Damages to power plant due to cycling and its mitigation strategies

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ABSTRACT

Large capacity coal based power plants were traditionally envisaged as base load plants and design basis for these plants focused on reliable operation of units with high plant load factor. These plants under increased cycling will experience decreasing levels of reliability due to greater potential for damage and failure of equipment when operated outside its design limits. Cycling refers to operation at varying load levels, including on/off, load following, and technical minimum load operation, in response to changes in load requirements. Cycling is expected to increase with the integration of more and more renewable energy generation directly on to the grid as renewable sources are unpredictable, intermittent, and periodic and subject to environmental conditions. This study deals with the cycling which is associated with stresses from varying temperature and pressure that trigger fatigue and fatigue-related damages. Relevant EPRI projects and contemporary research papers on flexible operation and cycling damages have been reviewed. The study shows that the damage accumulates with each cycle, and severity of damage is a function of type of load cycle. Different damage mechanisms for plant components are explained. Starts that involve greater temperature and pressure changes have more potential for equipment damage. It is estimated that a warm start is three times more stressful than a hot start and a cold start is five times more stressful than a hot start. The components that are subjected to higher thermal shock during cycling for example, economizer header offer very low fatigue life. A correlation between Equivalent Forced Outage Rate (EFOR) and number of starts establishes that the initial delay is about seven years between the peak in number of starts and the peak in EFOR. This confirms that although a substantial increase in the number of starts results in more failures, these failures will not occur until a significant period of additional service has accumulated. The extent of EOFR depends on several factors, including quality of maintenance, age and design of the plant. Strategies to mitigate the impact of cycling are devised and broadly categorized as minor-cost items, moderate-cost items, and items requiring additional research for development of superior materials and improved-design. Minor-cost items include additional sensors, C&I up-gradation, and changes in operating practices. Moderate-cost item include installation of furnace off-load recirculation pump, economizer off-load recirculation pump and trickle feed system that allow hot water to be transferred from an operating boiler to one that is off-load and thus avoid thermal transients by carefully managing the unit when off-load and by adding engineered systems. The study provides several interesting insights into the cycling phenomena and damage mechanisms. Mitigation measures suggested here can be implemented to alleviate potential problems due to cycling in existing and upcoming thermal power plants.

Keywords: Cycling, thermal transients, trickle feed

INTRODUCTION

Coal based large capacity power plants were traditionally designed as base load plants. This essentially meant redundancies in auxiliaries, margins in constituent equipment, rotary machines in particular, and designed for most economic generation under steady base load operation. During last five years, capacity addition was done at a rapid pace. However, demand did not rise at the pace as envisaged, leading to surplus capacity. This cycling or fluctuation of power demand is expected to worsen further with increasing penetration of generation from renewable energy resources. India has a large solar potential of an estimated 748 GWp and the Government has expanded its solar power capacity target of 100 GWp by 2022. Renewable energy sources such as solar energy and wind energy are, by nature, unpredictable, intermittent and periodic, subject to environmental conditions (e.g. night and day) and climatic changes,

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(fluctuations of wind and sun – clouds, rain, wind blowing etc.). Several renewable integration studies have recognized increased power plant cycling due to large scale integration of renewable and consequent increase in cost of generation [1]. In this new scenario, units low in merit order are forced to run even at lower than technical minimum load and peaking loads during morning and evening peaks. Increasing penetrations of variable renewable generation are having a far-reaching impact on the operation of conventional fossil fuel power generation. For many utilities and plant operators, plant operation and maintenance (O&M) expenditures are currently rising at a rate faster than inflation. Power plant operators and utilities have been forced to cycle aging fossil units. It warrants a detail study on cycling phenomena, its impact and mitigation measures.

