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# Synchronous Condenser Conversions at FirstEnergy Eastlake Plant

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## SUMMARY

In 2013 and 2014, General Electric Company (GE) converted Units 4 and 5 at the FirstEnergy Eastlake plant in Ohio, USA to synchronous condensers. These 3600 revolutions per minute (rpm) turbine-generators, rated at 305 and 756 Mega Volt Ampere (MVA) respectively, were placed into service in 1957 and 1972, and are now retired from power generation operation. The local area around Cleveland, Ohio still required dynamic voltage support, so various options were considered. The synchronous condenser conversion was selected in view of the static and dynamic voltage support it provides, as well as advantages of the installed infrastructure at the Eastlake plant.

The units are accelerated to speed using the "static start" approach and synchronized to the grid in the same manner as a gas turbine.

Units 4 and 5 feed 138 kV and 345 kV buses at Eastlake. Automatic voltage regulators on the excitation systems provide immediate voltage control in response to severe disturbances, and an automatic outer control loop implemented by FirstEnergy monitors those two buses to maintain their voltages within limits. Operation of that control loop is significantly faster than manual operator control.

Modifications of the 65-year-old Eastlake plant are described, including re-use of cooling water supplies, refurbishment of auxiliary equipment, relaying changes, and provisions for heat once power generation ceased at the plant.

## KEYWORDS

Synchronous – Condenser – Conversion - Reactive - Power

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# 1. INTRODUCTION

In 2011, FirstEnergy Corporation contracted with General Electric Company to convert Units 4 and 5 of the Eastlake station east of Cleveland Ohio to synchronous condensers. As FirstEnergy and PJM considered shutdown of the Eastlake plant, conversion of the units to synchronous condensers was identified as a way to maintain the integrity of the power grid in northeast Ohio.

Unit 5, a 756 MVA generator, was converted in 2013 and Unit 4, a 305 MVA generator, was converted in 2014. This paper discusses factors FirstEnergy considered regarding these conversions, the options available, plant modifications, operational aspects, and lessons learned.

# 2. FIRSTENERGY EASTLAKE PLANT

The FirstEnergy Eastlake power plant is a coal-fired station containing five steam turbine-generators that were designed and manufactured by General Electric. The plant is located in Eastlake, Ohio approximately 22 miles east of Cleveland on the shore of Lake Erie, and has been in service since the early 1950s. It is served by several 138 kV transmission lines connected closely to Units 1 – 4 in the station, as well as several 345 kV lines connected to Unit 5. See Fig. 1. The 138 kV and 345 kV lines are connected by connected via autotransformers at Eastlake. Besides the Eastlake plant, the Cleveland area is served by the Perry Nuclear Power Station. The Cleveland area had been served by the Ashtabula and Lakeshore coal fired plants as well, but these were planned to be shut down in conjunction with Eastlake.

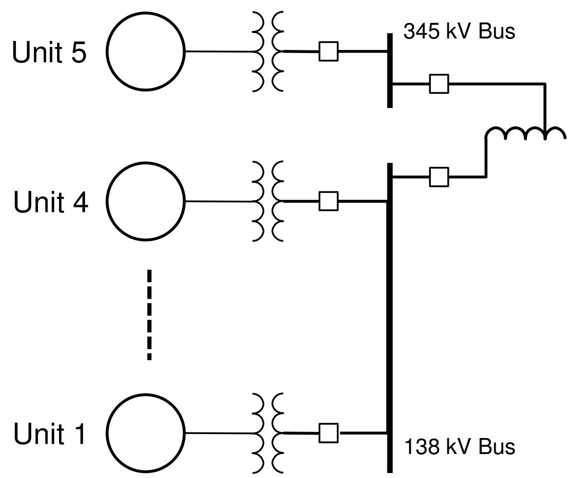


**Fig. 1. Simplified One-Line Diagram of FirstEnergy Eastlake Power Plant**

## 2.1 Eastlake 4

Eastlake 4 was in power generation service from 1957 until 2012 when it was shut down for conversion to synchronous condenser operation.

The Eastlake 4 generator is the first power generator to use a liquid-cooled (oil) armature winding. It operates at 3600 rpm and 18 kV and is cooled by hydrogen at pressures up to 45 pounds per square inch gage (psig). The rotor was converted to GE's diagonal flow cooling system in the 1990s. A separate AC motor/DC generator set provides excitation to the unit that is delivered to the rotor by brushes and collector rings.

