

Installation of An Integrated Turbine-Generator Control System for a Pulp Mill

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Abstract: A British Columbian pulp mill had experienced the “spiral of death” many times when the turbine-generator controls were unable to survive the loss of utility tie-line connections. The mill has two high efficiency rotary turbine-generator units rated 32.2 MVA each and a heat sink capable of generating 47 MW, approximately 87% of the mill power needs, though only 44 MW was being produced. The mill believed that with a load rejection strategy the mill had the potential to continue operation after the loss of a utility tie. In order to ride through the loss of the utility and to fully utilize the process heatsink, the mill needed to replace the 1960’s era turbine-generator control system supplied by the Turbine-Generator OEM. A triple modular redundant control system for each unit was installed. These systems integrate turbine governor controls and generator excitation control system in a single digital control. The systems are connected in order to jointly coordinate dispatch of real and reactive power demands and achieve load control for the mill. In a staged test, the mill was able to survive the loss of a utility tie-line, and has increased total generation. The new system completely automates the startup, loading and synchronizing of both generators.

Index Terms – Turbine, Generator, Governor, Exciter, Control System

I. INTRODUCTION

Pulp Mills originally installed co-generation to take advantage of the higher efficiency of high-pressure boilers – 4000 to 6000 kPa. Backpressure and automatic extraction turbines extract the work available in the high-pressure steam. Pulp and paper mill production units need process heat, typically at pressure levels of 1100 kPa and 450 kPa. These process users provide a “heatsink” for the co-generation process. The size of the co-generation opportunity is determined by the size of the process “heatsink” and the pressure differential available across the turbines. The work produced in the turbine is used to run a generator. The generated electrical energy is used to displace tie-line electrical energy. Tie-Line electrical energy at a cost of approximately 4 times the cost of co-generated electrical energy is a substantial premium energy source. Displacing tie-line energy with co-generated energy creates a large savings for co-generators. A pulp mill co-generating 30 MW may have

annual savings in the range of \$12 MM to \$5 MM (US) depending upon the serving utility rate.

In the 1990’s, co-generating plants in Pulp and Paper mills were expected to be key to greater profitability by allowing the mill to “ride through” loss of electric tie-line power. Most mills built in the 1990’s can and do have co-generation plants that can accomplish this. Most utility service losses are measured in minutes; the major loss to the mill as a result of this may be days of lost prime production. A loss of utility power to a pulp and paper mill usually results in loss of the steam plant/powerhouse and complete shutdown of the Kraft Recovery Cycle. If a mill can shed load and maintain an operating power plant by use of appropriate control strategies, the mill would re-synchronize with the utility when service is restored and the mill production cycle would resume, typically with loss of prime production measured only in hours.

II. THE NORTHWOOD PULP MILL

The Northwood Pulp Mill of the Canadian Forest Products Company is a two-line mill built in two stages. Mill A was built in 1964 and was installed without a turbine generator at the time. Mill B was built in 1981 and was installed with a turbine generator. A turbine-generator was added to Mill A in 1973. Each mill consists of a complete steam plant, digester plant, bleach plant and pulp drying machine. Each steam plant consists of a Kraft Recovery Boiler and a Hog Fuel – Power Boiler and Turbine-Generator.

A. Steam System

The mill has a Recovery Boiler capacity of 430,000 kg per hour at 4200 kPa. The Hog Fuel – Power Boiler has a capacity of 200,000 kg per hour at 4200 kPa. The mill steam demand is 30,000 kg per hour at 4200 kPa, 190,000 kg per hour at 1150 kPa and 410,000 kg per hour at 448 kPa. This heatsink provides turbines with an output of 47 MW and the total system requirement is 54 MW. The Mill A electrical load is 30.5 MW. Mill A imports 2.5 MW from BC Hydro and 4 MW from Mill B. Mill B electrical load is 23.5 MW. Mill B imports 4.5 MW from BC Hydro and exports 4 MW to Mill A. Mill A supplies the mill general site utilities, a sawmill and offices and thus has a higher electrical load than Mill B.

Mill A and B have interconnected steam headers at the steam generating high pressure (4200 kPa) headers and at both utilization pressure headers (1150 kPa and 450 kPa). Both turbines are closely coupled and paralleled and can share the task of header pressure control.

B. Electrical System

Mill A and B are also closely coupled on the electrical side. Each mill has a simple single bus arrangement with the generator and utility tie-line, each providing power to the bus. Mill A has a utility tie-line; load tap changing transformer rated 15/20 MVA. Mill B has a utility tie-line, load tap changing transformer rated 25/33/42 MVA. The Northwood Mill is serviced by BC Hydro through a single 69 kV transmission line feeding through two Oil Circuit Breakers, one for each transformer.

