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Fingerprinting the Malfunction of Devices

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Abstract

A methodology to generate fingerprints for malfunctioning devices in a system from the design information of the system is proposed. The aim is to reduce measurement to the minimum and to the simple at the expense of more computation. A simple combined cycle is considered. A baseline of fingerprints is generated by considering the degradation of one of the efficiency parameters of a single device; one degradation at a time. Different degrees of degradation are considered at different load fractions. The load fractions considered cover the range from 1 (design point) to 0 .4. The degrees of degradation considered cover the range from 1 (no degradation) to 0.6, the efficiency occurring at the considered load fraction. The needed design information is stated. Examples of fingerprints are presented in tables. Application of the base-line fingerprint methodology to existing plants in general is described. Extension to multi-degraded efficiency parameters is considered guided by the baseline fingerprints.

Keywords: Off-design performance of a device, device efficiency degradation, device malfunction fingerprints.

1. Introduction

Diagnosis deals with the health state of operating energy systems. The health analysis makes use of two sets of information: the accumulated data of the operating plant data-acquisition system and the design data of the plant and its devices. The analysis may depend largely on the accumulated data and tends to take the form of statistical analysis or may depend largely on the design data and tends to take the form of thermodynamic analysis. Both analyses target the sources of malfunction and the cost effectiveness of fixing them. This paper belongs to the latter analysis.

The paper's approach is to generate by computation the operation malfunctioning features from the design information of the system. The approach is meant to reduce the needed measurements to a minimum of simple measurements. The paper is an update of the paper by El-Sayed, 2006 that built on the initiation work on operation malfunction by (Valero, el 2002) and (Cziesla and Tsatsaronis, 2003).

The required design information consists of:

- The design point of the system and all its devices
- The off-design performance curves of the devices either derived from the design data of the devices or assumed from generalized relations
- The control strategy of the system regarding load variation.

For each considered load fraction, the system performance is simulated to establish the efficiency of the system and the efficiencies of its devices. Inefficiencies are introduced one at a time. One device is allowed to malfunction by assuming a degrading factor df for one of its efficiency parameters occurring at the considered load fraction. The system performance without degradation ($df = 1$) and with the degrading factor ($df \neq 1$) creates the malfunction fingerprints of the degraded efficiency parameter. The degrading factor is >1 if the efficiency parameter is a pressure loss or a temperature difference and is < 1 if it is adiabatic efficiency or effectiveness. The fingerprints show their marks on the device performance, on the system efficiency and on the system states. Computed and measured pressures and temperatures are selected as the marks on system states since pressures and temperatures are relatively simple to measure.

Because of the complex interactions among the system devices, the single inefficiency fingerprints often require further analysis to pinpoint the sources of more than one inefficiency malfunction.

2. The Combined Cycle Example

To examine the proposed approach, a low firing simple combined cycle shown in figure 1 is considered.

The design point (load factor =1) has a firing temperature (of state 3) around 870°C (1600°F). The compressor delivery pressure (of state 2) is 745 kPa (108 psia). Steam generated pressure and temperature (of state 6) are 2.16 Mpa and 436°C (313 psia and 817°F). Pinch at (state 13) is 8.3°C (15°F). State 11 is saturated vapor. States 10 and 8 are saturated liquid. Rated gas turbine power output is 100MW. The major efficiency parameters at the design point of the system are as follows:

Systems first law efficiency %	= 40.78
Systems second-law efficiency %	= 46.13
Compressor (1) adiabatic efficiency %	= 86.6
Gas turbine (2) adiabatic efficiency %	= 89.6
Steam turbine (3) adiabatic efficiency %	= 81.6
Feed pump (4) adiabatic efficiency %	= 88.5
Cooling water pump (5) adiabatic eff. %	= 62.1
Superheater (7) effectiveness %	= 91.6
Boiler (8) effectiveness %	= 95.4
Economizer (9) effectiveness %	= 95.9
Condenser (10) effectiveness %	= 86.5

Performance equations of participating devices of this example problem over the range of design to allowed off-design are listed on pages 215 and 216 of the book by El-Sayed 2003.

Fingerprint tables are generated, as described in the introduction, for the load fractions and devices of interest. Tables 1 and 2 are samples for load fractions 0.8 and 0.6 for each of the compressor, the gas turbine, the steam turbine and the condenser with the efficiency/ effectiveness computed at load fraction assuming no degradation (degrading factor $df = 1$) and assuming a degree of degradation ($df < 1$). For load fraction 0.8, the degree of degradation is assumed to be 0.8. For load fraction 0.6, the degree of degradation is assumed to be 0.7. Δ is defined as case $_{df<1}$ – case $_{df=1}$. Device fuel is the fuel due to device exergy destruction. Device marks on system states are computed pressures and temperatures to compare with their corresponding measured values. Changes in the measured fuel consumption rate are often the reason that triggers the need for fingerprints.

