O&M

Marmaduke Award: CFE Extends CTG Universidad Unit 2's Life with Conversion to Synchronous Condenser

CTG Universidad is a two-unit combustion turbine plant commissioned in late 1970 by the Comisión Federal de Electricidad (CFE) on the north side of Monterrey, Mexico's third-largest city and an important industrial center. By the 1990s, the two 14-MW turbines were obsolete, used sparingly, and slated for demolition in 2010. However, by 2002, portions of Monterrey began experiencing power restrictions caused by a lack of sufficient reactive power production, and that situation presented an opportunity for the plant. By repurposing an old combustion turbine for use as a synchronous condenser to provide local reactive power, CFE significantly reduced local power supply limitations. For that savvy plant repurposing, CFE's CTG Universidad Unit 2 is the winner of POWER's 2011 Marmaduke Award for excellence in power plant problem-solving. The award is named for Marmaduke Surfaceblow, the fictional marine engineer and plant troubleshooter par excellence.

Courtesy: SSS Clutch Co., Inc.

The Comisión Federal de Electricidad (CFE) is the Mexican national government agency responsible for generating, transmitting, and delivering electricity to the country's 35 million customers, although independent power producers (*productores independientes de energía*) now own 22.9% of Mexico's installed capacity. CFE currently owns and operates 187 power plants totaling 52 GW.

Monterrey, also called the "Pittsburgh of Mexico," is the capital city of the northeastern state of Nuevo León, one of Mexico's wealthiest, and the industrial hub for many international corporations. The region, home to about 25% of Mexico's industrial base, is particularly well known for its metals sector, chiefly iron and steel industries. Steel processing plants in Monterrey provide about half of Mexico's annual production. In Mexico, residential load is relatively high (88.4% of CFE's customers), yet in regions with large industrial loads, such as Monterrey, 1% of the customers often account for more than half of all electricity sales.

CFE's Universidad power station is located on the north side of Monterrey in a highly industrialized area that has experienced much growth since the combustion turbine plant was constructed in 1970 (Figure 1). Universidad houses two Brown Boveri BB11-L dual-fuel (natural gas and diesel oil) c stion turbines, each rated at 14 MW (although the generator is rated at 20 MW). During the first decade of operation, the plant provided baseload generation to the growing industrial region. As demand for electricity continued to grow, new, much larger, and highly efficient combined cycle plants were constructed to power the region, although those plants were located outside the city limits.

1. Ready for action. The Universidad plant entered commercial service in late 1970 with two Brown Boveri BB11-L combustion turbines, each rated at 14 MW. In the right foreground is the exciter that is used as a motor for starting purposes. In the center is the generator. In the background is the dual-fuel combustor mounted on top of the separate turbine and compressor sections. The excellent condition of the plant was one reason Universidad was selected for the owner's first combustion turbine synchronous condenser upgrade. *Courtesy: CFE*

The obsolete BB11-L units were soon relegated to peaking duty, although they were seldom run. By the mid-2000s, the plant was scheduled to be retired and then demolished by late 2010. Unexpectedly, the urban location of the plant was soon to prove invaluable to CFE.

Date	Milestone
Nov. 2002	CFE contacts SSS on project feasibility
Oct. 2003	Synchronous condensing concepts presented to CFE for BB11L and BB11B
Nov. 2003	Technical proposal and initial scope of work provided to CFE for BB11L
Dec. 2003	CFE decides to convert BB11L, Unit 2 at CTG Universidad Power Station in Monterrey
Jan. 26–27, 2004	Meeting at CTG Universidad for purpose of obtaining BB11L drawings and obtaining measurements
Feb. 2007	Unsolicited turnkey proposal submitted to CFE by Industria Sigrama to convert BB11L to synchronous condenser service
Feb. 2008	CFE project funding established
June 2008	Rotordynamic analysis number 1 confirms concept
Oct. 20, 2009	CFE public bid issued
Dec. 28, 2009	CFE announces Industria Sigrama as winner of public bid
Jan. 27, 2010	CFE signs contract with Industria Sigrama
Feb. 25, 2010	Project design review held at CFE in Monterrey
Mar. 2010	Rotordynamic analysis number 2 establishes need for new hubs
June–Aug. 2010	Modernization of controls completed at CTG Universidad
Sep.–Oct. 2010	Replacement of lube oil pumps and piping completed
Nov.–Dec. 2010	Removal of 700-mm shaft, removal of original turbine and generator-side couplings, installation of new couplings, and installation of clutch completed
Dec. 21, 2010	Startup of CTG Universidad Unit 2 with successful operation in power generation and synchronous condensing modes

