1. ABSTRACT

A first of its kind hydraulic turbo-generator system was deployed for a Pilot Test at a given Gas Plant through collaborative effort of the local National Oil Company and Energy Recovery. This system was designed to replace the absorption contactor Level Control Valve (LCV) found in amine units of gas processing plants. Hydraulic energy that is normally wasted in the LCV is now harvested by the IsoGen system and utilized elsewhere in the plant. This Pilot Test report describes the design and deployment of the technology, analyzes the operating data and system performance, and describes the lessons learned and overall success of the project. At the conclusion of the pilot period the IsoGen system was proven to be a viable technology ready for deployment in gas processing applications as well as a technology poised to create value for the Plant. The IsoGen system has already recovered over 1 Gigawatt hour of electricity over the 6 month pilot test for the Gas Plant.

Key outcomes include:

1. The IsoGen System is capable of efficiently capturing hydraulic energy from the rich DGA stream exiting the absorber. Total efficiency (Hydraulic to Electrical efficiency) was consistently over 70% which met the system performance requirement. The unit generated over 1 Gigawatt hour of electricity during the 6 month Pilot Test Period.
2. The IsoGen Turbine System was able to seamlessly control level within the contactor similar to standard LCV functionality.
3. Post-Pilot Teardown analysis of the turbine indicated that the design and metallurgy is impervious to the rich amine process fluid. Evidence of damage from flashing, cavitation, or erosion was nonexistent.
4. The core technology employed in the IsoGen System has been proven to be robust and able to withstand the challenging conditions found in amine sweetening plant applications.
5. Power quality output from the system incorporating a specialized VFD was demonstrated to exceed the requirements of the IEEE519-1992 standard.

Areas of improvement include:

1. Mechanical seal support system was not robust enough for challenging gas processing plant environment. Key components were not spared and predictive condition monitoring instruments were not provided.
2. ETAP modeling of system harmonics should be performed by VFD manufacturer before designing and fabricating VFD for IsoGen application.
2. PROCESS DESCRIPTION

The acid gas removal process is an energy intensive process commonly used to remove hydrogen sulfide and carbon dioxide from natural gas streams. The process involves an amine gas contactor that typically operates at pressures up to 1200 psi, and an amine regenerator that operates at slightly above atmospheric pressures. Energy is first consumed in pumping lean amine solution from the regenerator up to contactor pressure, and later dissipated in depressurizing the rich amine exiting the contactor at the level control valve (LCV).

It was decided by the end user to test an innovative energy recovery solution at a given Gas Plant train 3. The simplified Process flow diagram of HGP Train 3 is shown in Figure 1 Simplified Process Flow Diagram of the acid gas removal unit. Low pressure Lean DGA (2250 gpm and 110 psig) coming from Stripper H48-C-302 is pumped to 610 psi and sent to DGA contactor by DGA circulation pump H48-G-301 A (pump B standby). Acid gases in inlet natural gas are absorbed by contact with lean DGA in Contactor H48-C-301 and the sweet natural exits the contactor toward TEG unit for dehydration.

The pressurized rich DGA exits bottom of the contactor and flashing through the pressure let-down valve 33-LV-164B (valve A standby) were rich DGA loses its energy before going to low pressure DGA flash drum H48-D-302. The pressure drop across pressure let-down valve is approximately 446 psi.

The rich amine after partial filtration and heat exchange with lean DGA enter DGA Stripper H48-C-302 where under low pressure the acid gases are boiled out and exit from top of the stripper. After losing its acid gases, lean DGA exits at the bottom of stripper and a series of filtration, heat exchanger and air cooler, pressurized and sent back to the contactor by the lean DGA circulation pump.

As mentioned, the pressurized rich DGA loses a high amount of energy when passing through let down valve 33-LV-164B. This pressure let-down can be directly converted into a quantity of hydraulic energy which is available for recovery. In this case:
2250 gpm X 446 psid X 1/2299 = 436 kW of energy

The installed IsoGen bypasses the let-down valve and captures most of the otherwise wasted energy and converts it to electricity without comprising a LCV valve’s level control functionality. The generated electricity is then routed to the plant electric bus for utilization elsewhere.

A summary of flow and pressure for process streams along with Isogen energy saving calculations are given in Appendix A.
3. ISOGEN DESIGN

The IsoGen system is a standalone solution that converts hydraulic energy to electrical energy. It is designed to replace flow control, level control and choke valves in oil and gas applications. A wide range of process flows and pressure drops can be accommodated at peak efficiency using IsoGen’s unique auxiliary nozzle technology and variable speed induction generator.