When Mill B was installed, the two mill buses were connected through a bus-tie reactor. Subsequently, the reactor was replaced by a pyrotechnic fuse. The pyrotechnic fuse (also called the CLIP) is designed to operate in the first quarter cycle of fault current, well before any circuit breaker could operate. With the bus-tie open, the available fault current is within the capability of the circuit breakers to interrupt. With the bus-tie closed, the full capability of two paralleled generators and two paralleled utility tie transformers is available to supply the total mill load.

The load tap changing transformers have identical tap ranges and exactly the same number of steps above and below nominal voltage (13.8 kV) but the step voltage sizes are different. This combined with the different transformer ratings and consequent impedances results in ample opportunity for circulating VAR flow through the 69 kV bus, between the two transformers and through the 13.8 kV bus tie - even when the transformers are on the same step. In the case of the Northwood Mill there is usually a circulating VAR flow through the bus tie. Operator attempts at adjustment and control of the LTCs result in a sizable circulating VAR flow and can end up in extreme tap positions for each transformer.

C. Radial Turbines

The turbines, TGA for Mill A and TGB for Mill B are each ASEA Stal-Laval radial turbines. These units consist of two counter rotating rotors driving two reverse-parallel connected generators. Steam is admitted at the center of the machine and flows in a radial path, passing through blades on each rotor alternately. This is a very efficient unit with second law recovery of available work on the order of 80% to 85%. Each unit has an automatic extraction.

The throttle valve is similar in design to most axial flow throttle valves, consisting of multiple valves mechanically interconnected to open sequentially as the steam flow is gradually increased. The difference stops here. Each valve stage does not discharge into a separate nozzle block but instead all steam flows into the steam chest. There is one exception to this. There is an additional valve in the throttle valve called the overload valve. The overload valve is operated as part of the multi-valve throttle valve. This valve bypasses steam past the first stage of the turbine when flow becomes choked at high steam flows. The flow capacity of the radial turbine increases as a square of the radius of the stage. Up to 40% of the total steam flow can be handled by the overload valve. In this manner, the much greater flow capacity of the lower pressure stages can be utilized.

The radial turbine design does not allow for controlled automatic extraction in the manner that is used for axial flow turbines. This results in a rather elaborate strategy for providing controlled extraction pressure. The "automatic"

extraction port in the case of the radial turbine operates in the same manner as an uncontrolled extraction port. For an uncontrolled extraction port steam pressure at the port is higher or lower in proportion to the steam flow through the stage ahead of the port. Higher steam flows through the turbine result in a higher pressure at the port. Lower flows will result in lower pressures at the port. In the case of the radial turbine steam is extracted at an uncontrolled port. In order to have control of pressure, some of the steam flowing out of the port is "re-injected" into a lower pressure stage. The re-injected steam flow is throttled to take both excess steam not required by extraction steam users and to provide greater flow to exhaust for exhaust steam users in the same manner as the first stage overload valve. If extraction steam demand is high, steam from yet a higher pressure uncontrolled port is throttled and added to the extraction flow. Throttling action of the extraction valve is not expensive in a lost work sense as the pressure drop across the valve is held to a minimum.

In summary, for each turbine, the control effectors consist of a stop valve, a governor (throttle/overload) valve, two extraction/ non-return valves, an extraction re-injection (also called overflow) valve and a stand-alone non-return valve. The throttle valve and extraction throttle valves on both turbines are actuated by low-pressure hydraulic servo positioners. The extraction re-injection (overflow) valve on TGA is actuated by a low-pressure hydraulic servo positioner; the same valve on TGB is actuated by a pneumatic positioner.

D. Generators and Excitation

The two counter-rotating generators are protected and treated as a single machine. They share a single series field circuit supplied through slip rings. The excitation was supplied by an exciter machine coupled to the shaft of one of the generators. Outboard of the exciter bearing on the same shaft was an overhung permanent magnet rotor. The PMG stator output was rectified in a 3-phase, 6-pulse controlled bridge, operated by the voltage regulator. The output of this bridge was fed through exciter slip rings to the rotor of the exciter machine. The stator of the exciter machine was connected to a stationary, 3-phase, 6-pulse diode rectifier. The diode rectifier feeds DC excitation current to the slip rings of both generators in series.