Project milestones. *Source: SSS Clutch Co., Inc.*

Unexpected Interest

By 2002, CFE was experiencing the effects of its industrial customers' very high inductive power usage. The increased need for reactive power (megavars) was evidenced by load-limited power lines and unacceptable line voltage drop. In fact, Mexico's National Energy Control Center had identified reactive power–deficient zones on the Mexican grid. One of those zones was near Universidad in Monterrey. In past years, the plant had produced the necessary reactive power when operating, but that was no longer the case. The best and least expensive solution was identified as adding reactive power to the distribution lines closer to end users, thereby allowing additional real power (megawatts) to flow into the downtown Monterrey grid.

In December 2002, Lino Cárdenas Villarreal, then assistant general manager of CFE's Production Unit for northeastern Mexico, began exploring alternatives for locally produced reactive power. Having fresh experience with Alstom's GT24-based single-driveline combined cycle plant, which had recently been installed near the Monterrey airport and designed with the capability to operate as a synchronous condenser, Cárdenas asked SSS

Clutch Co., Inc. (SSS) if the two Universidad units were conversion candidates. A synchronous condenser is a synchronous motor connected to the grid with no load that is allowed to spin freely. By adjusting the voltage regulator, the generator-now-motor can either absorb or produce reactive power, thereby adjusting the local grid’s voltage and improving the power factor, especially at the end of long transmission lines. CFE soon learned that the 14-MW BB11-L had never been run as a synchronous condenser. However, SSS studied the plant design and concluded that the project was feasible.

Although the need for and feasibility of the project was nailed down, funding approval remained in limbo for several years. Finally, CFE issued a public bid late in 2009 for the conversion of Universidad Unit 2 to operate as a synchronous condenser in addition to its normal power generation mode. The “CFE Universidad BB-11L Synchronous Condensing Retrofit” project was won by Industria Sigrama S.A. de C.V. of Torreón, Coahuila, Mexico. Industria Sigrama retained overall project management responsibilities plus design and installation of the new control system, as well as electrical protection and coordination. Edel Ingenieros S.A. de C.V. was selected by Industria Sigrama to perform the mechanical engineering services on the project, including modifications to the compressor coupling and existing housing to accept the SSS clutch, turning gear modifications, and installation services for the modified lube oil system, filters, piping, and instruments.

The final project specifications required installation of a SSS clutch size 160FT into the intermediate block of the BB11-L, between the compressor and generator. This location allows complete mechanical separation between the compressor and generator when synchronous condensing duty is required. The project also included modernization of the unit’s control system with digital controls and replacement of its lubrication oil pumps, for reasons discussed below (Figure 2).

2. Clutch in the queue. In the left foreground is Unit 2’s generator with the SSS clutch, ready for installation, sitting on the table. The unit control panel is placed directly in front of the exciter. In the background, a technician is looking down at the top shell that covers the shaft, turning gear, and lube oil pump that were soon after removed and replaced by the SSS clutch. *Courtesy: Industria Sigrama*

By October 2010, installation and testing of the completely new digital control system was completed and was closely followed by installation of the new clutch (see sidebar)—one of the final installation tasks. The plant was successfully restarted and operated in both power generation and synchronous condensing modes on Dec. 21, 2010 (see the table for key project dates). Since that time, the newly reconfigured Unit 2 has been available for dispatching by either CFE’s generation department for power, or by CFE’s transmission and distribution organization for grid-stabilizing reactive power.

Four Modes of Plant Operation

The control logic for the combustion turbine generator equipped with the clutch was modified to incorporate several new modes of operation. The original sequencing logic for the drivelines remained (but with a locked clutch). The supervisory controls with new digital controls and operator station were updated to accommodate the new synchronous condenser modes. The purpose of the clutch is to automatically disengage and, thus, disconnect the drive the moment the turbine is shut down and its speed drops below that of the generator. The following describes how the clutch permits synchronous condenser operation using the existing combustion turbine driveline.

Standard Startup Mode. The controls first ensure that the clutch is disengaged before startup begins. With start initiated, the turbine turning gear is enabled. As soon as the driveline begins to rotate, the clutch automatically engages and hydraulic servos engage a locking sleeve on the clutch to prevent clutch disengagement during turbine startup, because the starter motor is at the generation end of the machine. An “engaged/locked” signal is returned to the sequencing controls, allowing turbine acceleration to full speed, generator synchronizing, and turbine loading. Shutdown is the process in reverse, with the clutch remaining locked. When shutdown is completed, the turning gear is engaged.