At the core of the IsoGen system is a single-stage turbine that drives a medium voltage variable speed induction generator. The generator’s output is conditioned to match grid voltage and frequency at near unity power-factor using a regenerative variable frequency drive (VFD). Because of the turbine casing’s back pullout configuration, turbine hydraulics can be replaced in a matter of hours without disturbing the process piping connections. The IsoGen turbine has external oil-mist lubricated anti-friction bearings that make the device highly resistant to debris suspended in the process flow. A rigid bearing housing, low shaft flexibility index (L3/D4), closed cycle oil-mist lubrication, and magnetic face seal bearing isolators ensure premium reliability in even the most severe operating environments. A state-of-the-art plan 74 dual gas shaft seal provides long life, high efficiency, and provides a high level of containment safety for the rich amine process fluid.

Both turbine and generator are designed to be API compliant and are rated for use in hazardous environments. Pressure drops and flows that lie outside of the turbine’s already large operating envelope are accommodated using a parallel bypass valve as
well as a series throttle valve. The generator and valves are controlled by a programmable logic controller (PLC).

The design is uniquely suited to plant conditions where flows and pressures vary over a broad range. A volute style turbine with two nozzles along with a variable speed generator gives the system the ability to operate at peak efficiency over a broad range of both flows and differential pressures as opposed to most hydraulic power recovery turbine designs which have a fixed best efficiency point. A proprietary control system manages the flow distribution to the two nozzles as well as the speed of the generator based on process conditions and desired level set point. This system provides two distinct advantages to plant operations. The first advantage is that the system maximizes energy production over varying process conditions. The second and arguably more important advantage is that the harmful effects centrifugal machines experience when running off design, such as excessive vibration and radial loads are avoided which increases both the service life and reliability of the machine. In a later section the value of efficient operation off of the Normal Operating Point will be illustrated.

The following diagrams show the layout of the IsoGen system, a sectional view of the turbine and components, and a view of the hydraulic geometry. A simplified piping and instrumentation diagram and a screen shot of the System HMI are also shown.

Figure 2 IsoGen System Overview
Figure 3 Turbine Overview

Figure 4 Turbine Hydraulic Geometry Cross Section
Figure 5 Simplified P&ID of IsoGen™ System

Figure 6 Screen shot of the IsoGen™ system HMI at the “Normal Operating Point”
4. ISOGEN FAT AND WITNESS TEST

As part of the effort of de-risking the IsoGen technology the end user representatives traveled to Energy Recovery’s facility in San Leandro to review the IsoGen system, Witness the operation of the unit, and participate in a joint FMEA which was conducted in April 2013.

Test criteria defining success and acceptable performance were extracted from industry standards, including API 610 and API 682, among others. An operating window was established based on gas plant data representative of winter and summer process conditions as shown in Figure 7 Plant historical data and test operating window.

A “normal operating point” was defined at the averaged center of the representative process data, as well as a “rated operating point” at the upper bounds of flow and differential pressure. Eight additional test points were defined to encompass the supplied process conditions and represent a test of the system’s operating window. A tabular representation of the test points is presented in Table 1 Acceptance Test Summary.
Table 1 Acceptance Test Summary

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Performance Requirement</th>
<th>Witness Test Measured Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Normal Operating Point</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydraulic to electrical efficiency</td>
<td>Greater than 70%</td>
<td>77.3%</td>
</tr>
<tr>
<td>Power factor</td>
<td>Greater than 0.90</td>
<td>0.99</td>
</tr>
<tr>
<td>Bearing housing vibration</td>
<td>Less than 0.18 inch/s RMS</td>
<td>0.05, 0.07, 0.09 (X, Y, Z in/s)</td>
</tr>
<tr>
<td>Turbine bearing temperature</td>
<td>Less than 93°C</td>
<td>68.5°C, 66.6°C, 51.0°C (Inboard, outboard, radial)</td>
</tr>
<tr>
<td><strong>Rated Operating Point</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydraulic to electrical efficiency</td>
<td>Greater than 70%</td>
<td>75.7%</td>
</tr>
<tr>
<td>Power factor</td>
<td>Greater than 0.90</td>
<td>0.99</td>
</tr>
<tr>
<td>Bearing housing vibration</td>
<td>Less than 0.18 inch/s RMS</td>
<td>0.06, 0.08, 0.10 (X, Y, Z in/s)</td>
</tr>
<tr>
<td>Turbine bearing temperature</td>
<td>Less than 93°C</td>
<td>68.7°C, 66.7°C, 50.7°C (Inboard, outboard, radial)</td>
</tr>
<tr>
<td><strong>All Other Operating Points</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Factor</td>
<td>Greater than 0.90</td>
<td>0.99 – 1.00</td>
</tr>
<tr>
<td>Bearing housing vibration</td>
<td>Less than 0.18 inch/s RMS</td>
<td>0.08, 0.10, 0.13 (X, Y, Z in/s Maximum recorded value over all points)</td>
</tr>
<tr>
<td>Turbine bearing temperature</td>
<td>Less than 93°C</td>
<td>68.3°C, 66.5°C, 51.1°C (Inboard, outboard, radial. Maximum recorded value over all points)</td>
</tr>
</tbody>
</table>