Proper operation of the radial flow turbine requires that the rotors be excited at the initial admission of steam to the turbine. This will lock the shaft into the exact counter-rotating synchronism required by the radial turbine. This is different from a single shaft, axial flow turbine where excitation is applied when the turbine has fully accelerated to operating speed. In order to avoid overfluxing and possibly saturating the generator stator iron, the generated voltage must increase in proportion to the speed, hence exciter control is needed. This is the same requirement as constant volts/Hertz in low power alternating current drives.

III. PROJECT OBJECTIVES

In pursuing a project to replace the turbine generator controls, the mill developed several objectives that would insure the long-term viability of the co-generation plant.

A. Supplier Issues

The mill has had good experience with this highly efficient turbine design. The manufacturer is based in Northern Europe, making the supply of parts and of specialists to the Northern Canadian location difficult and time consuming. Certain parts for the control equipment were not available as standard stocked parts in North America and it was impossible to obtain replacement components for obsolete hydraulic and electronic systems. Though the rugged design and conservative application of these components did not result in frequent breakage, the control system components were reaching the end of their life and failures were becoming more frequent.

B. System Design Issues

The hydraulic system that embodied the governor, though very competent, was not understood by the mill technical personnel. Most control systems in a pulp mill are implemented in a combination of electric, electronic and pneumatic controls. Until very recently in the pulp and paper industry, hydraulic control systems were a rarity. Modern hydraulic control systems utilize electro-hydraulic servo or proportional valves to control flow and pressure and thus mechanical speed and force. Computation and signal processing is accomplished in an electronic control system, final actuation uses electro-hydraulic servo or proportional valves operating hydraulic actuators to control the process variable. In the case of the turbine governors, specialized hydraulic devices utilize variable pressures as signals. Governor computations are done using signal pressures with specially designed hydraulic components. These components are not typically available "off the shelf". The turbine governors use a customized "speed governor" that can only be manufactured by the turbine supplier. The mill wanted to get away from a system that, though it worked well, looked like an unapproachable black box to mill technicians and engineers.

The exciter system utilized several standard control components that could easily be replaced by components commonly available in North America. Major portions of this system were also customized. These include the PMG and the exciter machine itself.

Electronic controls were an important part of both the governor and exciter systems. The electronic technology utilized for these components was an analog based system. Analog systems were very common in the 1960's, 1970's and 1980's. In the 1990's these systems were replaced by digitally based systems with analog interfaces at the input and outputs. All computation and signal processing is done on numerical data. In the analog systems all information is processed as a voltage (or current) analog of the measured value. A numerical value of 450 in a digital system might be represented as 0.45 volts in an analog system; either value might correspond to a measured pressure of 450 kPa. Analog signals are subject to noise; analog components are subject to deterioration. In time, all analog systems lose performance due to these factors.

In order to address these issues, the mill decided to replace the turbine and generator controls with a digital electronic system using components and expertise readily available in

North America - at the same time retain the performance and safety features of the highly efficient European equipment.

C. Mill Uptime

The Northwood mill depends upon continuous operation of one turbine generator in order to achieve full production. In the event of an outage of one generator, say TGA, the mill can operate at full load. The bus tie between the two busses provides a means to power Mill A, utilizing the greater capacity of the Mill B transformer. The Mill A transformer would be overloaded in the event that the bus tie was to open. If both generators are out of service, either Mill A or Mill B can operate, not both. The transformers are marginal to run both mills at full capacity and the utility could not guarantee to supply enough power for both mills. Given this situation, continuous operation of both generators is not just a cost reduction for the mill but a necessity.

The mill believed that continued operation of both generators was important enough that a new control system for the units be designed so that no single point of failure would result in major loss of production. At the time that the project was begun, this was interpreted to mean that if a component were to fail, there would be a replacement component on site or within a days transport. This was certainly not the case with the control equipment for the turbine-generators. At best, if all components were available in Europe, and Turbine-Generator service people were available in North America, the mill could expect one or two days down on one unit. This was not acceptable.

D. Mill Operation

As discussed previously, the turbine-generators were paralleled on both the steam and electric sides. The steam plant would base load one unit for steam header control and one unit, possibly the same unit, for bus voltage control. The other unit would be programmed to actively control the header pressures and the bus voltages. The transformer tap changers would be adjusted in an attempt to minimize the circulating VAR flow. The mill wanted a control system that would allow the turbines to jointly control steam header pressure and to jointly control both bus voltage and VAR import. In this manner both units would swing the varying loads in a constant operator-set ratio of loads. Both units could then be loaded equally or in proportion to operational needs. This was not possible with the original controls. A new system would have to be able to jointly control the steam pressure and voltage control tasks. Most importantly, joint control would allow full utilization of the process heat sink. The pressure reducing valves would be fully closed and the greatest possible power output from the two turbines would be obtained. The excitation controls and direct control of the transformer tap changers would allow automatic control of imported VARs and minimization of circulating VARs.