Increased cycling requires scheduling of additional operating staff and increased training. Under cycling, plant operators are required to carry out load variation, start up and shutdown regularly - and to do it quickly and efficiently. The requirements to understand and operate the plant under highly dynamic conditions of cycling including transients [2], place a high degree of responsibility on plant operators. The scopes for error and to cause damage to the plant are greatly increased. The operating persons also need to better understand the impact of cycling and part load operation on major performance parameters (heat rate, APC, Sp. oil consumption, sp. water consumption). It warrants a higher order understanding of plant performance analysis and optimization [3, 4] by following concepts of advanced technology.

CYCLING AND ITS SIGNIFICANCE

Cycling refers to the operation of electric generating units at varying load levels, including on/off, load following, and minimum load operation, in response to changes in system load requirements. Every time a power plant is turned off and on, the boiler, steam lines, turbine, and auxiliary components go through unavoidably large thermal and pressure stresses, which cause damages. Operating a power plant in any mode triggers damage mechanisms, and damage to material and equipment accumulates over time. Steady-state load operation, associated with base load operation, can lead to stresses from operating constantly at high temperatures and pressures. Cycling load is associated with stresses from varying temperature and pressure that trigger fatigue and fatigue-related damages.

CREEP AND THERMAL FATIGUE

In principle, because creep is time and temperature-dependent, two-shifting and low-load operation would be expected to reduce damage caused by long-term creep. During a unit start or at periods of low-load running, there may be some circumstances when localized overheating can occur as mentioned in ETD (European Technology Development) Report [5]. While these problems are well known to plant operators, it should be recognized that the cumulative effects of repeated overheating during thermal and load cycling can give rise to extended periods of operation above the design temperature, which may result in accumulation or acceleration of creep damage. Creep-related phenomena in two-shift units are degradation in the microstructure and the concomitant reduction in material properties, which has already occurred during the previous term of base load operation. These micro-structural changes will have occurred simply as a result of exposure to temperature but will have been accelerated by the presence of stress. The most obvious signs of such degradation are the onset of spherodization in carbon-manganese and 2.25Cr1Mo steels. The implications of this are likely to be 1) reduced material ductility compared to virgin material and 2) reduced resistance to creep and/or fatigue cracking. However, by far the most common problem experienced as a result of two-shifting is thermal fatigue damage. This is manifest either in the form of cracking of an individual component or in the mechanical failure of structures. Cracking of a component is attributed to severe thermal gradients arising from excessive steam to metal and through wall temperature differences associated with rapid rates of steam temperature change as generally observed during startup, shutdown, and load changes. The principal components at risk typically comprise any thick-walled sections, such as boiler superheater headers, steam pipe work, valves, high-pressure (HP) and intermediate-pressure (IP) turbine inlet stages. HP heaters and economizer inlet headers are also frequently exposed to similar effects as a result of rapid cooling by cold feed water. Thin-walled sections, such as boiler tubes and reheater headers, are less prone to the problem. On a wider scale, structures such as boiler framework and tube attachments, boiler supports, and pipe work support systems are also vulnerable to thermal cycling.

CONSEQUENCES OF CYCLING

Under cycling operation, damage to plant equipment accumulates with each cycle, and severity of damage is a function of type of load cycle. High pressure, high temperate large coal based plants have thick wall pressure part components and have a typical ramp up / down rate of 1.5%-2.5% and a primary frequency response of 5%. These plants under increased cycling will experience decreasing levels of reliability due to the greater potential for damage and failure of equipment operated outside its design limits. Such incidents will result in the increasing frequency unplanned outages to repair or replace equipment. The consequences will involve higher capital costs to replace equipment failing design life, higher operating costs to repair and maintain equipment, and accompanying declines in net unit revenue. Load-following involves rapid increases and reductions in process temperatures, which create significant thermal stress on pressure boundaries. When plant loads change, the consequences are numerous:

- Pulverisers or mills and other auxiliary equipment go off and on
- Furnace temperatures and heat profiles are altered
- Pollution control requirements change
- Steam and flue gas velocities vary

All these changes can affect the design basis of the equipment. Besides potential damage to components, other consequences of cycling are: increasing heat rate, decreasing revenue, higher emission rates, impact on O&M staff and reliability of the plant systems.