5. ISOGEN INSTALLATION AND COMMISSIONING

IsoGen installation at train 3 was performed by the end user and the local contractors following the guidelines provided by Energy Recovery, Inc. in the “IsoGen Installation and Commissioning plan”. The IsoGen system replaces one of the two redundant level control valves used for contactor level control. It was important that the commissioning activity be commenced as soon as possible after the installation of the IsoGen system, so that level control redundancy for train 3 could be restored quickly.

Preliminary work for the installation included designing piping and pipe supports to route from the elevated LCV down to ground level where the turbine would be installed. The design was relatively simple and piping was installed without shutting down the gas train. A concrete foundation was poured to support and absorb vibration from the turbine system similar to that of any piece of rotating equipment. Additional Civil Work was limited to bringing electrical, control wiring and utilities to the skid location. All of
this work was within the abilities of the plant to manage appropriate contractors to accomplish.

Unfortunately contractors did not adequately level the equipment base before pouring the epoxy grout which permanently adheres the base to the foundation. This resulted in the mounting bed for the turbine being not level and not-coplanar with the generator mounting bed. The rather unconventional step of putting tapered shims under the turbine mounting points corrected the situation and allowed for near perfect generator-turbine alignment.

ERI engineers and technicians were present to review and assist with the mechanical completion effort performed by the Plant personnel. After pre-commissioning activity completion, all parties agreed that the quality of the installation was excellent and the Mechanical Completion Certificate was issued. The Isogen system was ready for final commissioning activity. The steps planned for in the commissioning plan included field training for the end user staff. The commissioning plan steps are as below:

- Un-couple generator, perform 4 hour mechanical run test. Update PLC as per the end user request
- Perform multiple simulated startups with generator uncoupled to test & troubleshoot any issues from PLC update. Verify IsoGen PLC functionality and test communications with the plant Central Control Room.
- Conduct classroom training session for plant staff.
- Conduct field training for plant staff.
- Schedule start-up time with operations personnel. Perform any required reviews and open block valves.
- Start-up IsoGen unit.
- Monitor Isogen unit operation and troubleshoot as necessary.

These steps were executed successfully and efficiently by the end user and Energy Recovery personnel working closely together in a well-coordinated fashion. Several simulated system starts and stops were performed. The IsoGen PLC functionality was fully verified and communications with the plant Central Control Room were tested and proved to be operating as expected. The system was then successfully brought online.

6. ISOGEN PILOT TEST PERFORMANCE AND ANALYSIS

6.1. Operating Conditions

The IsoGen system was designed based on process data provided to Energy Recovery in 2012. Figure 8 Process Flow and Pressure at IsoGen Skid shows the process conditions during the first 190 days of the pilot test and Figure 9 Turbine Operating and Test Points shows the pilot process conditions along with 2012 representative summer and winter process data and the Normal and Rated Operating points for the IsoGen System. The field test process data, shown in the lower right portion of the chart differs meaningfully from the design data due to changes in the process flow requirements as well as larger than expected hydraulic losses in the modified piping. Due to the unique
variable geometry and variable speed turbine design the IsoGen is able to easily accommodate current process conditions without experiencing a loss of efficiency or increased vibrations. Power generation is reduced proportional to the reduction in available hydraulic energy.

Figure 8 Process Flow and Pressure at IsoGen Skid
Efficiency, Power, and Cumulative Energy Generation are shown in Figure 10 Efficiency, Power and Energy below. Efficiency has held steady over the duration of the data indicating stable turbine operation. Power generation has varied throughout the data as process conditions, specifically rich amine flow, have varied. It is worth noting that turbine efficiency stays relatively constant as available energy varies. Cumulative energy generation is being recorded and has averaged 6.4 MWh per day.
Figure 10 Efficiency, Power and Energy

6.3. Turbine bearing housing condition monitoring

RTDs and Vibration Transmitters have monitored the condition of the rolling element bearings on the turbine bearing housing. Trends are shown in Figure 11 Turbine Temperature and Vibrations below. Bearing temperatures are within specification and are remaining stable. Daily variation in bearing temperature due to ambient temperature and solar loading is demonstrated.

