3R (outdoor)

① 250 ms allows for the typical recloser operating times of 180 ms or 200 ms for this application.

② Typical loading on PCP drives.

③ With multiple vendors/drives, Chevron was reluctant to modify existing firmware on each drive.

In addition to these specifications, the design was to minimize application issues by allowing for retrofit to any of the existing drives in the field or new drive installations. This meant that modifications to the drives must be limited to an electrical connection (only) from the existing equipment to the new “ride-through” equipment. Using capacitive storage, two options are possible:

1. Use the three-phase input to charge the capacitors (**Figure 2**).

2. Use the DC bus and drive rectifier to charge the additional capacitors (**Figure 3**).

The AC coupled solution was selected because using the existing charging circuit on the drive allowed for too many variable conditions with the existing retrofit applications and new applications. For example, the size and rating of the existing pre-charge capacitors and fuses were of concern.

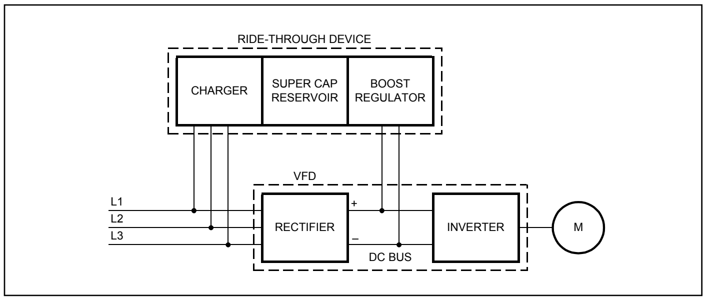

Figure 2. AC Charged Capacitor Circuit

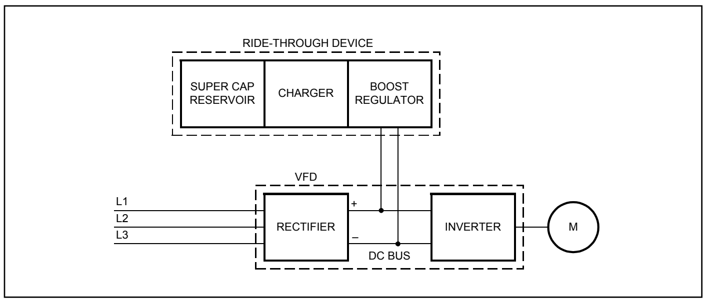

Figure 3. Capacitor Charged with Existing Drive Charging Circuit

An electronic DC voltage regulator was used to regulate the output of the ultra-capacitors to maintain the DC bus voltage to an acceptable level in the drive (90 percent of nominal DC bus voltage).

Prototype development

Based on a preliminary evaluation of the available data, the specification was developed for the ride-through prototype as shown in **Table 3**. Because of the significant time constraints, the design used slightly larger ultra-capacitors than initially considered, but it turned out that the marginal difference in price was not worth the difference in the performance, so the larger capacitors were used in the final design.

Table 3. Prototype Specifications

Requirement	Specification
Ride-through time	700 ms ①
Nominal voltage	480 V
Maintained DC bus voltage	90% of nominal
Ride-through type	Ultra-capacitors
Capacitor rating	22 kW/50 kJoules
Maximum voltage disturbance	Full interruption (0V)
Firmware adjustments to drives	None
Actual cost per drive	$9,000–$12,000
Enclosure	NEMA 3R (outdoor)
Connection type	Three-phase plus DC bus
Protection type	Fuse and disconnect
Dimensions	42" x 36" x 16"

① Based on expected loading of 30 hp on the 60 hp drive.

Figure 4. Ride-Through Prototype

Prototype testing

Testing requirements

A test plan was agreed upon to evaluate the voltage tolerance (called voltage immunity testing) of the VSDs used in the Boscan Field on the PCP pumps. The intention of this testing was to determine the benefit of the ride-through module and to determine if it could allow the drive to operate properly during recloser operations. The intention was to test the existing drives to evaluate the effectiveness of the ride-through for retrofit applications and to test an equivalent new drive for potential new applications.

The voltage immunity testing was performed without the ride-through module attached to the drive and with the ride-through module to determine the incremental improvement of the prototype design.

Test facility

EPRI Solutions operates an independent test facility in Knoxville, TN (USA). One of the many capabilities of the EPRI Solutions facility is a power quality lab with provisions to physically test VSDs under load and with and without power conditioning such as ride-through or sag correction. The lab is capable of generating various voltage disturbances such as three-phase sags, two-phase sags, single-phase sags and interruptions. The EPRI Solutions lab was selected because of its electrical capabilities as well as its reputation and past experience with the test engineers in performing voltage immunity testing.

