Power plants are required to develop plans for efficient and timely system restoration. A key component of those plans are the use of large combustion turbines connected directly to higher-voltage transmission systems, which have to merge with plant configurations. Performing a site assessment at the beginning stage can determine feasibility of black start conversion early.
BACKGROUND
Due in part to the 2003 Northeast Blackout and, more recently, to the events at Fukushima, a renewed emphasis has been placed on developing plans for a more efficient and timely system restoration process. A key component of revised restoration plans includes the use of large combustion turbines connected directly to higher-voltage transmission systems in lieu of smaller units such as hydro and diesel engines that are more typically connected at the distribution level.

Processes must be established to assess the viability of a new or existing large combustion turbine generating facility for black start service, including key mechanical and electrical considerations and often overlooked plant auxiliaries. Facilities must also consider methods and design criteria for various large combustion turbines in both simple and combined cycle configurations following a system blackout.

INTRODUCTION
On August 14, 2003, the U.S. experienced a power outage in the northeast that expanded from Ohio around the Great Lakes through Michigan, Pennsylvania, New York and into Canada. The outage began just before 4:10 p.m. EST and was not fully restored until early on August 18, nearly four days later. During the outage, more than 55 million people in the U.S. and Canada were affected, along with water supplies, transportation, communication and countless businesses.

A major impediment to restoring power more quickly was the fact that many grid restoration plans relied on small hydroelectric or aero-derivative combustion turbine plants connected to lower-voltage transmission and distribution systems as their first restoration step. This required bringing online a relatively large number of small machines that, once interconnected, could bring up midsized plants and then eventually energize the higher-voltage lines to bring online the large coal-fired and nuclear plants.

Typically grid restoration plans are designed to create relatively small electrical "islands" which operate independently from one another and maintain their own voltage and frequency levels. These islands are typically centered around larger generating facilities that vary their output to match the megawatts (MW) and mega volt ampere reactive (MVAR) profile of the restored load. The number of islands will depend on the size of the blacked-out region and the black start restoration plan. Once the islands are stable, the process of system restoration begins by adjusting the frequency and voltage of two adjacent islands to synchronize the systems at pre-selected intertie connection points. This process is repeated until all the islands are interconnected and the entire system is restored.

Each island interconnection requires coordination of the system operators and must be done with a step-by-step process while monitoring the growing system stability. As the system expands it becomes more stable, but until it gets large enough, a single event or a significant MW or MVAR imbalance could lead to another system collapse, requiring the process to start over again.

Based on this process, the time required to restore the grid is directly related to the number of islands and time required to establish each one. Therefore, identifying larger power facilities throughout the region that are connected to main high-voltage transmission systems that, in turn, are interconnected both within the system and to neighboring regions is critical to reducing grid restoration time. Additionally, the ability to either directly start or limit the number of steps required to start the large power facilities will decrease the time to establish each island.

Since the 2003 Northeast Blackout, efforts have been made to re-examine traditional grid restoration plans to determine the possibility of directly energizing high-voltage transmission lines to reduce the steps required to start large coal-fired plants and restore off-site power to the nuclear plants. To import and export the large amount of reactive power associated with high-voltage transmission lines and system restoration, however, requires larger generators with excitation and control systems designed for the large VAR swings. Based on recent system studies, the minimum generator sized to energize a typical 345-kV transmission line is 100 MVA, which is typical of a GE Frame 7EA. However, larger units like the GE Frame 7FA or Siemens V84 have more capability to handle the VAR fluctuations.
Other design considerations for black start generation include the startup time from the onset of the blackout condition until full restoration of the high voltage transmission line leaving the power station. The major reason to consider black starting a large combustion turbine facility is to take full advantage of the direct connection to the higher-voltage transmission system and to have the capacity to directly restart a large coal-fired or nuclear facility. By reducing the restart time of the large facilities, the grid restoration time is reduced, allowing normal operations to be restored sooner.

**TRADITIONAL RESTORATION PLANS**

Prior to the 2003 Northeast Blackout and still today, many restoration plans include small diesel-drive generators, hydroelectric units or small combustion turbines interconnected to lower-voltage transmission or distribution systems. These plants are fast starting, but often are hindered from providing quick grid restoration due to the inability to re-energize the distribution line without first clearing the small local loads. This, depending on the blackout event, could be further deterred by accessibility of the line crews to reach critical switching stations.

Depending on the distance between the black start facility and the next-largest generating plant, the ability to energize the length of line could also become very difficult or impossible for the smaller units due to large VAR swings during the initial energization and loading. The small unit’s excitation systems are typically not designed with extended VAR capacity limits and will trip offline, requiring the restoration to start over again.