E. VAR Management

The management of VARs presented an interesting opportunity to Northwood. In other installations in North America, the rotors for the ASEA Stal-Laval units had failed due to rotor circuit deficiencies. Repair of a rotor is an extensive, expensive and costly procedure. The rotor must be removed, re-wound, rebalanced and re-installed. Some users of the ASEA generators felt that the rotor insulation failures

were due to continuous high level excitation currents acting to heat the highly mechanically stressed rotor insulation over a period of time. Though well within operating constraints, other users felt that the rotor insulation was failing prematurely. If the mill could reduce the excitation currents to a safe and stable level well below the rotor current limits, the mill could expect a much longer rotor insulation life. This would involve importing a good portion of the Mill VAR needs from BC Hydro. The power supply agreement with BC Hydro allows the mill to maintain any power factor as long as the mill likewise imports less than 85% of Contract Demand. A new control system should be able to minimize the generator field current, minimize the circulating VARs and optimize import of VARs from the utility without setting demand limits. The system should be able to automatically implement the rate sheet rules without operator intervention.

F. Loss of Tie-Line

The pulp mill should be able to continue operation through a complete loss of the electric utility. This would mean that although the mill would probably lose production during the period of time that the utility tie-line was dead, the steam plant would remain in operation and reconnection would merely mean re-synchronizing with BC Hydro. If the steam plant were to lose power suddenly, the recovery boilers' chemical process is upset, potentially creating a safety hazard. Reheating the chemical process and cleaning smelt out of the boiler usually takes hours. Other boilers would have to be purged and re-started. Without steam for an extended period, the digester contents would deteriorate, as would the pulp quality. The mill may take days to get back to prime production. If the steam plant could maintain operation, though the transient loss of utility tie-line, the pulping process could be immediately restarted without loss of product or product quality, the pulp machine could restart production as soon as the machine was cleaned out and the systems restarted. The mill could run, albeit at a lower rate of production. When the utility returned, the mill would be already producing or on the way back to full production if the outage was short.

What usually happens is described as the "death spiral" at Northwood. This a scenario familiar to many mills that have experienced similar events precipitated by the loss of serving utility. The start is a loss of tie-line. This may be brought on by an event originating within the mill or by an event in the utility. The mill generators are instantaneously overloaded. The only quickly available stored energy is in the spinning mass of the generator rotors. As the stored energy is converted to electrical energy, the generators start to slow down. This is detected by an underfrequency relay monitoring the switchgear bus voltage. The relay starts to shed load, typical settings for this to begin is at 59.5 Hz. The load is shed in large increments. Each load is supplied by a high voltage circuit breaker; load shedding is affected by tripping these breakers in a predetermined sequence. First stage load shed is usually mill water treatment, wood yard, offices, labs, and waste water treatment. In most cases, this is insufficient to stop the frequency decay. Second stage tripping starts to occur at 59 Hz. The digester, bleach plant and pulp machines are all tripped. Machine drives will usually trip on 5% voltage excursions and/or 5% frequency excursions, these excursions may shutdown the machine room even before the circuit

breaker trips. At this time, the mill has probably shed enough electrical load to balance heatsink against electrical generation, but the loss of the electrical drive loads in the process areas will of necessity shut down that portion of the process heatsink represented by that area. The turbines are again overloaded and the frequency continues to decline. If the turbine control system is capable, the governor has switched into frequency control and has sacrificed exhaust header pressure control. Steam plant operators have also started to open the "drag" valve that exhausts low-pressure steam to the sky. Physics helps somewhat in that motors driving centrifugal loads start to decrease in power output as the frequency drops. If all of these factors can stabilize in a few seconds, the turbines stop decelerating and the frequency has not decreased to less than 57 or 56 Hz the mill may survive and the governors may be able to recover control.

Typical turbine H values for axial turbines of this size are in the range of 3 MJ/MVA. A 200% turbine load (100% overload) will stop a turbine of this size in 3 seconds. Radial turbines have a lower H value, meaning even shorter time periods for the governor to recover. It safe to assume that given this time constraint, a control system must respond automatically, without human intervention. All planning for a loss of utility tie-line must be programmed into the overall mill control system. A key factor in this overall control system is a turbine governor that will automatically and bumplessly transfer to speed/frequency control. The generator excitation system will likewise have to switch control modes into bus voltage control.