Test protocol

Table 4 describes the test protocol. First, each drive was tested for immunity to sags of various magnitudes and duration (immunity testing). Next, in the case of either the existing drive type or the new 60 hp drives, the drive was tested with the ride-through product applied.

Table 4. Test Protocol

1) Test existing 60 hp drive loaded to 30 hp a. Without the ride-through module b. With the ride-through module c. Applied single-, two-, and three-phase sags and interruptions d. Repeated above tests for load of 40 hp
2) Repeat above test protocol for new 60 hp drive for 30/40/50 hp load

The EPRI Sag Generator recorded all voltage and current waveforms associated with each of the above tests. The voltages included Van, Vbn, Vcn and Vdc bus. The currents included Ia, Ib and Ic line currents to the drive.

Test setup

Figure 5 shows the test setup for evaluating the prototype at the EPRI Solutions lab.

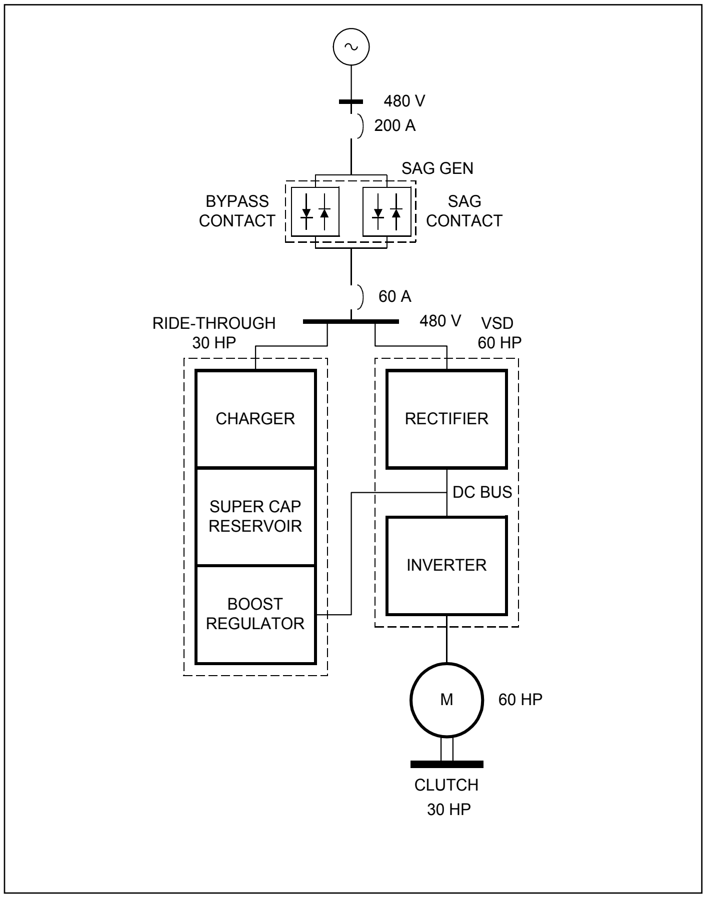

Figure 5. Ride-Through Prototype

Immunity testing results

The ride-through/immunity curve for the existing 60 hp drive immunity test is shown in **Figure 6** for load levels of 30 hp and 50 hp. For voltage disturbances above the curve for a given load, the drive was able to ride-through the event. For voltage disturbances below the curve, the drive tripped. **Figure 7** shows a waveform from one of the tests where the DC bus started to collapse but did not trip. **Figure 8** shows the results of the immunity testing for the new 60 hp drive.

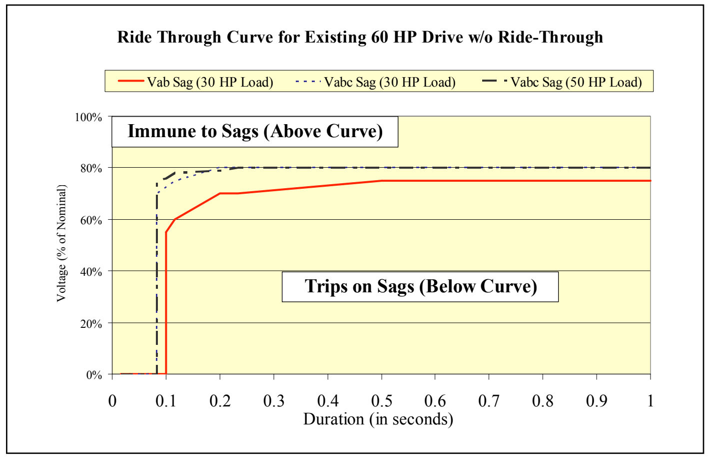

Figure 6. Ride-Through Curve for Existing Drive without Ride-Through (Unprotected)