Also, O&M staff needs to be aware of the functional requirements of cycling, the commercial aspects of plant running costs and efficiency, and the long-term effects of operation on the life expectancy of the plant. New preventive maintenance and predictive maintenance strategies may need to be adopted due to:

- Changes in the availability of the unit
- Additional stressors that might change the preventative maintenance frequencies
- Additional training to acquire the needed skills

Component damage accumulates with each cycle and severity is a function of type of load cycle. Damages do occur due to frequent start stops. Starts are defined differently by each utility and unit, but are typically categorized as follows:

- Hot starts are less than 8 hours of shutdown, with turbine metal temperatures above 400°C.
- Warm starts are 8-48 hours of shutdown, with turbine metal temperatures greater than 200°C.
- Cold starts are more than 48 hours, with turbine metal temperatures less than 200°C.

Starts that involve greater temperature and pressure changes have more potential for equipment damage. Damage increases with greater frequency of cold starts [6]. A warm start is three times more stressful than a hot start, while a cold start is five times more stressful than a hot start as par an estimate mentioned in EPRI report no. 1004412 [6]. Results of a study by Aptech, United States [7] on co-relation of cycling and Equivalent Forced Outage Rate (EFOR) (shown in Fig. 1) establishes that EOFR for cycling units are greater for than for base load units for nearly all cases. Figure 1 explains that the initial delay is about seven years between the peak in number of starts and the peak in EFOR. As the plant ages, this delay appears to reduce to about three years, and then reduces further as the plant further ages. This confirms that although a substantial increase in the number of starts results in more failures, these failures will not occur until a significant period of additional service has accumulated.

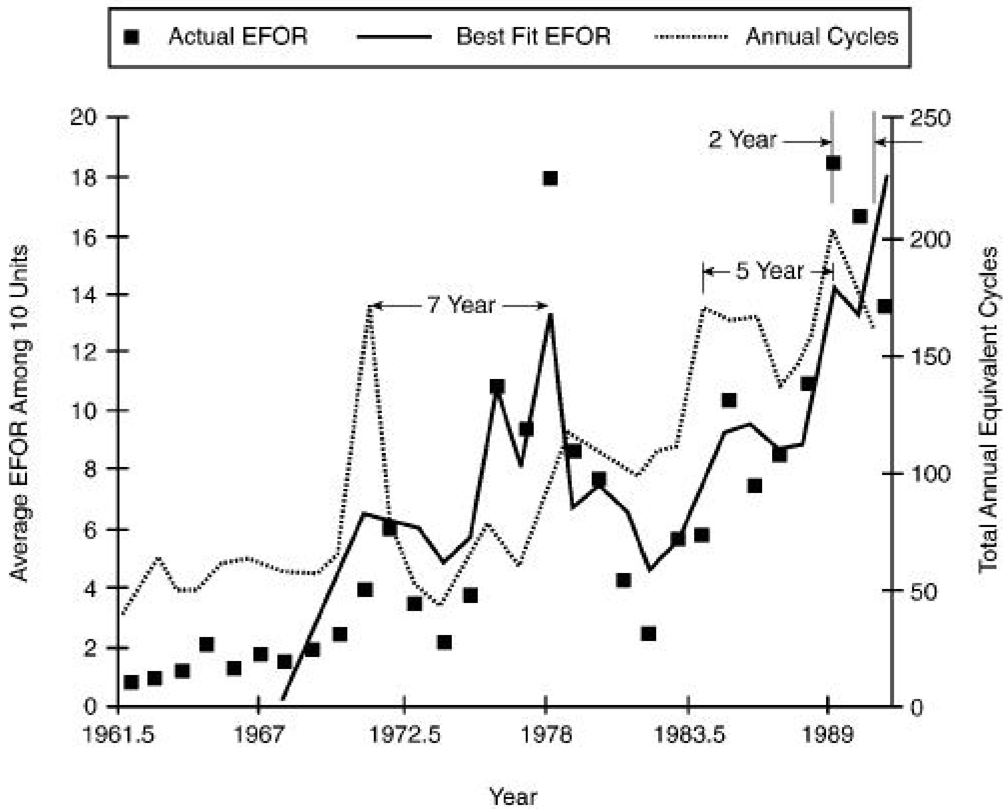

Figure 1: Relationship between cycling and EFOR (Courtesy: Aptech, United States)