The first step of a typical restoration plan consists of smaller units energizing distribution lines, which in turn start up larger combustion turbine units or small coal-fired units. This next level of units in the restoration plan will begin the process of re-energizing the higher voltage systems to provide startup power to the large coal-fired or nuclear facilities. This begins the process of creating multiple islands and re-establishing the grid.

Stepping from lower distribution to higher-voltage transmission systems adds many hours and possibly days to the overall grid restoration. In addition, the limited ability to perform actual testing of the plan could lead to restoration failures due to unexpected VAR flows. This could result in longer power restoration delays for customers within the island.

The traditional use of smaller black start units affects both the number of islands and the time required to establish stability in each. Therefore, it has the potential to add significantly to the time required for complete grid restoration.

**RESTORATION WITH LARGE COMBUSTION TURBINES**

Since the 2003 Northeast Blackout, the need to reduce the steps to achieve total grid restoration has become apparent. Today, utilities and grid operators are examining the feasibility of converting larger combustion turbine facilities into black start units to be used as the first step. In addition, with the ever-increasing size of combined cycle units, the potential exists for combustion turbines to become the main component of the power islands and, thereby, eliminate the need to start the coal-fired units, which could further reduce the grid restoration time.

The main advantage of using large combustion turbines for black start is they are typically connected to higher-voltage transmission systems, which are major power flow arteries with fewer load taps. However,
as discussed above, these systems have capacitances that are much greater than the lower-voltage systems and must be accounted for with excitation and control systems.

With the current abundance of natural gas supplies in the U.S., the size of combustion turbine facilities continues to increase and is beginning to replace even the large coal-fired plants. This becomes a major advantage for black start since, unlike comparable coal-fired units, as the total output of the facility increases, the requirement for on-site generation to support black start typically does not. This is because combustion turbine starting methods, which are typically the largest black start load, are very similar for medium- and large-class turbines.

Another advantage of using the larger combustion turbine facilities as the first and possibly only step in the restoration plan is the ability of the facilities to quickly ramp up to full load. Even the larger F-class and G-class machines have typical startup times of less than three hours. Therefore, using large combustion turbine facilities as the main component of restoration would allow islands to be established within the first few hours after the blackout event. Depending on the number of islands and the process of synchronizing at the intertie points, the grid could be re-established within 12 hours after the event, which is a marked improvement over the four days required in 2003.

**STARTING METHODS AND DESIGN CRITERIA**

To start a larger combustion turbine during a complete system blackout requires enough local generation to supply the auxiliary power of the combustion turbine and its starting system plus — depending on the plant configuration — large boiler feed pumps, circulating water pumps, cooling towers, water treatment systems and other ancillary systems. Since the black start generation must be sized for both the continuous running loads of the auxiliary system and the starting requirements of the large motors and/or the combustion turbine’s starting system, the total generation required will most likely exceed the normal plant auxiliary system running load.

Before a combustion turbine can be fired and brought to operating speed, it must first be started with some type of auxiliary starting equipment. For large combustion turbines, the auxiliary starting equipment typically consists of either a cranking motor or a load commutated inverter (LCI). Both starting methods work to start the turbine rolling, accelerate it to a speed necessary to purge the turbine (and heat recovery steam generator if attached), decelerate the turbine to firing speed, and then accelerate it to a point where the combustion turbine is self-sustaining. A typical acceleration curve for a combustion turbine looks similar to Figure 1.

Electric motors are the traditional starting method for combustion turbines and can be found on most smaller and some vintage large combustion turbines. Motor-based starting systems typically consist of an induction motor and a hydraulic torque converter. The torque converter is adjusted at the different stages of the startup process to provide the range of torque needed for each stage. Once the turbine has achieved self-sustaining speed, the starting motor and torque converter are disconnected from the combustion turbine.
Starting motors can range in size from approximately 100 horsepower (HP) for the smaller combustion turbines to over 2,000 HP for the larger machines. It should be noted that since the application is considered “intermittent duty,” these starting motors are typically operated well in excess of their nameplate rating (150 percent or more) during certain periods of the starting sequence.

When designing a black start power system for a combustion turbine with a starting motor, the following should be taken into consideration when sizing the power source:

- Plant auxiliary load necessary for startup
- Starting motor inrush current
- Maximum motor load (not motor nameplate rating) during starting sequence

Most large combustion turbines today use an LCI, also commonly referred to as a static frequency converter (SFC) or a static starter, in lieu of a starting motor. An LCI is an adjustable-speed drive system that uses power electronics to transform a constant frequency, constant voltage, three-phase input into a variable frequency, variable voltage, three-phase output. A block diagram of a typical LCI system used for starting a combustion turbine is shown in Figure 2.