Bearing housing vibration is very low and well within accepted limits. Small cyclic variations are due to thermally induced alignment variation.
Figure 11 Turbine Temperature and Vibrations

6.4. Instrument panel and dual gas seal

Figure 12 Seal and Control Panel Temperature, shows instrument panel interior panel temperature and the differential pressure of the Plan 74 Dual Gas Seal. Both have achieved steady state operation within acceptable limits. Note the seal support system experienced difficulties detailed in the Lessons Learned section of this report, however over the trial period seal dP and Nitrogen flow remained relatively constant.
6.5. Electric systems

The electrical system was designed and installed to meet the end user, API, NPFA, IEEE and NEC 2012 standards. The challenges noted below were the main areas of concern for the design.

6.5.1. Variable frequency drive

Adding VFD to HGP had many challenges from the operations issues to the harmonic analysis of the VFD these items are discussed below;

- Startup and Synchronization
- Generator Speed
- Bus Connection
- Neutral Resistor
- Motor Specifications
- Harmonics
- Generator Condition Monitoring
6.5.2. Startup and Synchronization

The VFD is a sub-part of the IsoGen™ system and is controlled ‘remotely’ by the IsoGen control systems PLC. Although the main panel of the VFD includes manual start, stop and speed controls that can be used during field commissioning to rotated the assembly (slowly) as a motor the VFD must be in ‘Remote’ (and not Local) mode during normal generation mode. If the VFD is left in ‘Local’ mode the PLC will report a fail to start due to VFD’s operational mode.

Synchronization is achieved by the high speed switching circuits of the VFD. The line side of the drive consists of Symmetric Gate Commutated Thyristor (SGCT) that can only be switched at the line frequency of 60Hz. During the startup of the system the mechanical assembly is automatically rotated to confirm all the sensors are functional before opening the throttle valve and allowing process flow to ‘over haul’ the generator. It is true to say the system starts by rotating the turbine as a motor before being overhauled by the process fluid and turbine and at this point becomes a generator.

Both in standby and running conditions the VFD is always on and waits for the control signals from the system PLC and the plant operator to run.

Startup and Synchronization have been successfully demonstrated by the ease of starting the IsoGen system by the simple press of a start button.

6.5.3. Generator Speed

It is not necessary for the speed of the turbine to match the equivalent electrical speed of the line side, and further may vary from 1800RPM to 3600RPM (30Hz to 60Hz). This generator configuration is known an asynchronous generation and not the more commonly known generation system synchronous where the generator and bus frequencies match. Note the generators speed is calculated based on process conditions and is adjusted automatically to maximize the power generated by the IsoGen™ system.

During the varying plant conditions the speed of the turbine automatically changed to maximize the efficiency of the IsoGen™ system and maintained a buss connection at 4160V 60Hz. Below in Figure 13 Generator Speed and Power. The turbine speed varies from 3000 to 3600 RPM and remains connected to the plant bus delivering power from 130 to 320kW.
At the initial design stage the requested electrical connection point for the VFD was BUS-2 S2 that is configured as a motor starter. The electrical consideration for this was to keep the generator and circulation pump of the same bus (for harmonic mitigation), later it was confirmed that either of the circulation pumps from Bus-1 and Bus-2 can be used in the process. At this point the VFD connection point was moved to location B204. Electrically this is acceptable as the input circuitry for the VFD includes a motor starter to protect the VFD for short circuit and overload conditions therefore an input breaker is sufficient for the system. As standard the VFD does not have an output contactor, this was added as an electrical safety item to prevent accidental overhauling of the turbine and ‘self-generating’ potentially making the system have high stray voltages. Adding a motor / generator contactor that is opened when not in use adds an additional level of protection to the system.