The generator was originally rated at 256 MVA, but following tests in the GE factory and under load, its rating was increased to 305 MVA. As part of the conversion to a synchronous condenser, the armature winding was replaced in 2013.

### 2.2 Eastlake 5

Eastlake 5 was in power generation service from 1972 until 2012 when it was shut down for conversion to synchronous condenser operation. As a generator, it was rated at 756 MVA operating at 3600 rpm and 24 kV. It is cooled by hydrogen and has a water-cooled armature winding. The rotor uses diagonal flow cooling. The original Alterrex[1] excitation system was replaced by an EX2100e high initial response exciter during the conversion.

## 3. REACTIVE POWER OPTIONS

Options for reactive power include synchronous condenser conversions, capacitor banks, static VAR compensators (SVCs), uprates of existing turbine-generators, and new synchronous condensers. The choice depends on many factors including the nature of the need, the location, timing, and cost.

The conversion in place of an existing turbine-generator to synchronous condenser operation offers a number of advantages compared to other options. The synchronous condenser provides both steady state and dynamic reactive power, including the ability to overload the unit at significant levels for periods of seconds to minutes. When it includes a high initial response (HIR) exciter, the unit can respond to disturbances on the grid in the millisecond time frame. The conversion also leverages the existing plant installation (rotating machine, buildings, foundations, cooling, transformers, and switchgear).

Capacitor banks are widely used to provide a base level of reactive power. By automatic or manual switching, that capacity can be varied as system conditions change. These banks, however, cannot absorb reactive power or respond dynamically. SVCs extend the performance of capacitor banks through electronic switching of both capacitive and inductive elements. The effectiveness of either option decreases when the system voltage is depressed. Capacitor banks and SVCs can be added where space permits and there is existing access to the transmission system.

It may be possible to increase VAR support by uprating an existing turbine-generator. This option provides the same static and dynamic performance of a dedicated synchronous condenser and allows continued power generation. But if the unit is not competitive in the power generation market or faces emissions questions, its operation would likely be uneconomical. It is possible in certain cases to place a clutch between the turbine and the generator so that the turbine could be shut down with the generator remaining online as a synchronous condenser. This option may be possible for smaller units, especially for gas turbine driven generators less than 100 megawatt (MW). However, in many cases there is insufficient space between the turbine and generator to retrofit that clutch.

A new synchronous condenser offers the same technical performance as a converted unit. However, that installation requires additional investment in plant and equipment already present for a conversion of an existing unit. It tends to make sense only when the dynamic performance of the synchronous condenser is needed in places where there are no conversion options.

FirstEnergy chose to convert the Eastlake plant as part of a diversified approach to ensuring reliability following generation unit retirements. SVCs, additional capacitor banks, and transmission line upgrades are being used as well. Studies indicated that converting Eastlake to synchronous condensers provides the necessary dynamic reactive voltage support to address reliability concerns. The location of the Eastlake plant in relation to the city of Cleveland allows voltage support in close proximity to the load, and as a conversion in place, it does not require the additional space necessary for other solutions.

## 4. CONVERSION IN PLACE

The conversion in place makes maximum use of the existing equipment in the power plant. The details of the conversion depend significantly on the plant layout, type of excitation system, turbine-generator layout, and the possibility of multiple units in the plant being converted.

[1] Alterrex, EX2100, EX2100e, and Mark are trademarks of General Electric Company.

## 4.1 Acceleration of the Units

For the conversions of Eastlake 4 and Eastlake 5, General Electric elected to use the static start option used for modern gas turbines. A variable frequency drive (VFD) energizes the condenser as a motor and accelerates it to rated speed. The VFD back feeds, accelerating current through the unit auxiliary transformer (UAT) into the generator. That current, in conjunction with magnetic flux in the generator, produces the accelerating torque. The magnetic flux, in turn, is created by injecting excitation current into the generator rotor during acceleration. When the unit reaches 3600 rpm, it is at rated voltage and ready to be synchronized to the grid.

## 4.2 Electrical Modifications

The installation at Eastlake includes two VFDs, each of which can be connected to start either Unit 4 or Unit 5. Units 4 and 5 can be started simultaneously, if desired, with each using one of the VFDs.