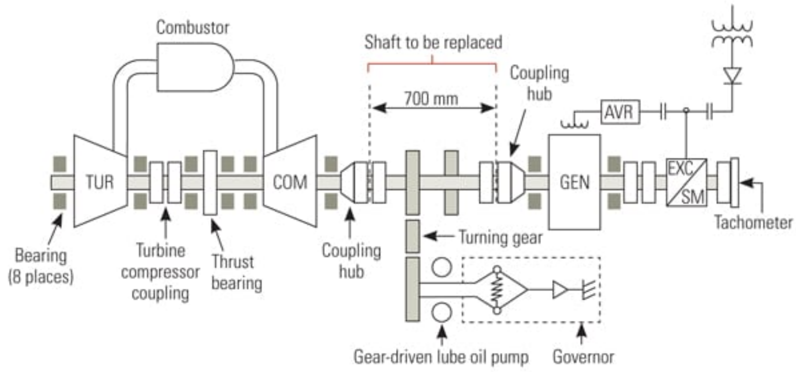
Synchronous Condensing Mode from Power Generation Mode. In some circumstances, synchronous condensing mode may be required while the combustion turbine is online and operating. If so, the load is reduced to 1 MW to 2 MW and then the operator selects the clutch unlocked mode. Once the lock is unlocked, the clutch is free to disengage automatically when the turbine decreases its speed relative to the generator. The clutch can be unlocked whenever torque is being transmitted from the turbine to the generator. It is not necessary to reach a specific point of low torque. When the load on the turbine is close to zero (and the clutch is unloaded), the clutch will automatically disengage and separate the generator from the combustion turbine. A "clutch unlocked" signal tells the turbine controls to shut down. Because the driveline is still rotating at synchronous speed, the generator is immediately available as a synchronous condenser. Interestingly, due to the viscous drag of the clutch, the turbine will usually continue to rotate at around 100 rpm when shut down. The turbine turning gear is engaged when the turbine speed decelerates to zero rpm.

Power Generation Mode from Synchronous Condensing Mode. Should power generation mode be ordered while the unit is in synchronous condensing mode, the first step is to disconnect the generator from the grid and begin startup of the separate combustion turbine. When the generator decelerates to below about 500 rpm, clutch locking is preselected. At the instant the generator speed decelerates below the turbine speed, the clutch automatically engages and locks. The startup of the combustion turbine then continues as a normal startup.

Synchronous Condensing Mode. A more typical event is to dispatch the plant as a synchronous condenser from a stopped position. As before, the sequencer asks for a "clutch locked condition." If unlocked, the clutch "lock-in" is pre-selected, the turning gear is started, and the clutch automatically engages and locks. The motor/exciter then accelerates the turbine generator to start the turbine so it can accelerate to full speed and synchronize with the grid. The clutch is unlocked, the turbine is shut down, and the generator is now synchronous condensing. To secure from synchronous condensing mode, disconnect the generator from the grid and let the generator coast down. When the generator speed matches the combustion turbine speed (now on turning gear), the clutch automatically engages and locks, and the entire driveline is rotating at turning gear speed.

Unique Turbine Design

SSS may have determined the project was feasible, but that doesn't mean the conversion of a unique 40-year-old combustion turbine was straightforward or without many technical challenges. Unlike modern turbomachines of this rating that arrive on the job site prepackaged on a single skid that can be dropped onto foundation bolts, the BB11-L was a field-assembled set of independent, free-standing modules that form a single driveline (Figure 3): turbine, compressor, turning gear and main lube oil pump, and generator/exciter.