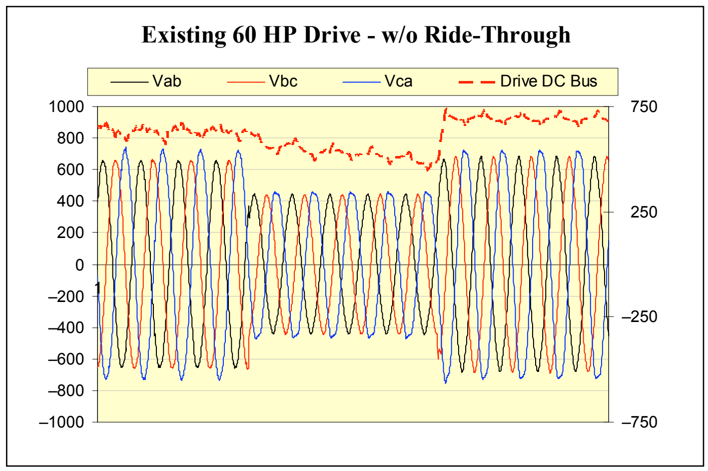

Figure 7. Sample DC Bus and Input (480 V) Waveform from Immunity Testing on Existing Drive (5 Cycles, 83.3 ms at 65% V Unprotected)

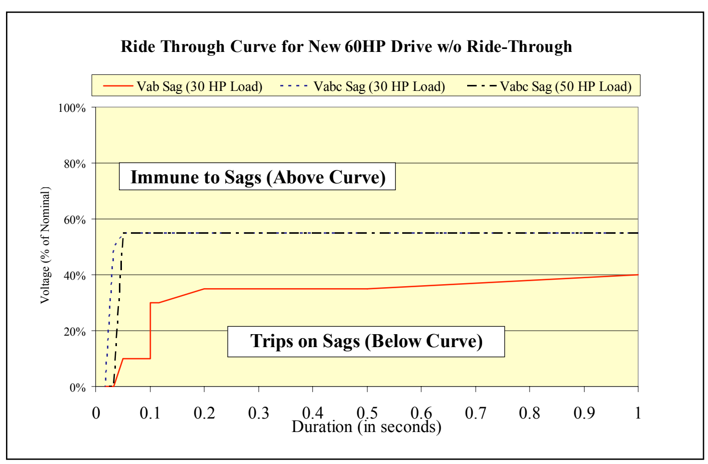

Figure 8. Ride-Through Curve for New Drive without Ride-Through (Unprotected)

Ride-through testing results

With the application of the PCP ride-through prototype, the drive was able to ride-through sags/interruptions of 0V for up to 700 ms. Notice how the region that is immune to sags has been extended in **Figure 9**. **Figure 10** shows a waveform from one of the tests on the existing drive, illustrating the constant DC bus voltage during the 12 cycle interruption. **Figure 11** shows the results of the immunity testing on the Eaton 60 hp drive with the ride-through installed.

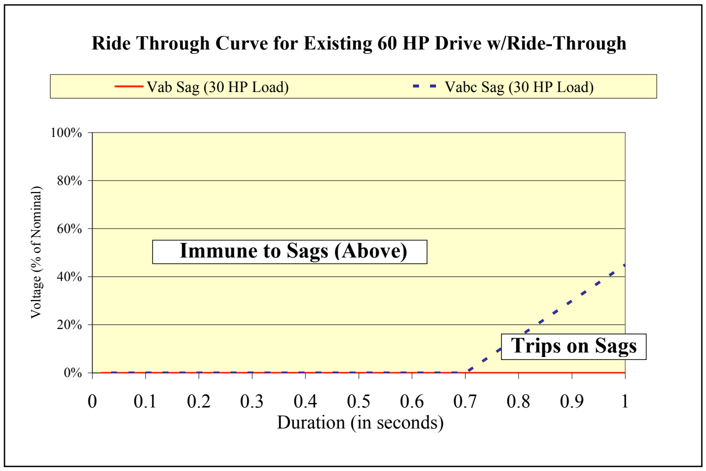

Figure 9. Ride-Through Curve for Existing Drive with Ride-Through (Protected)