Fig. 2 shows some of the details of the VFDs, excitation systems, and connections to Units 4 and 5. This system is controlled from the station control room using synchronous condenser controls running on a Mark VIe controls platform. The two 4 kV VFD buses comprise existing switchgear that was retired as part of the conversions, as well as new 4 kV cables between the Unit 4 and 5 electrical rooms. The existing connections between the switchgear and the two auxiliary transformers were retained.

The excitation system for Unit 5, shown in Fig. 3, has been upgraded to an EX2100e high initial response static exciter. It is fed from a 4 kV switchgear bus through an excitation transformer.

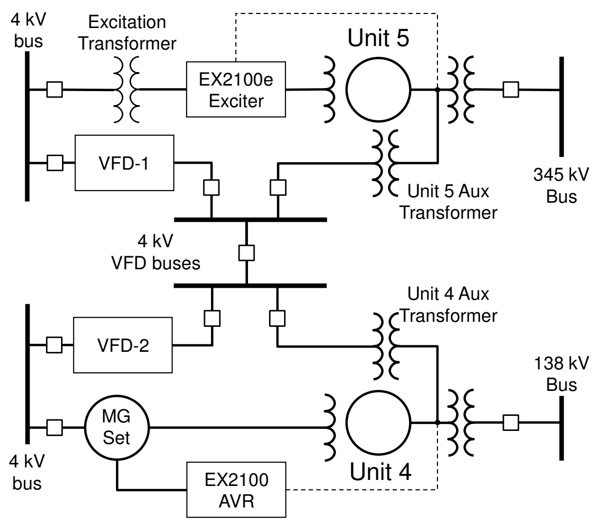


**Fig. 2. High-Level Electrical Configuration for Starting Unit 4 and 5**

## 4.3 Mechanical Modifications

The mechanical modifications to the two units were slightly different. The Alterrex exciter on Unit 5 was removed from service and replaced by the EX2100e static exciter. On both units a platform was installed outboard of the collector rings to provide a turning gear, a clutch, and a steady rest bearing/thrust bearing assembly. See Fig. 4.

The turning gear spins the rotor at 6 – 8 rpm so the rotor can cool down following a shutdown and to ensure proper bearing lubrication and zero breakaway torque during initial acceleration. The clutch allows the turning gear to stop once the rotor has accelerated to speed. The new thrust bearing replaces the thrust bearing on the turbine shaft.

Provisions were included on the drive and non-drive end of the rotor for trim balancing and to torsionally detune the rotor train to avoid torsional modes at twice-rated frequency if tests during commissioning indicated the need. New lube oil pumps sized for the remaining bearings and the new bearings were installed.

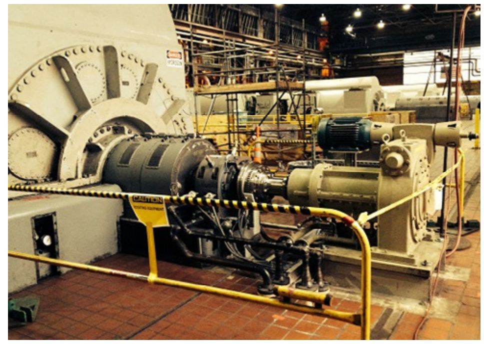

**Fig. 3. EX2100e Excitation System for Unit 5 Located on the Turbine Deck**

**Fig. 4. Collectors, Steady Rest/Thrust Bearing, and Turning Gear for Unit 4**

### 4.4 Operating Controls and Relaying Improvements

The control systems for Units 4 and 5 include portions of the existing plant distributed control system (DCS) for balance of plant and electrical systems as well as new Mark VIe controls for each unit. The operating screen (HMI) of the controls is the operator's interface for starting, synchronizing, and operating Units 4 and 5 on the grid.

Once all permissives have been met, the acceleration begins from turning gear speed. The acceleration rate is controlled by the VFD according to a predefined schedule. Throughout that sequence, the VFD sets both the accelerating torque (current) and the excitation current from the excitation system. At all times, the unit magnetic flux (V/Hz) is maintained within suitable limits. The VFDs were selected so that they could accelerate Unit 5 to 3600 rpm in approximately 20 minutes.