G. Project Objectives Summary

The mill had five objectives:

- The Turbine and Generator controls will be replaced by a modern, digital control system using, to the greatest extent possible, standard components and service support available within one day.
- The Turbine and Generator controls will survive a loss of tie-line connection. If the mill load shedding strategy is successful, the generators will be ready to re-synchronize when the tie-line connection is re-established.
- The control system will manage VAR import to the specifications of the utility rate requirement while minimizing generator rotor heating.
- The Turbine and Generator control systems will allow dynamic load division between the two units for steam header pressure control and bus voltage control.
- The Turbines will recover the greatest possible power available by fully utilizing the mill process heatsink while accurately controlling the 1150 kPa and 450 kPa header pressures.

IV. PROJECT SCOPE

The project scope was divided into three parts at the beginning:

- Governor;
- Excitation;
- Generator Protection.

Three separate performance specifications were written for each segment of the project. The mill made decisions about

what equipment would be retained and which equipment would be replaced in each of the scope categories. Some equipment associated with safe shutdown of the system was retained and serviced.

A. Governor

The new governor was to be a digital governor with electro-hydraulic servo valves interfacing to the existing steam valves, Emergency Stop, Throttle/Overload, 2 Extraction Throttle Valves, Overflow (Re-Injection) Valve and Extraction Non-Return Valve. The mill investigated several alternative valve actuators. The original valve actuators were low-pressure oil cylinders. An electric and a shaft driven oil pump provide the system pressure. The hydraulic oil system is shared and provides lubrication oil to the bearing journals.

Modern turbines are supplied with separate lubrication and governor oil systems. This design allows for different oil characteristics and filtering. The Mill considered purchasing a separate high pressure hydraulic power supply and actuators for each valve but decided to retain the low-pressure hydraulic power supply and actuator cylinders.

- The cost of this alternative seemed prohibitively high, especially given that the mill had good experience with the low-pressure system.
- An additional system would increase the parts count, with the necessity of maintaining separate components for the low-pressure system and a new high-pressure system.
- Replacement of the actuators would require custom machine work and valuable construction schedule time.
- The shaft driven oil pump as the primary supply has the advantage that it is always available when the turbine is turning, retaining this pump avoids the complication of providing a secure electrical power supply to the turbine at all times.

There are no standard low-pressure hydraulic servo valves available. A low-pressure system would have to retain the low-pressure pilot valves. Any actuator would have to work directly upon the spool of the pilot valve for each cylinder. It would be necessary to use custom equipment and make custom modifications to the pilot valve. This is an exception to the projects first objective.

Governors are offered in two configurations:

- Simplex
- Triple Modular Redundant

The mill considered both configurations and settled upon the Triple Modular Redundant (TMR) configuration. The system uses three processors all running the same program. The processors vote on all outputs. If they all agree on the desired output, there is no problem. If only two out of three processors agree on an output, the odd processor "fails" and the system operates in a duplex mode where one designated processor is a master and the other processor is a backup. When the "failed" processor returns to agreement, the TMR operation resumes. In TMR arrangements, any processor can be physically removed from service and returned to service without disturbing the continuous operation of the system. TMR has dual redundant Input/Output systems with dual redundant field devices. In this manner, no single point of failure will cause the system to cease operation.

When the mill compared the Simplex Governor alternatives to the TMR alternative the small premium price for the TMR governor was insignificant in relation to the potential gains in system up time. For comparison the cost of the Simplex Governor includes the cost of spares for all parts in the system. The TMR cost includes the cost of all operating components of the system and does not include spare components for dual sensors and actuators.

The controls associated with operation of the turbine stop valve were retained. These components included two solenoid valves, hydraulic overspeed valves on each generator and hydraulic over thrust valves and a hand operated trip valve. Pressure transmitters were added to this system to sense and alarm a trip of the turbine and to interface the new governor for emergency shutdown. The shaft connected speed governor was retained as an element of the shaft system but disconnected.

B. Excitation

The mill decided to apply a shunt excitation system. This type of excitation system uses controlled bridge rectifiers with a power source derived directly from the generator terminals. The generator already had slip rings so application of the system entailed disconnection and removal of the old diode rectifier and connection of the new exciter to the slip rings. The exciter machine and PMG rotor were disconnected and retained as an element of the shaft.

The old exciter system was subject to lag in the build up of the field in the exciter machine followed by another lag in the build up of the field in the generators. A shunt exciter can instantly change the voltage in order to force the needed current. The time constant of the main field winding is still a factor but the higher instantaneous voltage capability of a shunt exciter can reduce this lag.