With an LCI starting system, isolation switches are used to connect the LCI to the combustion turbine generator during the starting process. With the LCI connected, the generator is operated as a synchronous motor and the LCI is able to adjust the speed of the turbine as necessary for the startup sequence described above. Once the combustion turbine has been accelerated to self-sustaining speed, the LCI is turned off and disconnected from the generator.

LCI systems typically range in size from about 5 MVA to over 14 MVA, depending on the size of the generator and, more importantly, the compression ratio of the combustion turbine’s compressor section. A higher compression ratio will require a larger LCI to start and bring the combustion turbine up to a self-sustaining speed.

Because of the large load associated with the LCI starting system, a significant power source is required for black start operation. In addition to the source’s ability to supply the necessary starting load, an LCI requires the source feeding the input transformer have a minimum available short circuit current. If the electrical system does not have adequate short circuit current, the total harmonic distortion (THD) at the plant’s electrical distribution

---

**FIGURE 2: Typical LCI Starting System**
system will not be enough to meet IEEE 519 limits and could be severe enough to hamper the LCI's ability to function properly.

The required amount of short circuit current will depend on the LCI's converter topology (6 pulse will require more than 12 pulse) and its output power. The OEM may also dictate a minimum short circuit capacity for their system. It may be possible to supply slightly less than the OEM-stated minimum available short circuit current without affecting system operation. It is, however, recommended that a study be performed to model the LCI harmonics data, the black start generator data, and various loading conditions to determine if a harmonic mitigation strategy, such as filters, is required to meet acceptable harmonic distortion levels.

When designing a black start power system for a combustion turbine with an LCI starting system, the following should be taken into consideration:

- Plant auxiliary load necessary for startup
- Maximum LCI load during starting sequence
- LCI input short circuit requirements

**LARGE COMBUSTION TURBINE SITE ASSESSMENT**

Once a site has been identified by a system planning study as a desirable location for a large combustion turbine to serve as a black start resource, a site assessment should be performed to determine the feasibility of converting the facility to black start service. Factors affecting conversion feasibility can generally be broken down into mechanical, electrical, controls, civil, utilities and regulatory compliance.

The mechanical assessment begins with the plant’s configuration. If the combustion turbine is in a simple cycle configuration — or if the unit is configured in combined cycle but has a bypass stack upstream of the HRSG and an automated damper that can allow the unit to be easily and quickly configured in simple cycle — there are no significant mechanical issues related to black start conversion. If, however, the unit is configured in combined cycle mode without a bypass stack, several mechanical systems have to be assessed for operation during a black start scenario.

First, it must be determined how much of the steam produced by the HRSG can be dumped to the steam turbine's condenser during combustion turbine operation. If the condenser cannot handle full steam flow for a sustained period of time, the condenser capability may become the limiting factor for maximum sustainable combustion turbine load during a system restoration. If the HRSG steam flow cannot be dumped to the condenser at all, the next alternative is to vent the steam into the atmosphere. In this scenario, the plant would need sufficient on-site demineralized water storage and/or on-site water treatment systems capable of supplying makeup water for the steam cycle. If the condenser is in service, the plant also will need a sufficient raw water supply to provide makeup water for the plant’s cooling water system. Sizing for both demineralized and raw water tanks should be sufficient to supply the plant’s water needs for the time specified by the system restoration plan.

Electrically, the site’s distribution system must be evaluated for possible connection points to a new, on-site generation supply. Depending on the size of the new power source, multiple connection points may be required. LCI starting systems are typically connected to the plant’s medium-voltage distribution system but also could be fed directly from an auxiliary transformer secondary winding. Starting motors are either fed directly from the plant’s medium-voltage distribution system or can be fed from a separate auxiliary transformer. Ultimately, the size and configuration of the existing combustion turbine starting system will dictate the voltage and connection point of the new black start supply.

From a controls standpoint, the combustion turbine controls system will require evaluation to determine if an isochronous governor mode is available. If not, an isochronous mode and the ability to close the generator to a dead bus must be added to the combustion turbine’s control system. Because of the new on-site generating equipment being added, the balance of a plant control system will also require evaluation for spare I/O or necessary floor space to expand the control system to handle the I/O interface with the new black start equipment.
A suitable space will be required on-site for the new black start power source. The amount of space required will vary depending on the type of black start power source and the amount of power required to start and run the facility during a blackout condition. Underground support in the proposed location should also be investigated and the geotechnical report for the existing facility should be consulted to determine the type of foundations required for the new equipment.