Once at rated speed, the controls pause awaiting a synchronizing command from the operator. The standard synchronizing facility of the controls adjusts the speed and voltage of the unit to place it within the synchronizing window and then closes the circuit breaker in the high voltage (HV) switchyard. This synchronization places the unit on the grid in a bumpless transition with little to no stress (synchronizing torques and forces) to the unit.

The operator can either manually set the reactive power output via the EX2100e automatic voltage regulators or place the unit in automatic, allowing a control loop to maintain the unit terminal voltage (18 kV for Unit 4 or 24 kV for Unit 5) at a defined set point. That set point and the voltage on the respective grid define the reactive power produced or absorbed.

The shutdown sequence, the controls reduce the reactive power to zero to provide a smooth transition off the grid. Once at zero reactive power, it opens the HV breaker and the unit decelerates.

Throughout the operating sequence, the controls monitor the performance of each unit for temperatures, pressures and flows and include trip functions for bearing vibration. While very unlikely, overspeed trip levels are defined. Those trip functions and emergency stop buttons have been integrated with the existing generator protection systems (ground fault and differential protection, for example) through the existing lock-out relays.

If the unit is tripped, the HV breaker in the switchyard opens and the unit decelerates. If the situation does not require an instantaneous trip, excitation will be removed at 95% speed.

The unit protection relaying was reviewed and revised for the conversion. The majority of the relay changes consisted of removing protection that was necessary when the unit operated as a generator. Examples would be the removal of reverse power and under frequency relays as the generator is connected directly to the grid.

### 4.5 Other Plant Modifications

Cooling water is required for the lube oil system, the generator stator and plant transformers. As a coal-fired generating station, the cooling for these systems was by various means, including closed-loop cooling, condenser circulating water, and low pressure (LP) or high pressure (HP) service water. Since a synchronous condenser requires less cooling than a generating station, FirstEnergy decided to use the underutilized Unit 5 closed-loop cooling water system for cooling both Units 4 and 5. This eliminated the need to operate large circulating pumps, allowed a number of systems to be permanently removed from service, and reduced water intake, allowing the plant to meet new rules of Section 316(b) of the Clean Water Act.

With the retirement of the units as generators, there will no longer be a steam source available for heating and so new supplemental heating has been installed at the plant. The heating improvements consist of electrical convection heaters and radiant heaters in key areas as well as heat trace and insulation of piping. General areas of the plant will have no heat.

## 5. OPERATIONAL ASPECTS

### 5.1 Ownership of Assets

FirstEnergy Corp. contains Transmission and Generation divisions. While generating power, the Generation division operated and maintained the units. The assets were transferred to American Transmission System Inc. (ATSI) in order to facilitate the conversion to a transmission function as synchronous condensers. Once converted, the synchronous condensers are Transmission assets. As synchronous condensers, the transferred assets will provide the required voltage support.

Activities involving operation, maintenance, inventory management of spare parts, programs for accounting and compliance with FERC required efforts from both sides of the company. FirstEnergy's transmission business owns the synchronous condensers but uses its personnel with generation experience to operate and maintain the assets.

### 5.2 Performance on the Grid

The Eastlake 345 kV system operates without many set point changes. However, the 138 kV system operates with numerous set point changes due to the system demand requirements. The control set point for operation of this unit was not clearly established prior to energization, as there was no precedent in operation of such a large unit within the PJM footprint.

The steady state VAR output is determined by the system voltage (138 kV or 345 kV bus voltages) and limitations on the generator terminal voltage. Fig. 5 shows the steady state reactive power of Unit 4 as a function of the switchyard voltage. The 105% and 95% curves are the upper and lower limits of terminal voltage.