The shunt exciter cannot guarantee that excitation potential will be available when the turbine starts to roll. Traditional shunt systems generally "flash" the generator field by briefly applying voltage from the station battery. This induces enough flux to generate a terminal voltage that can be used as a power source to start the excitation process. There is a problem with this procedure. The machines start at slow speed and must be excited from the start. The field flashing procedure is normally done on axial flow turbines where the turbine is already at a fairly high speed.

The shunt excitation system would need an alternative source of power for turbine startup. When the turbine was producing enough potential to power the system, the excitation source would switch to the generator terminal source. The system was specified with two controlled bridges. One bridge is fed from the generator terminals; the other bridge is fed from the mill low voltage power system.

It should be noted that the mill is incapable of "black" starting the steam plant. To modify the steam plant to do this would require extensive modification, conversion of some of the drives on a hog/power boiler to turbine and provision of startup diesel generator for those drives that cannot be driven by steam drive turbine.

Both controlled bridges would be controlled by a digitally based voltage regulator and an alternative "manual" regulator for use when voltage feedback failed. Standard exciter equipment includes a field circuit breaker and a field discharge resistor.

C. Generator Protection

The original generator protection system provided a complete electro-mechanical relay system. This included all of the recommended protection functions including:

- Phase Differential (87);
- Voltage Restrained Overcurrent (51V);
- Negative Sequence (46);
- Loss of Field (40);
- Overload (49);
- Reverse Power (32);
- Ground Overvoltage (59N);
- Residual Overcurrent (50R);
- Voltage Balance (60V);
- Undervoltage (27);
- Overvoltage (59).

The mill wanted to replace these relays with a single, digitally-based generator protection relay to serve all of the standard generator protective functions previously provided by individual relays with additional features including fault oscillographic capture functions and 100% ground fault protection using neutral third harmonic voltage.

In addition, the mill wanted to replace the traditional and standard electromechanical metering functions with a digital and networked metering package. Though full implementation of a networked metering system was not in the project scope, the generators and the utility tie lines would be upgraded to the new equipment.

This would greatly enhance the information capture features and considerably simplify the wiring.

D. Other Scope

In addition to the three major scope areas, the system was to supply a host of other features:

- Redundant, digital communication between governors, exciters and the mill distributed control system;
- Operator HMI with a complete graphics package to allow startup, synchronizing and loading of the Turbine-Generators;
- Complete synchronizing system with operator selection of three alternative circuit breakers for each generator. This includes manual synchronizing, semi-automatic synchronizing, automatic synchronizing and independent, synchro-check supervision;
- Turbine startup automation including auxiliary controls, and interlocking;
- Interface to the utility tie transformer tap changers and automatic voltage regulators;
- First out, sequence of events and high speed trending for system internal variables.

V. PROJECT IMPLEMENTATION

Several bid packages were prepared to fully implement the scope. The suppliers are hardware orientated and do not offer complete packages that would cover the complete scope. Traditionally the suppliers work hand in hand with turbine-generator suppliers. In this case, the turbine-generators were existing and the mill did not want to limit their choice to the OEM. The mill engaged an engineering firm to provide the

interface and expertise to coordinate the various bits and pieces of the scope.

When the bids were received, it was apparent that some suppliers could supply only single portions of the equipment, e.g., either the governor or the exciter. Some of the suppliers could supply both governors and exciters. In all cases, the suppliers were experienced and could demonstrate both simplex and TMR governors. No supplier offered an integrated system, but stuck to a traditional offering where the exciter and the governor were implemented in separate processors and in some cases separate divisions of the same company offered similar equipment. Most suppliers could provide communication packages that would inter-communicate between the various bits and pieces of the complete system.

Integrated System

The project team traveled to several installations. Each supplier recommended an industrial installation that would display the suppliers' equipment to the highest advantage. At this stage, the project team wanted one supplier for the governor system and the excitation system. All the governor bidders were able to demonstrate all of the features and requirements of the project scope for both the simplex and TMR alternatives. Only two of the bidders had quoted both the governor and the exciter and none of the bidders quoted an integrated system.

The mill selected a governor supplier based on a selection procedure that took into account price, performance, experience, and service support. Input was solicited from all stakeholders in the mill. The selected bidder was neither the highest cost nor the lowest cost alternative but instead presented a good compromise between all concerns.

At the same time that the Mill selected the governor supplier, the mill also made the choice to purchase a TMR governor. This was consistent with the project objective to have no single point of failure affect mill productivity.

Selection of the excitation system was a problem. The mill had selected the highest cost excitation system. The belief was that this system was the only alternative that met all of the specification requirements and could demonstrate intercommunication capability with the selected governor suppliers system. The excitation system was more than the mill wanted and needed. The problem was the cost. There seemed no alternative, yet the cost of the excitation system would drive the project budget over the limit where additional funds would have to be approved.