DAMAGE MECHANISM FOR MAJOR COMPONENTS

Boiler

- Thermal fatigue cracking in thick-walled sections and valves (one such damage in water wall attributed to severe thermal gradients is shown in Fig. 2)
- Increased boiler tube failures due to differential expansion
- Fire side circumferential cracking in water walls
- Thermal fatigue cracking in SH and RH ligaments
- Corrosion and fatigue can be combined to accelerate damage

Economizer

- Thermal fatigue and corrosion in economizer inlet

Deaerator

- Stress corrosion cracking in weldments

Piping

- Creep fatigue in main steam and reheat piping, flow accelerated corrosion in steam piping

HP Turbine

- Thermal fatigue cracking in thick-section rotors, casings and valve
- Erosion of valve components

LP Turbine

- Moisture erosion of blades

Generator

- Wear of copper insulation due to differential expansion, loosening of stator windings

FW Heaters

- Thermal fatigue of thick sections of the tube plates and end covers

ESP/SCR

- Impairment of emission control during low load and transients

Figure 2: Water wall damage attributed to severe thermal gradients

INTERACTION AND CONSEQUENCES OF CREEP AND FATIGUE

Based on ASME N-47 [8] for a typical power plant steel (2.25Cr1Mo), for example, consider a component originally designed for 10,000 cycles, which might have been designed to operate in a unit that two-shift on a daily basis over 30 years. Assume also that the component operates in the creep range and was designed for 150,000 hours of operation. If the unit were to operate on a base load regime, it will accrue some thermal cycles - probably about 1,000 - over the projected life. If the component operates on a two-shifting unit with 300 cycles per year while operating in the creep range, the actual life may be as low as 40% of the anticipated fatigue life. Where operational cycling is introduced on a former base load unit, the residual life can be greatly reduced to between 40% and 60% of the original design life because of the combined effects of creep and fatigue. The key implication is that older units designed for base load operation and used in this capacity over many years are susceptible to component failure when they are eventually forced to cycle regularly. A study on typical fatigue lives of high-temp components shows around 30% of tube failures and almost 50% of turbine equipment failures can be related to cycling. Headers also appear to be particularly susceptible components (tube stub or ligament cracking). Economizer inlet header and header stubs exhibit a very low fatigue life. One such failure in economizer header is shown in Fig. 3. A breakdown of cycling-related failures obtained from UK utility [7] is summarized in Table 1 which explains that the percentage of failures attributed to cycling is the highest for headers.

Figure 3: Cracking in economizer header attributed to severe thermal gradients

Table 1: Breakdown of cycling-related failures obtained from UK utility

Component	Total no of failure	Percentage of failures due to cycling
Boiler tubes	33	33
Headers	6	83
Superheater tubes	47	19
Reheater tubes	10	40
Condenser	27	38
HP heater	17	70
LP heater	3	33

STRATEGIES TO MINIMIZE POSSIBLE DAMAGES DUE TO CYCLING

Radical strategies are needed to reduce the level of possible plant equipment damages due to thermal cycling over a number of years. However, the costs of preparing a long-term strategy need to be balanced with the likely future of the plant. The most comprehensive approaches include the following actions which are categorized in to minor-cost items, moderate-cost items and items that require additional research.