All the utilities that supply the generating facility will require evaluation to determine if they will be available during a blackout condition. If the unit relies on a stable natural gas supply for operation during a black start, the overall reliability of that supply should be heavily scrutinized. If the unit can operate on a secondary fuel, the on-site fuel storage capacity should be examined to determine if an adequate supply is available to meet the time specified by the system restoration plan. Since maintaining an on-site secondary fuel source is expensive and requires routine maintenance, the typical actual fuel stores should be evaluated against the site's maximum available storage capacity.

Raw water for generating plants is typically supplied from a municipality. If the plant has a raw water tank, it should be sized as necessary to meet the time specified by the system recovery plan. Without an adequately sized raw water tank, the plant’s raw water supply should be examined to determine its viability during a blackout condition. Plants typically discharge wastewater to a municipal sewer system. There is typically a lift station between the plant and the municipality that has a limited storage capacity. This capacity and the plant's normal waste generated during startup should be evaluated to determine if it is adequate. If not, it is important to have an emergency power supply for the lift station so wastewater could be discharged during a black start. The municipality’s wastewater handling system should also be analyzed to confirm that it has the capability of accepting wastewater during a system blackout.

CRITICAL ASSET STANDARDS
When a generator becomes part of a black start restoration plan, it typically will be classified as a critical asset. As a critical asset, the plant must meet the North American Electric Reliability Corporation (NERC) critical infrastructure protection (CIP) standards, which are quite extensive and require both plant physical security and cybersecurity. Generator facility physical security measures typically include fencing, gates, card readers, video surveillance and other measures necessary to protect the facility. Cybersecurity must also be added in the form of firewalls and other software upgrades. While these costs will vary depending on the existing infrastructure at each facility, the initial capital investment and ongoing costs associated with meeting CIP standards can be significant and must be part of the overall economic analysis of black start conversion.

There are typically two issues related to a facilities air permit when considering a black start conversion. First, it is unlikely that the combustion turbines will be able to meet their current air permits when operating at the low loads required during system restoration. Second, a new emission source will be added to the site in the form of the startup power supply. Since the effect of both issues
on the air permit varies so significantly from state to state and from generating facility to generating facility, it is recommended that the facility’s associated state agency be contacted to confirm the permitting requirements and to avoid any unnecessary delays in the permitting process. It is also recommended that agencies responsible for implementing the restoration program contact the permitting state agency to discuss the incorporation of a force majeure clause for operation of emergency equipment over the permitted hours of operation when natural disaster strikes. In addition, it may be worthwhile for each generating facility to check with the permitting authorities to see if a similar clause could be included in either the construction permit or operating permit to allow operation during such events.

All the above factors can make a site more or less ideally suited for black start conversion. Many of these items involve making relatively minor plant improvements to support black start. Some, however, will determine overall viability of the facility for black start service. A thorough investigation of the facility at the very beginning stages of considering a resource for black start conversion is highly recommended.

CONCLUSION
Integrating large combustion turbines into blackout restoration plans appears to be a reasonable solution for the issues associated with the development of more efficient and timely restoration plans. Large combustion turbines, however, typically have more complex starting requirements that can be further complicated by plant configurations. By performing a site assessment using the factors presented herein, the general feasibility of converting a facility to black start service can be determined.

BIOGRAPHY

CHRISTOPHER B. RUCKMAN, PE, is manager of the Electrical and Controls Department and leader of the Burns & McDonnell electrical engineering team, designing new power generation facilities and upgrading existing plant electrical infrastructure. He has over 20 years of power and controls engineering experience, including detailed design for new and retrofit power generation projects. Chris is an active member of the IEEE PES Power Systems Relaying Committee, served as vice chairman of the Synchronous Generator Protection Tutorial and currently serves as chairman of the Black Start Generator Protection Working Group. Chris earned his Bachelor of Arts in physics from William Jewell College and a Bachelor of Science in electrical engineering from the University of Kansas. He is a registered engineer in California, Kansas, Kentucky, Minnesota, Nebraska, Ohio, Oklahoma, Texas and Wisconsin.

ABOUT BURNS & MCDONNELL
Burns & McDonnell is a family of companies bringing together an unmatched team of engineers, construction professionals, architects, planners, technologists and scientists to design and build our critical infrastructure. With an integrated construction and design mindset, we offer full-service capabilities with offices, globally. Founded in 1898, Burns & McDonnell is a 100% employee-owned company and proud to be on Fortune’s list of 100 Best Companies to Work For. For more information, visit burnsmcd.com.