6.5.5. Neutral Resistor

The VFD manufacturer ‘Rockwell’ requires the motor / generator not to have the neutral point connection on the motor side to prevent a common mode voltage across the drive. The VFD has an internal neutral point that is used to determine any abnormal operation.
6.5.6. Motor Specifications

During abnormal conditions the motor / generator has seen over-speed conditions when the turbine has runaway condition caused by an electrical system fault (E.g. VFD failure, electrical bus instability, plant brown out etc). The bearing system of the induction generator that is made per API 541 4th Edition with CSA Class 1, Div 2, Group B/C/D, T3, has special considerations to allow an over-speed of maximum 5400RPM runaway for 20 seconds. It is possible during high ambient temperatures for the bearing temperatures to exceed 93°C during operation in an environment hotter than 42°C (Per API 541-2.4.7.1.15). Synthetic oil was added for the bearings to further mitigate the bearing temperatures.

To mitigate the high ambient conditions the machine was designed with a copper bars rotor, H Class insulation and to operate with a service factor of minimum 25%. The system remained within the temperature set points during summer operation and during a turbine runaway condition no increase in bearing temperatures further indicates the bearing system remained un-harmed.

6.5.7. Harmonic Analysis

During installation and commissioning a concern was raised by the Plant’s electrical staff that the Rockwell Variable Frequency Drive may inject harmful harmonics into the plant electrical bus. After commissioning it was discovered that the harmonics were higher than expected. Energy Recovery worked with Rockwell’s engineers to implement a fix for the drive, this fix included replacement of the line side filter capacitors.

After the variable frequency drive modification the harmonics of the electrical system were studied in extensive detail by attaching a power analyzer to the system for a period of two weeks. The average results are shown in Table 2 THDi & TDD.

<table>
<thead>
<tr>
<th>THDi &amp; TDD</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>THDi</td>
<td>5.22%</td>
<td>4.71%</td>
<td>5.40%</td>
</tr>
<tr>
<td>TDD</td>
<td>2.44%</td>
<td>2.16%</td>
<td>2.49%</td>
</tr>
</tbody>
</table>

Table 2 THDi & TDD

To meet IEEE519-1992 and Plant Power Systems Engineering Department requirements the TDD must be below 5% at the PCC, where the PCC is considered as the Line connection to the VFD. A detailed report on the issue is provided as an appendix of this report.

6.5.8. Generator Condition Monitoring

The induction generator utilizes RTDs on both the windings and the journal bearings to monitor condition. Figure 14 Generator Temperature shows trends of these RTDs and
indicates the generator is stable and operating within specification (120 F max bearing temperature and 180 F max winding temperature)

![Generator Temperature Chart]

Figure 14 Generator Temperature

7. TEARDOWN AND COMPONENT ANALYSIS

The IsoGen turbine was shut down in September 2015 after 164 days in service. This period was agreed by all parties to be sufficient to close out the Pilot Test Period. The main purpose of the shutdown was to inspect the internal turbine components for indications of wear or degradation. The shutdown was also an opportunity to replace the mechanical seal which had developed a minor leak and to test the viability of storing a “back pullout assembly” (defined as the sub assembly containing the turbine, mechanical seal, and bearing housing) as an onsite spare to quickly address component failures.

Disassembly of the turbine went well though due to the location of the skid underneath a steel structure lifting the heavy turbine assembly was a challenge. Otherwise if was found to be a simple task to disconnect the instruments and bring the assembly to a workshop for teardown and inspection. Installation of the alternate back pullout assembly went similarly well. A laser alignment tool was utilized and the generator was determined to be sufficiently aligned with the new assembly that further alignment adjustment was unnecessary.
Photographs and measurements indicated that there was no observable wear, erosion, or corrosion to any of the internal components in contact with the Rich DGA. This was expected based on the superior metallurgy employed in the turbine design as well as the function of the turbine itself. In a standard level control valve all hydraulic energy is intentionally converted into kinetic energy in the tight clearances of the valve which then is then lost through shear in the resulting drag and turbulence. Because of the high velocities local static pressure is significantly reduced leading to excessive flashing and cavitation which leads to erosion damage to the valve and internal piping. Because the turbine absorbs most of the energy from the amine the adverse conditions at the exit of the turbine are much less severe than those at the exit of a traditional level control valve.

Figure 15 Turbine Discharge and Case Wear Ring

Figure 16 Turbine Runner
Figure 17 Turbine Wear Ring

Figure 18 Turbine Runner Discharge

Figure 19 Turbine Runner Internal View
7.1. POST INSPECTION RELIABILITY ISSUES

A number of issues occurred on or after the resumption of operation of the IsoGen system after the teardown analysis. Specifically the following operational issues occurred:

- Gas seal panel differential regulator failure  
  a. Tripped system 9/10/2015
- VFD shutdown due to plant voltage brownout  
  a. Tripped system 10/15/2015
- Control valve position feedback deviation  
  a. Tripped system 10/16/2015 and 11/2/2015
- Mechanical seal failure
• High vibration shutdown  
  a. Tripped system 11/6/2015

The following paragraphs will elaborate on the issue faced and lessons learned to avoid the issue in the future.