The governor supplier approached the mill with an alternative and new excitation system. The system was non-traditional in the sense that instead of supplying a separate TMR control system for the exciter, the TMR control system for the governor would supply all regulation and control for both the turbine and the generator field. The controlled bridge rectifiers would be treated as a field actuator, like the governor electro-hydraulic servo valves. The controlled bridges would accept a 4-20 mA signal corresponding to the desired field current. The bridges would be current regulated using well established analog technology developed in the DC drive market over the last several decades.

This alternative, though untried, presented a much lower cost and had the additional advantage that a single maintenance and engineering interface would cover both

systems. The mill would have a single, seamless Human Machine interface and a single programming language running a single program with both turbine governor and generator excitation tasks. In addition, all of the other programming tasks required in the scope could be handled in a single TMR system.

The mill would have preferred that the exciter rectifiers be supplied with a digital regulator. Digital regulators are a well-established feature of most DC and AC drives and provide diagnostic and troubleshooting features that are impossible to supply with analog regulators. The supplier evaluated this request and thought that the bridge supplier that they would prefer to work with did not supply digital regulators and that they were much more comfortable with the bandwidth available using analog regulators.

Due to cost considerations and the press of schedule, the mill decided to purchase the excitation system through the selected governor supplier and use analog bridge rectifiers. The risk was low, even though the system had not been tested in any real-world application. The governor supplier had demonstrated capability in interfacing their TMR regulator to existing exciters, merely replacing the voltage regulator function. The analog bridge rectifier technology is well tested and understood by the mill. The only risk was in the marriage of the systems and the suppliers' untested capability to supply a complete package. This was evaluated as a very low risk.

VI. INSTALLATION

The project had several issues to address before final installation of the integrated control system. There was little or no issue with the control system itself. Typically all issues related to actuating devices and sensors, the inputs and outputs of the control system.

A. Electro-Hydraulic Servo Actuator

In order to meet the project objective that no single point of failure in the control system would cause a general system failure, all actuator outputs would have to be dually redundant. This presented a problem in that the modulating valve outputs of the governor (Throttle/Overload, Extraction #1 and Extraction #2, and Overflow (Re-Injection)) are all single valves. It is a problem to supply two pilot valve low-pressure actuators.

There is only one valve pilot valve spool to be moved by the actuator. There are mechanical linkages that could implement this with two separate actuators. The problem with this approach is complexity. The mill desired to replace the force balance mechanical feedback mechanism used by the old governor with a new, direct acting connection between the actuator output rod and the pilot valve spool. The feedback in this case would be completely electronic in nature. In keeping with the dual sensor/actuator scheme, for each modulated valve, the control system provides two valve position reference outputs. A valve position loop is implemented in an analog valve controller that utilizes LVDT valve position feedback and servo-valve signal output. For each steam valve position, the system supplies two servo-valve signal outputs.

The compromise solution was to develop a dual coil servo-valve. This solution partially solves the problem of no single point of failure. Either coil can shift the servo-hydraulic actuator internal spool. The actuator itself is singular. If an

actuator mechanically fails, the system will fail. However, if there is an electronic or electrical connection failure, the system will continue to function.

B. Excitation System

The excitation system turned out to be impressive in design and operation. The system as installed is robust and simple in concept and implementation. The system was selected to supply up to 600 Vdc at 500 A. This provides 164% forcing capability and fits with standard voltages for 6 pulse bridges. A current rating 40% in excess of the generator maximum field current was required as an option to upgrade the rating of the generator in the future. As discussed previously, the electrical power supply for the field consists of two fully controlled, analog, 6-pulse, 3-phase bridge rectifiers. The two rectifiers are paralleled through auctioneer diodes. Each bridge has a 5-pole disconnect switch in order to isolate the bridge completely from both the generator field and the AC supply. As discussed above, one bridge is supplied directly from the generator output and the other is supplied from the mill low voltage power system. Each bridge is supplied by a dry-type transformer. In the case of the generator exciter supply, a fused disconnect switch is used. This was required by the Canadian Electrical Code.

Each bridge has an analog current regulator, current feedback and a separate current reference provided by the integrated control system. Note that both bridge current regulators will see the same current feedback from separate LEM sensors in series in the exciter output. If the current reference for the bridge that is selected to be inactive is biased below the desired field current, that bridge will see a feedback in excess of its reference. The inactive bridge current regulator will phase back the thyristors, attempting to decrease the current feedback. The inactive bridge will be phased back thus producing a lower voltage than the active bridge. The diode in series with the active bridge will be in conduction because the active bridge voltage will be the voltage required to drive the reference field current, this voltage will be higher than the voltage output of the inactive bridge. The diode in series with the inactive bridge will be back biased by the higher voltage of the active bridge and will be blocking conduction.