Minor-Cost Items

- Additional Sensors
  - Tools for identifying presence of condensate in the SH and RH before startup
  - Thermal stress monitoring
  - Deformation of water walls near penetrations (see Fig. 2)
  - To monitor performance and prevent damage.
  - To monitor dissolved O_2, high-temp thermocouples

- To identify and quantify the impact of cycling operation

- Additional control and instrumentation
  - Many control strategies and tuning methods are non-optimal for current flexible operations.
  - New C&I configurations are needed to better control fatigue stresses
  - Allow plants to operate outside their historical operating envelope without equipment damage.
  - Upgraded combustion control systems are necessary to improve flame stability and monitor primary and secondary air flow
  - Boilers will need upgraded control systems to avoid oscillation of steam pressure and temperature, and to maintain drum level.
  - Modified automatic controls for turbine to reduce stresses
  - Control system can be adjusted to suit a range of operating scenarios necessary to reach full load or any other loading scenario.
- Modifications to operating procedures
  - For example, economic two-shifting can be achieved with due care and application of sound engineering and operational practices.
  - Many utilities have performed trials on two-shift operation to reduce startup and shutdown time.
  - Generally, startup times can be nearly halved from original base load procedures so that large machines can be synchronized within 35 to 50 minutes of inserting the first burners depending on unit size and configuration—and full load can be achieved in similar times.
  - Thermal transients can be avoided by carefully managing the unit when off-load and by adding engineered systems to alleviate the potential problems.
  - Thermo-siphonic circulation drum boilers may be fitted with off-load circulating systems to pump water slowly around the evaporative section
  - A primary constraint on ramping operation is matching steam and turbine metal temperatures.
  - Sliding pressure results more efficient point with less throttling losses and improved HRH temp, in addition to a decrease in BFP power.
  - One drawback to sliding pressure is that it slows down the response rate so the unit will have slower ramp rates while in sliding pressure operation.
- Training of O&M personnel
  - Retraining plant engineering and maintenance staff for new operating procedures and maintenance strategies
  - Plant data for critical components can be screened to identify and understand the most damaging conditions.
  - Operators can then seek to minimize the extent of such conditions during future unit starts.
  - Maintenance staff can be trained to conduct targeted inspections during outages
  - Regular walk downs to recognize damage such as boiler tube distortion, flow-accelerated corrosion, and support system damage.

Moderate-Cost Items

- Installation of new equipment, modifications or retrofits to reduce thermal transients
- Furnaces
  - Combustion systems can add low-load burners, supplementary fuel capability, and wide-range coal nozzles
- Improved startup time by ensuring integrity of insulation
  - Headers, steam pipe work and boiler stop valves
  - Turbine control valves and turbine casings.
- Drains to progressively warm the boiler, steam legs, and turbine in a well-controlled manner to promote flow
- Upgrading the drain system to increase its capacity and operability.
- HP heater drains may also need to be rerouted if they cannot adequately drain to the next lower pressure heater without flashing
- Economizer off-load recirculation pump and furnace off-load recirculation pump, the scheme is explained in Fig. 4. Forced circulation boilers could use the existing BCP but may benefit from the installation of a smaller pump, specifically designed for off-load duty.
- Condenser air evacuation

- If the existing installation is unable to raise vacuum within the required time, capacity must be improved or additional capacity installed.
- Trickle feed system to reduce thermal shock
  - Allow hot water to be transferred from an operating boiler to one that is off-load.
  - During the shutdown period and prior to a hot start, the boiler can be topped up without the use of a Boiler Feed Pump.
  - Reduces the thermal shock to economizer inlet headers as well as tendency to ligament cracking
  - In most cases, water from economizer inlet of operating boiler is transferred to economizer inlet of off-load boiler.

Items Requiring Additional Research

- Development of stronger ferritic materials for thick-walled components of high-temp headers
- Reduced thickness decrease temp gradients across the wall.
- Improvements in creep-strength and resistance to cycling-related damages
- Use of advanced nickel alloys such as INCONEL alloy for use in supercritical boiler and turbine designs which would allow reduced wall thickness and improved transient response
- Reliable high-temp strain gages that can be inexpensively integrated into the Plant Information systems.