### 7.1.1. Gas seal panel differential regulator failure

The support panel for the dry gas mechanical seal was inspected as part of the post-pilot system evaluation. During the inspection process a fitting was loosened allowing the silicone isolation fluid to leak out of the regulator. Refilling the regulator in the field is possible yet the necessary equipment was not at hand so the regulator and isolator assembly was brought back to the manufacturer facility to refill. A backup filled regulator assembly was provided as an on-site spare to mitigate impact of situation in the future. Future versions of this panel may include an electronic differential tracking regulator rather than the mechanical version for increased reliability.

### 7.1.2. VFD shutdown due to plant voltage brownout

A voltage dip (brownout) on the bus where the IsoGen system connects triggered an emergency shutdown of the IsoGen. This behavior is by design because when the electric load for the generator gets disconnected then the system has nowhere to put the generated energy. The turbine can run away due to this ‘load rejection’ so an emergency shutdown is triggered. The system is available for restart as soon as normal power is restored and the fault is cleared. Figure 22 VFD Trip, shows the brown out occurring at 04:20 and the turbines speed spiking as the VFD disconnects from the plant bus. Note the continuing bus instability after the VFD trips offline.

![Plant Bus and Turbine Speed Trip 10/15/2015](image-url)

Figure 22 VFD Trip
It was noted that during this emergency shutdown vibration levels recorded at the turbine bearing housing increased by about 3 times normal running levels for about 5 seconds. While these vibration levels are not harmful in the long term for the system they may have initiated subsequent issues with the system. Dozens of emergency stops similar to this were performed on the system during the system development in the ERI facility and an emergency shutdown was performed as part of the FAT test.

7.1.3. Control valve position feedback deviation

The IsoGen control system shutdown the system after it noted a deviation in the throttle valve position feedback from the control value. This function is part of the safety system such that it will shut down the system if it detects a valve is malfunctioning. In this case the valve positioner was working correctly however the feedback device linkage had come loose and was no longer accurately reporting position feedback. Adjusting the positioner system resolved the issue and Energy Recovery is working with the positioner manufacturer to see if additional actions can prevent this occurrence. It is suspected that the high vibration from the emergency shutdown may have caused this linkage to come loose.

A second occurrence of the feedback signal caused the system to shutdown, the throttle positioner LY-201 was swapped with the bypass positioner LY-203 to allow the system to be bought back online. Action was taken to ship a spare positioner. Several days later LY-203 started to show feedback errors and was replaced with spare.

7.1.4. Mechanical seal failure

Upon resolving the positioner feedback issue noted above the IsoGen system was unable to restart due to inadequate nitrogen pressure in the mechanical seal. The seal had developed a nitrogen leak on the primary sealing rings wherein nitrogen was leaking into the process fluid. It should be noted that process fluid was not leaking past the secondary seal rings into the external environment. The system was disassembled and the failed seal was sent to John Crane for failure analysis. The root cause was determined to be improper assembly of the seal onto the turbine shaft. Since the turbine back pullout assembly was assembled and tested at the manufacturer facility and was run for some time in the plant it is assumed that the seal assembly was marginal and the last bit of high vibration was enough to cause it to fail. Note the failure report is included as an appendix. John Crane has trained Energy Recovery and the Plant personnel in assembling the dry gas seals into the system and is available to support future assembly work on site.

7.1.5. High vibration shutdown

The turbine is fitted with three vibration sensors for tri-axis monitoring. Any excursion of 0.4IPS for 5 seconds or longer the system will shutdown to protect the turbine and plant equipment.

Due to the unexpected failure of the seal in the second back pullout assembly the Energy Recovery team deployed to hastily reassembly the turbine taken apart for this pilot report in order to replace the assembly with the above seal failure. During
assembly a step was missed and the turbine was not aligned properly to the case. As a result there was an internal rub of the turbine wear ring to the turbine runner. Because this was a nonmetallic wear ring the system was able to operate relatively normally for a period of several hours before the contacting surfaces created enough wear to cause a high vibration shutdown. The rubbing caused damage to the turbine runner and wear ring and other components such as the bearings and seal will be replaced out of caution. The overhaul and assembly instructions are being rewritten to emphasize the important step that we left out. Additionally the design is under review to find ways to make it more robust and negate the need for the alignment step which was missed.