In order to change the active bridge in software, the negative current reference bias is switched from the presently inactive bridge to the presently active bridge. The current regulator on the inactive bridge will see no error, thus the conduction angle will not change at this time. The output voltage of the system will drop because the presently active bridge is still in conduction and the regulator is reducing voltage in order to reduce the current to the lower reference. The field current will start to drop, the current regulator on the inactive bridge will increase the conduction angle of the inactive bridge in order to bring the current back to the reference value. This will increase the voltage of the inactive bridge. When the voltage of the inactive bridge exceeds the voltage across the field, the diode in series with the inactive bridge will be forward biased and start conduction. At the same instant, the diode in series with the formerly active bridge will be back biased and will cease conduction.

In this manner, the diode auctioneer will allow only one bridge to be in conduction at any one time. In the event that the alternating supply for the active bridge is lost, the

auctioneer will immediately select the bridge with an active alternating voltage. The current regulator for the inactive bridge will sense the drop in current below the reference and increase the conduction angle and thus the voltage. The integrated control system will sense the loss of the alternating voltage supply to the active bridge and switch the bias off to the inactive bridge, increasing the bridge reference to the desired value.

As the system is started, alternating voltage is supplied from the mill low voltage system. The generator is not excited and hence has no output potential. The bridge connected to the low voltage power system is selected in software as the active bridge. As the generator speeds up while the turbine is warming, the voltage regulator increases the generator voltage in order to hold constant volts per Hertz. The bridge connected to the generator may be selected as the active bridge at any time once the generator minimum voltage (12 kV) is exceeded.

During commissioning, the robustness of this system was tested under load by opening the 5-pole switch for the active bridge. The control system detected the loss of the operating bridge and immediately switched to the other bridge. There was no noticeable drop in generator voltage as the system detects the switch operation.

C. Interface to the Mill Control System

The project originally planned to use the mill standard distributed control system as the HMI interface to the integrated control system. The HMI supplied by the supplier was intended as a backup. The project had planned to utilize internal resources to program the DCS operator screens. Pressing commitments and schedule constraints forced the project to look to outside resources for this programming. This option turned out to be too costly so the project elected to start-up using the HMI supplied as part of the integrated system. The DCS function in this area was to operate and control steam header pressure using the pressure reducing valves, bypassing steam around the turbines. The interface between the integrated systems and the DCS communicates most of the turbine-generator status, data and alarms. At some future time, the Turbine-Generator HMI will be transferred to the DCS as mill resources become available. At startup the integrated system would perform all control system functions for the turbine including alarms, and trending.

VII. CONCLUSION

The Northwood Mill has been operating the integrated control system on TGB since June 1998 and the integrated control system on TGA since November 1998. The turbine operators believe that the system is far superior to the old system. Startup and synchronizing is usually a one-button operation supervised by the operator. The control system ramps up the turbine speed according to the turbine supplier's recommendations for warm-up. The operators can select to manually adjust the generator speed and voltage for manual synchronization, or allow the control system to make the adjustments. The operator can then select to allow the system to synchronize automatically or the operator may close the breaker. Usually the operator selects automatic synchronization. The control system will then load the generator up to 3 to 5 MW under load control. At that point the operator may select any of several governor and exciter priority control modes.

The Integrated control system has been tested for load pickup and load rejection under loss of utility tie-line. The system successfully switched to isochronous control mode, the voltage regulator switched to bus voltage control mode. This was a highly controlled test, under controlled and supervised conditions. The mill on one occasion experienced the sudden loss of utility power and new controls maintained a power and steam balance that avoided the dreaded "death spiral".

The mill is able to use both integrated control systems to dynamically share the steam pressure control and voltage control functions. This has allowed the mill to fully realize the benefit of the process heatsink. Generation has increased on the average of 2-3 MW, resulting in a real savings in tie-line energy at around \$500,000 per year. Likewise, the mill had gained automatic control of the circulating VARs and can fully utilize the provisions of the utility contract, allowing more VAR import.

The project objectives have substantially been met. The mill has installed a system where a single component failure will not cause a turbine-generator trip. Spare parts for the system have not been bought, as all equipment is redundant. Any parts are readily available in North America. The maintenance group is comfortable with the system to the extent of making tuning and timing adjustments and can use the system for troubleshooting. The mill now has the confidence that it will continue to survive the loss of utility power and that the "death spiral" is a thing of the past.