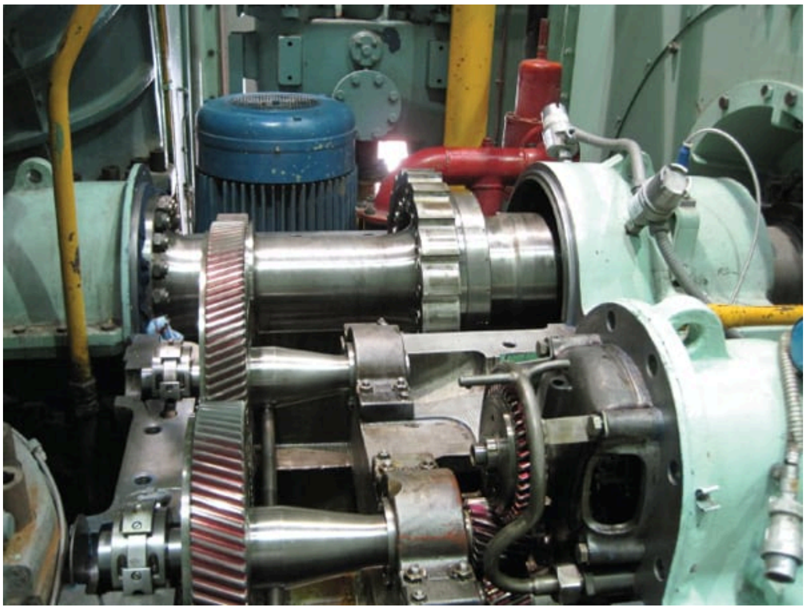
Notes: AVR = automatic voltage regulator, COM = compressor, EXC = exciter, GEN = generator, SM = starting motor, TUR = turbine.

3. Modular turbine. The 1970-vintage 14-MW Brown Boveri BB11-L was a collection of individual modules that were field-assembled into a single combustion turbine driveline. The dark squares represent the location of driveline bearings, with a thrust bearing located at the connection of the turbine and compressor shafts. Conceptually, the 700-mm shaft was removed and a clutch would take its place. In addition to incorporating a clutch, a new location for the turning gear was selected, the gear-drive main lube oil pump was replaced by a DC and AC pump, and the mechanical governor was replaced with an electronic governor. The starting motor/exciter are bolted to the outboard end of the generator shaft. *Source: Industria Sigrama*

Normal operation of the BB11-L was also unique: The source of power for startup was the exciter, switched to run as a DC motor. When the power train reached about 2,000 rpm, the DC starting motor electrically switched to direct current generator (or rotating exciter) for the main generator. Conventionally, the automatic voltage regulator (AVR) determined the voltage at the generator terminals. When the generator was subsequently synchronized to the grid, the generator could supply real and/or reactive power by adjusting the power factor controller, within the +15 MVAR to –10 MVAR range set by the manufacturer.

Challenges Overcome

It's often a long leap between concept and reality when performing retrofit projects on older equipment such as the BB11-L. The conceptual design was to remove the existing 700-mm shaft that connects the compressor and generator and replace that shaft with a clutch assembly that would function as a flexible coupling able to absorb a certain amount of misalignment during power generation but able to disconnect during synchronous condenser operation. Aside from the clutch itself, the plan was to install a new gear-toothed coupling input hub (on the compressor output shaft) and a [illegible] output hub (on the generator input shaft). This approach required the removal and relocation of the driveline turning gear and removal and r[illegible]ement of the motor-operated lube oil pump (Figure 4).



4. Shaft in a half-shell. The top shell (shown in Figure 2) was removed from this assembly located between the compressor on the left and the generator on the right. An idler gear (center) connects the main lube oil pump (foreground) to the main shaft. This shot was taken just before the new SSS clutch replaced the 700-mm extension shaft that connects the compressor and generator. *Courtesy: Industria Sigrama*

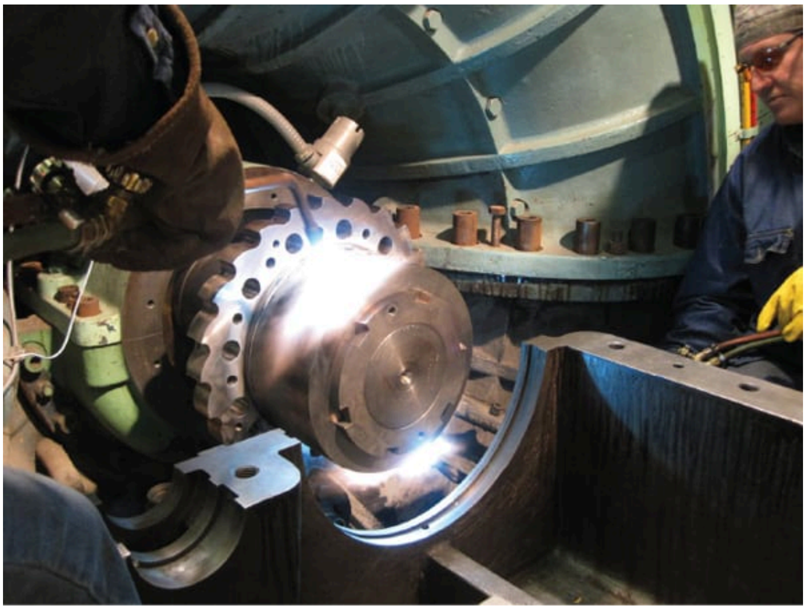
The driveline was originally designed to grow in the direction of the generator when in power production mode, up to about a quarter of an inch. However, in synchronous condensing mode, the combustion turbine is not operating, so the expected shaft displacement does not occur. It fell to SSS to design a clutch assembly that could also accommodate this driveline displacement. In addition, the clutch weighed more than the 700-mm spool piece it was replacing.