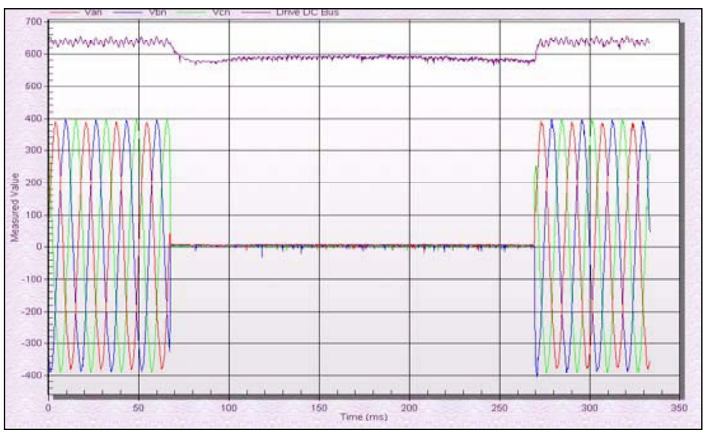

Figure 10. Sample DC Bus and Input (480 V) Waveform from Immunity Testing on Existing Drive (12 cycles, 200 ms. at 0 V Protected—No Trip)

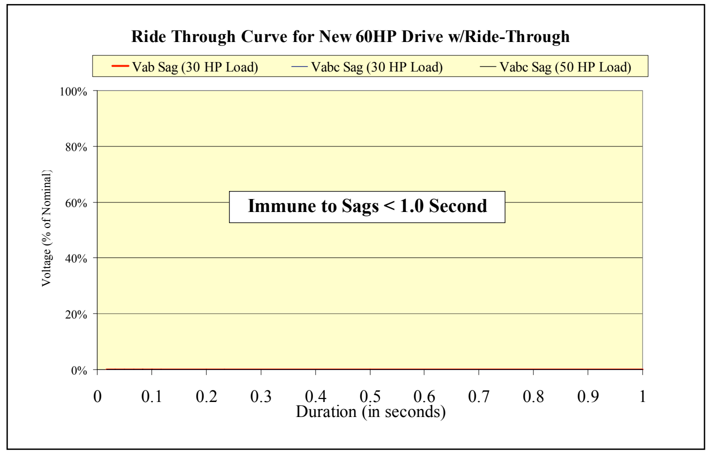

Figure 11. Ride-Through Curve for New Drive with Ride-Through (Protected)

Test results summary

The following is a summary of the test results recorded during the prototype testing at the EPRI lab:

- Excellent ride-through of 700 ms (42 cycles) at 0 V for the existing 60 hp PCP drive loaded to 30 hp
- At 40 hp load (higher than the normal loading on these drives), the ride-through exceeded 300 ms
- The minimum requirement of 250 ms was met for both loading conditions, which would allow for all expected recloser operations. This allowed for application of the same ride-through module on all existing drives (retrofit)
- Comparable results were recorded on a new 60 hp drive. Actually, the prototype gave a slightly better performance on the new drive because it was able to withstand 1000 ms (60 cycles) at 0 V

Field testing and results

Figure 12 shows a summary plot of field data captured at one well site prior to the installation of the ride-through modules. Each data point is a summary point for a sag or interruption event. Each data point on
Figure 12 represents a waveform indicating the retained voltage and duration of the event. For example, the event shown in **Figure 13** would correspond to a 12 percent retained voltage, 5 cycle (83 ms) event.

As shown on **Figure 12**, a significant number of events occurred at this well location. This plot is typical for this particular field.