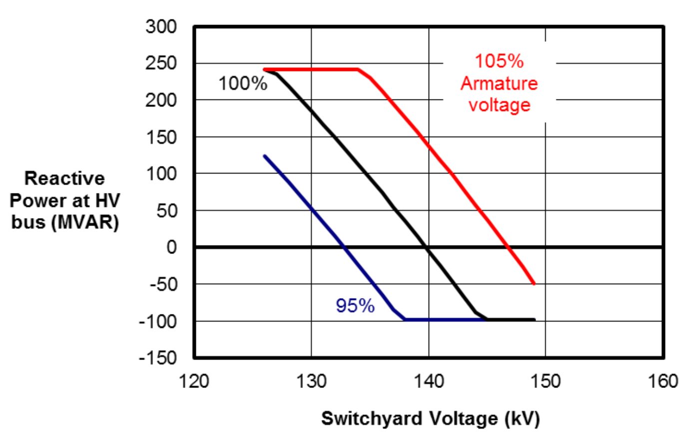


**Fig. 5. Net Reactive Power at 138 kV Bus for Eastlake Unit 4**

The excitation systems of Units 4 and 5 maintain each unit's terminal voltage. When in local control, the automatic voltage regulator (AVR) maintains that voltage at a point set via the operator's screen. FirstEnergy has implemented Automatic Control in which the voltage on the bus each unit is connected to is monitored and controlled by an outer control loop. In response to voltage variations on that bus, the 345kV bus in the case of Unit 5, that control loop periodically changes the voltage set point of the EX2100e excitation system for Unit 5 to increase or decrease the unit's 24 kV terminal voltage. Whereas the AVRs operate in a millisecond time frame, this outer loop sends voltage adjustment commands to Unit 5 approximately every 10 seconds.

In Automatic Control, a control loop looks at the current system voltage (345kV or 138kV) and then continually pulses the terminal voltage set point (up or down depending on the system voltage) to achieve the desired system voltage.

The effectiveness of this Automatic Control loop is evident in Fig. 6. Unit 5 is initially offline and there are significant variations on the 345 kV bus. When Unit 5 is online and the Automatic Control is operating, the variation in VARs is apparent and the bus voltage variation is significantly reduced.

Due to its rapid response in Automatic Control, Unit 5 as a condenser reacts to the voltage changes on the 345 kV bus more quickly than it did by manual adjustments as a generating unit. This in turn can cause the synchronous condensers to operate at their limits. Consideration and changing of operating philosophies need to be considered regarding what is beneficial to the entire operating system. The remaining Eastlake 138 kV generating units have not been manually adjusting their voltage because the Unit 4 synchronous condenser has been responding to the voltage changes so quickly there is never a need. This has resulted in Unit 4 running at or near its VAR limits more often than desired.

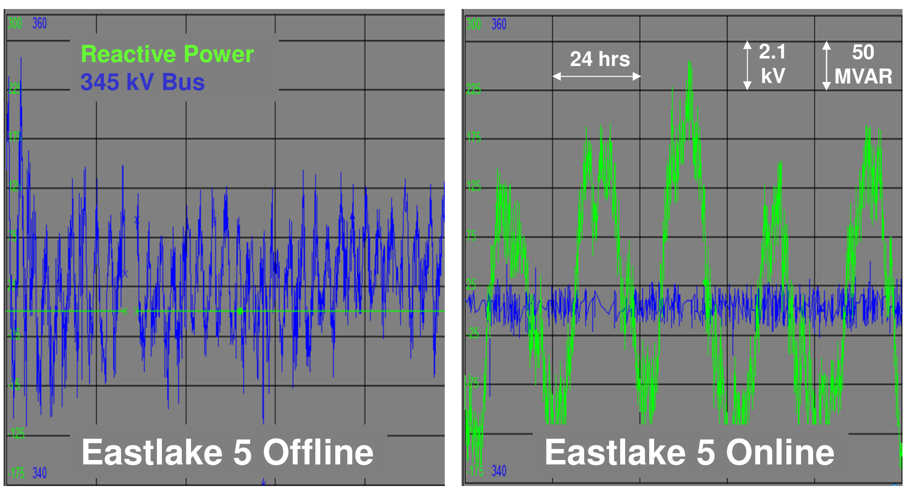


**Fig. 6. Voltage and Reactive Power Variation on Eastlake 345 kV Bus With and Without Automatic Control**

## 6. LESSONS LEARNED

Timing of work is a critical aspect of a conversion project. Eastlake is not a green field site, so a conversion could not fully start until the units were decommissioned as generators. Having all possible staging complete prior to full mobilization is key to successful completion of a conversion in place.

These units were generation assets that were transferred to transmission assets, so it was necessary to engage employees from both parts of the company. As a result, employees with different Federal Energy Regulatory Commission (FERC) classifications were involved and it was important to maintain observance of the FERC "no conduit" rule.

The plant equipment was of the 1958 and 1972 vintage. Since a significant portion of the equipment was reused, attention to selective refurbishment should be considered to assure proper operation and reliability as a synchronous condenser.

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