8. LESSONS LEARNED AND AREAS OF IMPROVEMENT

While the basic success criteria for the IsoGen Pilot test were met, there were several areas where lessons were learned and opportunities for improvement in both system design and project execution were noted. It is expected that future installations of this technology will easily incorporate the learnings in this section leading to trouble free installation and operations.

8.1. Mechanical Seal

The Plan 74 dual gas seal experienced a failure during the Pilot Test period. This failure was caused by multiple failures of a sub-component of the seal support panel, namely the nitrogen pressure booster. The failure mode is relatively simple, for a gas type seal the barrier gas pressure must always be higher than the gland pressure such that the seal faces float on a thin film of nitrogen. This nitrogen film keeps the process fluid from contacting the seal faces and keeps asperities on the seal faces from making contact causing wear. The positive nitrogen pressure must be maintained at all times so that process fluid remains in the seal gland, even when the shaft is not turning. The upside of this type of seal is because the seal faces do not contact the seal can be expected to last over 10 years before rebuild is necessary.

The nitrogen booster increases the pressure of the gas from the plant nitrogen system to a requisite pressure higher than the gland pressure. The original design of the seal support panel had three shortcomings: 1. The nitrogen booster has seals and other components that wear over time causing it to be a maintenance item yet an online spare was not incorporated in the panel. 2. The model of nitrogen booster supplied by John Crane had design and quality deficiencies which lead to substantially reduced operating life and reliability. 3. The machinery condition monitoring system for the seal did not include the proper instruments to detect and alarm based on a decline in performance of the nitrogen booster. The system only alarmed after nitrogen pressure was low enough that the seal faces were at risk of coming in contact during shutdown.

Moving forward changes to the seal support system are to include booster manufacturer (replacement with a higher quality unit), redundancy by using a dual booster configuration and condition monitoring that will preempt adverse conditions for the seal
and allow for maintenance without shutting the system down. Additionally opportunities were identified for better documentation, equipment marking, and operator training to reduce the chances of improper operation of the seal support panel. Additionally the end user and Energy Recovery will collaborate with suppliers to design a seal and support system most suited to this turbine application in Rich Amine service.

8.2. Harmonics

The power system design and requirements including the generator and Variable Frequency Drive (VFD) as specified by the Plants’ Power Systems Engineering Dept. was successfully designed and implemented with the exception of the electrical harmonic levels. These high level of harmonic electrical currents caused concerns during the trial period as brought to attention from Plant’s Power Systems Engineering Dept. This led to the Plant requesting ERI’s Electrical Engineering dept. to perform onsite harmonic monitoring and mitigation including revisiting the electrical system specifications.

The VFD’s power system specifications and electrical models were not totally understood until after the system was installed at the facility. At that stage in the project it became apparent that the electrical system consisting of the VFD and Plant’s power distribution network where not working together as expected. This resulted in the IsoGen™ system not complying to the Plant’s stringent power specifications and further analysis and a redesign of the VFD line filters was necessary. The hardware change corrected the harmonic issue however this design iteration could have been avoided if the electrical system was correctly modelled in ETAP prior to the specification of the VFD.

8.3. Skid Installation

A large rotating machine such as the IsoGen requires a rigid connection to a massive foundation in order to minimize vibrations which can limit the service life of subcomponents such as bearings and mechanical seals. The machine base (or skid), must also be installed level and without torsion or bending moments applied so that the motor and turbine mounting points are horizontal and the two machines can be effectively aligned and coupled.

Skid installation was performed by outside contractors hired by HGP per the Energy Recovery installation documents, however the contractors did not level the base before securing it to the foundation with epoxy grout. This resulted in the machine base being distorted and the inability to align the turbine to the generator. Tapered shims were fabricated and installed under the turbine to compensate for this and proper alignment was achieved. In the future the end user or Energy Recovery representatives will perform a detailed review and sign off on base leveling before grout is poured.

8.4. Pipe Pressure Losses

The generated power was noted to be less than predicted during the factory acceptance test. The reason for this was both the turbine flow and differential head were less than the rated operating point for the machine. While the reduced flow (due to plant requirements) was not anticipated, the reduced differential head is due to factors that in
hindsight could have been predicted. Plant data used as the design basis for the machine included the gas contactor pressure and the flash tank pressure from the plant DCS. The total difference between these two pressures was assumed to be available power for the turbine when in fact there were some losses in the pipe run and flash tank elevation that ought to have been considered. Additionally a strainer was added to the inlet of the IsoGen skid as the result of a process FMEA which added a small amount of head loss. The unique design of the IsoGen system allowed it to operate at full efficiency with no additional vibration or excessive radial bearing loads despite process conditions during the field test being well below the normal operating point for the machine.