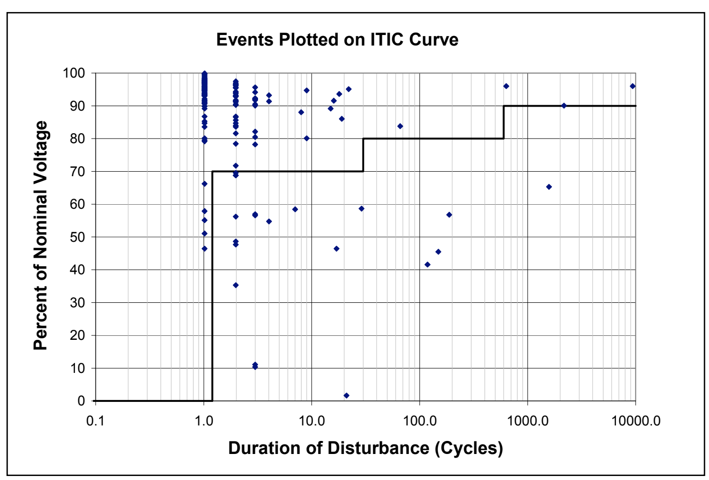

Figure 12. Voltage Magnitude Duration Plot from Field Data

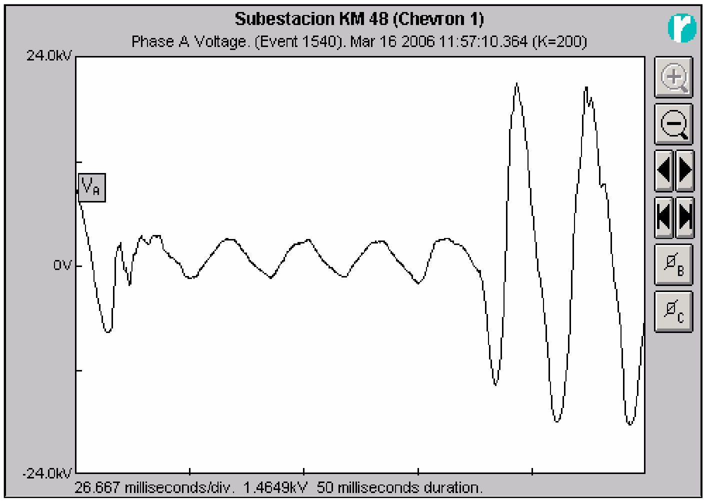

Figure 13. Sample Waveform from Field Data

As expected, the field data showed a significant number of voltage variations. Most of the events were voltage sags or short-term interruptions resulting from the operation of a recloser. The installed ride-through equipment would have prevented all of the events shown in **Figure 12**.

Additional data should be available during the presentation of this paper to demonstrate the effectiveness of the ride-through solution.

Conclusion

Eaton and ChevronTexaco evaluated multiple solutions in an effort to coordinate a well-designed recloser system with variable frequency drives installed on PCP wells in the Boscan Field near Maricaibo, Venezuela. Selection criteria included technical feasibility, cost, and time for implementation.

In the end, the selected solution was an AC charged retrofit DC solution incorporating ultra-capacitors and a power electronic DC regulator to supply a well regulated DC bus during voltage sags and the interruptions caused by recloser operations. This same solution was also tested and is appropriated for new drive applications. The solution is expected to operate properly with the two tested systems as well as other similar VSDs in the Chevron system.

The test results demonstrated that the prototype meets or exceeds all of the design requirements. At the writing of this paper, field operations have installed six units in the field with very favorable results.

Field operations intends to install retrofit units on all of the critical PCP pumps in this field, and is considering applying this solution to other VSDs in other oil fields.

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Authors' biographies

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Tom Dionise is a Power Quality Advisory Engineer with Eaton. He has 24 years of power system experience involving analytical studies and power quality investigations of industrial and commercial power systems. More recently, he has been involved in data center audits, power quality field measurements, and power quality problem solving. In 2001, he helped create the PQHotline to offer power quality consulting, and regularly troubleshoots callers' power quality related questions. He is a senior member of the IEEE®, Vice Chair of the Metal Industry Committee, and member of the Generator Grounding Working Group. Tom has served in local IEEE positions, and had an active role in the committee that planned the IAS 2002 Annual Meeting in Pittsburgh, PA. He is a licensed Professional Engineer in PA and has a MSEE from Carnegie Mellon and a BSEE from Penn State.

David Shipp, P.E., BSEE '72, is a Principal Engineer for Eaton. He is a recognized expert in power system analysis and has worked in a wide variety of industries. He has spent many years performing the engineering work associated with his present day responsibilities, which include a wide range of services covering consulting, design, power quality, arc flash, and power systems analysis topics. He has written many technical papers on power system analysis topics and has received an IAS/IEEE Prize Paper Award for one of them. Twelve of his technical papers have been published in IEEE/IAS national magazines and one was published EC&M. He is very active in national IEEE and helps write the IEEE color book series standards. He spent 10 years as a professional instructor, teaching full time. He occasionally serves as a legal expert witness. He is an IEEE Fellow Engineer.

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