Final Driveline Design. The first order of business on this project was to perform a rotordynamic study of the proposed driveline with the new clutch and without the existing turning gear and gear-operated main lube oil pump. The reason this analysis was so important relates to the clutch configuration. The clutch is a semi-rigid clutch, which when disengaged leaves two halves: one half supported by the compressor and the other half supported by the generator shaft. SSS engineers were convinced that the overhung moments (the additional weight of the clutch halves in relation to the location of the existing bearings) would be excessive.

On the other hand, by using a spacer-type clutch, the teeth act like a double-engagement coupling, and the hub could be reversed on the compressor shaft. This hub design has the effect of reducing the overhung moment, countering the effect of the increased weight to be supported. A rotordynamic study confirmed this approach was possible.

However, CFE preferred to retain the existing hubs (the generator, particularly) because of their unique tapered bore and three keyway design and because CFE engineers were concerned that their removal would be a problem, as the hubs had not been removed in 40 years (Figure 5). This approach to securing the clutch required SSS to manufacture a large, heavy adaptor, because the clutch outside diameter was considerably larger than the existing hub. A second rotordynamic study confirmed that this approach was not possible, as a 3,600 rpm lateral critical speed would result, the same operating speed of the driveline. This approach was then discarded and the original plan to replace the existing hubs was selected.

Fortunately, the problems expected with removing the hubs from the 40-year-old shafts did not materialize. A 50-ton hydraulic jack and the direct application of heat quickly coaxed the hubs from their shafts. The two tapered, rigid hubs, each with unequally spaced keyways (the three keyways are visible in Figure 5), once removed, were shipped to the SSS factory in the UK. There, high-accuracy dimensional data using a coordinate measuring machine were collected. New tapered shaft rigid hubs were machined to match the compressor and generator shafts and the matching SSS clutch hubs.



5. Gentle persuasion. Both original hubs had been in place for more than 40 years, so there were concerns about how difficult removal might be. The application of heat and a 50-ton hydraulic jack made short work of hub removal. This photo shows the new hub being installed on the compressor shaft. The hub is not only tapered but also has three keys, an unusual design. *Courtesy: Industria Sigrama*

Even with the new split hubs, an additional 1 inch minimum of axial space was required to install the clutch. Unfortunately, the turbine couldn't be moved axially due to the thrust bearing, and movement of the generator was also limited. The solution was to disassemble the exciter fan to free up enough axial space to remove the existing 700-mm shaft and to install the new clutch. The new hubs and the clutch were subsequently installed on those shafts (Figure 6).

6. Tight fit. Once new hubs were machined and pressed back on the compressor and generator shafts, the SSS clutch was installed. Next, the top shell was reinstalled. New motor-driven DC and AC lube oil pumps replaced the old gear-driven main lube oil pump shown in the foreground. *Courtesy: SSS Clutch Co., Inc.*

New Turning Gear Location. As noted earlier, adding the SSS clutch necessitated removal of the driveline turning gear and gear-driven lube oil pump. The gear-driven lube oil pump was replaced with motor-driven pumps without problem. However, the turning gear is critical to ensuring that the extra-long driveline stays straight during shutdown periods, so its relocation was a must.

Also, the new turning gear had to be on the input side of the clutch to enable the turbine to be rotated for cooling when the generator was operating in synchronous condensing mode as well as coming off generation mode (see sidebar). Three locations were considered: at the hot free end of the turbine; in between the compressor and turbine; and in the inlet volute of the compressor, a location with limited radial space. The compressor location was selected because the connection only required external teeth on the new SSS input hub, mounting was comparatively simple, and no lubrication was required, a big plus.

With the location of the new turning gear decided, a new transition casing between the compressor and intermediate block was fabricated to give more radial space and clearance for the disk with the turning gear teeth. Also, the casing was modified, after installation, to get sufficient oil drain capacity from the inside of the casing. The turning gear connection point was also strengthened to support the added weight and to resist the torque reaction from the turning gear ratchet device.