A more detailed study of the piping design at the early stages of system design will make sure the system design is optimum. Refer to Figure 7 Plant historical data and test operating window for detail of the difference between the normal operating point (design point) and process conditions observed during the pilot test.

9. CONCLUSIONS

Through the collaborative effort of many organizations within the local National Oil Company and Energy Recovery the IsoGen turbo-generator system was successfully pilot tested and proven to be a viable technology to save valuable energy in amine gas processing applications. Specific conclusions from the Pilot Test include:

1. The IsoGen System is capable of efficiently capturing hydraulic energy from the rich DGA stream exiting the absorber in a gas processing plant. This energy was successfully routed within the plant resulting in the recovery of over 1 Gigawatt hour of electricity over the 6 month Pilot Test Period.

2. Despite the complexity of the IsoGen System as compared to a simple actuated valve, the system proved to be capable to control level within the contactor with ease and plant operators quickly learned how to operate the system and bring it on and off line as needed without interrupting operations. The system design proved to be a close fit to the existing LCV such that it allowed the system to be installed as a direct replacement of the valve with no further changes or additions to the plant piping or control system.

3. Teardown analysis of the turbine indicated that the design and metallurgy is impervious to flashing, cavitation, or erosion. Condition monitoring of the bearing temperatures and vibrations indicated consistent performance with no signs of degradation.

4. With the exception of some challenges related to the mechanical seal support system the IsoGen System has been proven to be robust and able to withstand the challenging conditions found in amine sweetening plant applications.

5. Power quality output from the system incorporating a specialized VFD was demonstrated to exceed the requirements of the IEEE519-1992 standard.
APPENDIX A: PROCESS FLOW DIAGRAM AND ENERGY SAVING

### Description

<table>
<thead>
<tr>
<th>Stream</th>
<th>RICH DGA</th>
<th>LEAN DGA</th>
</tr>
</thead>
<tbody>
<tr>
<td>RICH DGA from DGA Contactor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rich DGA from UV-164B</td>
<td>Rich DGA to Throttle Valve</td>
<td></td>
</tr>
<tr>
<td>Rich DGA to IsoGen Turbine</td>
<td>Rich DGA to Flash Drum</td>
<td></td>
</tr>
<tr>
<td>Lean DGA from Stripper</td>
<td>Lean DGA to Circ Pump A</td>
<td></td>
</tr>
<tr>
<td>Lean DGA to Circ Pump B</td>
<td>Lean DGA to Circ Pump B</td>
<td></td>
</tr>
<tr>
<td>Lean DGA to IsoGen Contactor</td>
<td>Lean DGA to IsoGen Contactor</td>
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### Pressure, psi

<table>
<thead>
<tr>
<th>Stream</th>
<th>Case 1: Lean DGA Circ. Pump</th>
<th>Lean DGA</th>
<th>Standby</th>
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<tbody>
<tr>
<td>Pressure, psi</td>
<td>540</td>
<td>80</td>
<td>80</td>
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<tr>
<td>Flow, gpm</td>
<td>2250</td>
<td>2250</td>
<td>2250</td>
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</tbody>
</table>

### Assumptions

- Contactor pressure: 540 psi
- Lean DGA pump suction pressure: 110 psi
- Lean DGA pump discharge pressure: 610 psi
- Flash drum pressure: 80 psi
- Turbine exhaust pressure: 94 psi
- Lean DGA flow rate: 2000 gpm
- Rich DGA flow rate: 2250 gpm
- IsoGen efficiency: 73%
<table>
<thead>
<tr>
<th>Train 3, Configuration 2x100%</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>DGA Circ. Pump</td>
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<td></td>
</tr>
<tr>
<td>DGA Circ. Pump + IsoGen</td>
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<tr>
<td>Lean DGA flow from stripper</td>
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<td>2000 gpm</td>
</tr>
<tr>
<td>Rich DGA flow from contactor</td>
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<td>2250 gpm</td>
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<td>Rich DGA pressure from contactor</td>
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<td>Flash drum pressure</td>
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<td>Lean DGA Circ. pump suction pressure</td>
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<td>IsoGen</td>
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<td>Turbine flow</td>
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<td>Turbine inlet pressure</td>
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<td>ANNUAL ENERGY SAVING</td>
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<tr>
<td>CO2 GAS EMISSION REDUCTION</td>
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</table>