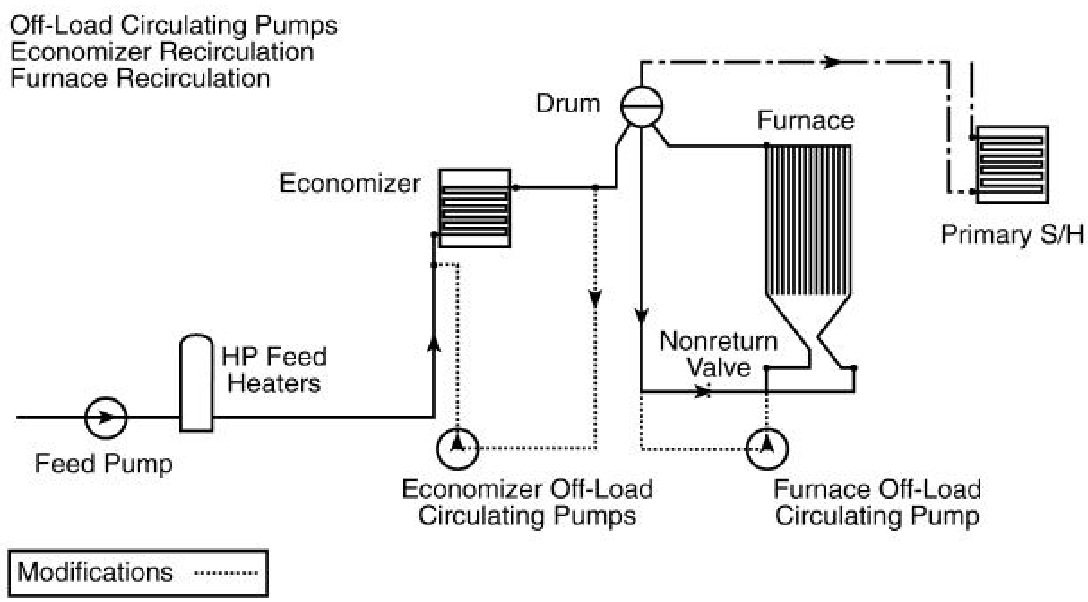

Figure 4: Economizer off-load recirculation pump and furnace off-load recirculation pump.

CONCLUSIONS

The changes in plant operation that are necessitated by variable duty cycles expose plant equipment to fatigue-related damages which are associated with varying temperature and pressure. Findings on flexible operation and cycling damages outlined in pertinent EPRI projects and other contemporary research works have been summarized here. Plant component specific damage mechanisms under cycling have been identified. The study provides following interesting insights into the cycling phenomena and its consequences in thermal power plant systems:

- An estimate shows that a warm start is three times more stressful than a hot start and a cold start is five times more stressful than a hot start.
- EOFR for cycling units are greater than for base load units for nearly all cases.

- The initial delay is about seven years between the peak in number of starts and the peak in EFOR. As the plant ages, this delay appears to reduce to about three years, and then reduces further as the plant further ages. This confirms that although a substantial increase in the number of starts results in more failures, these failures will not occur until a significant period of additional service has accumulated.
- The components that are subjected to higher thermal shock during cycling, for example, economizer header offer very low fatigue life.
- The extent of forced outages depends on several factors, including quality of maintenance, age and design of the plant.

Strategies to mitigate the impact of cycling are devised and broadly categorized as minor-cost items, moderate-cost items, and items requiring additional research for development of superior materials and improved-design. Minor-cost items include additional sensors, C&I up-gradation, and changes in operating practices. Moderate-cost item include installation of furnace off-load recirculation pump, economizer off-load recirculation pump and trickle feed system that allow hot water to be transferred from an operating boiler to one that is off-load and thus avoid thermal transients by carefully managing the unit when off-load and by adding engineered systems to alleviate potential problems. Mitigation measures suggested here can be implemented in existing and upcoming thermal power plants in order to minimize the effects of cycling.

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