Cold Alignment Approach. The first step in aligning the entire driveline, in its final operating configuration described above, was to establish the cold alignment. In past years, the generator was always balanced separately from the compressor, but the compressor was always balanced with the 700-mm shaft in place. However, there were no "in place" balance provisions for Unit 2, nor was there even a balancing instruction or plan. Hints were given of the cold alignment dimensions by the position of the rigid hubs on the compressor and generator shafts. By heating the hubs and then moving them farther onto the shaft, it became possible to effectively shift the generator rotor closer to the compressor, and vice versa.

Universidad staff said that the generator rotor could only move 6 mm from magnetic center—presumably, this was 6 mm in addition to the thermal growth of the generator and compressor rotor, which was 5.8 mm (0.230 inches). In the end, CFE decided to align the machine similar to the original design so that the generator would run on its magnetic center when generating but might be off axially by as much as 6.35 mm when synchronous condensing.

This approach to alignment worked well, but it did cause an unanticipated problem with the clearances inside the generator housing. When the machine cooled after a switch from generation mode to synchronous condensing mode, the exciter fan started rubbing the housing. After a New Year's Day phone call between CFE, Sigrama, and SSS, a very simple solution was identified. The exciter, as a separate machine, is connected to the generator with a gear coupling. A 5-mm spacer plate was added to the coupling to make it longer and permanently eliminate the problem.

Other New Equipment. Several additional conforming upgrades were accomplished as part of the project:

- Removal of the original-equipment gear-driven lube oil pump required adding new duplex motor-driven pumps (one DC- and one AC-powered), new oil piping, valves, and connection to the existing lube oil supply line.
- A Woodward electronic governor was installed in place of the mechanical governor.
- The power relay and AVR were modified for synchronous condenser service.
- The original analog controls were replaced with digital controls to manage the operating permissions and provide system protection and the new operator interface (Figure 7). The existing combustion turbine sequencing remained untouched.

7. Upgraded controls. The 1970s-vintage analog controls (left) were upgraded with a digital control system (right) that managed the new sequencing and control requirements of the plant. The combustion turbine startup sequencing management remains with the original controls. *Courtesy: Industria Sigrama*

More Upgrades Coming

Additional upgrades are pending for Universidad. Monterrey's electrical distribution system operates at 13.8 kV, the production voltage of the plant. However, the main transmission feed into the city is 115 kV. CFE engineers are considering adding a transformer that would allow the plant to feed directly into the 115-kV system, bypassing the city's 13.8-kV distribution system. This would allow the plant to put reactive power directly into the 115-kV system, where the MVARs can do the most good.

CFE appears to have tentatively picked its next synchronous condenser retrofit site. For grid purposes, CFE divides Monterrey into quadrants. Universidad is located in the north quadrant. La Leona, located in the west quadrant, also has two BB11-L combustion turbines, and Fundidora, on the east side, has a single BB11-L, although the condition of that machine is uncertain. In the south quadrant, Tecnológico has a single, but larger, 25-MW BB11-B that is under active consideration for conversion.

8. Tight teamwork. The principle participants in the project were, from left to right: Carlos González, CFE; Guillermo Cavazos, Edel; Rolando Garza, Edel; Frank Dougherty, SSS; Alfredo Hernández, Sigrama; Alejandro Salazar, CFE; Martín González, SSS; Javier Garza, CFE; Gerardo Arozco, Sigrama. SSS President Morgan Hendry is not shown because he was taking the photo. The enthusiasm for this project was evident by the presence of three generations of Universidad plant managers during construction and startup. *Courtesy: SSS Clutch Co., Inc.*

The major success of the synchronous condenser upgrade of Universidad Unit 2 is directly attributed to the cross-border teamwork exhibited by CFE engineers, suppliers, and the plant staff (Figure 8). With the successful demonstration of Unit 2's modifications, CFE is now seriously considering similar upgrades to other aging gas turbine generators of all makes and models throughout Mexico. CFE believes that older gas turbine generators that have been well maintained and that are located in, or can be relocated to, reactive power–deficient regions might well prove invaluable long past their usual retirement dates.

Thanks to Morgan L. Hendry, president, and Frank T. Dougherty, regional director, Latin America of SSS Clutch Co., Inc. (shown in the opening photo) for their invaluable assistance in the preparation of this article.

*— **Dr. Robert Peltier, PE** is POWER's editor-in-chief.*

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