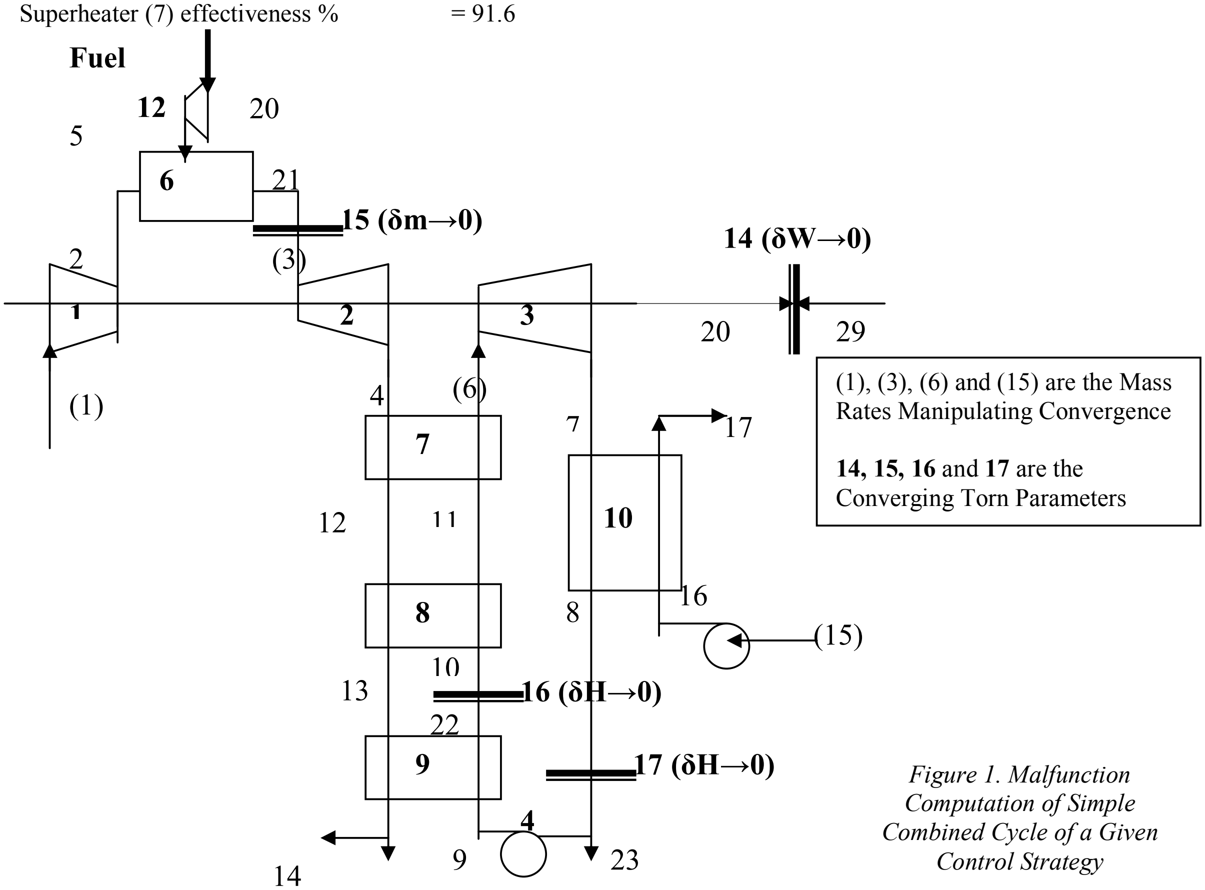

Figure 1. Malfunction Computation of Simple Combined Cycle of a Given Control Strategy

TABLE I. LOAD FRACTION = 0.8, DEGREE OF DEGRADATION 0.8
(SINGLE-INEFFICIENCY FINGERPRINTS)

Fingerprint	Device			
	1	2	3	10
	compressor	gas turbine	steam turbine	condenser
Iterations: load & malfunction	3, 4	3, 5	3, 3	3, 4
Device design efficiency	0.8660	0.8967	0.8190	0.8654
Device efficiency at load fraction	0.8379	0.8940	0.7956	0.8756
Degraded device efficiency	0.6927	0.7184	0.6406	0.6213
Device Δfuel kW	13999	11248	5390	429
Device Δfuel/fuel$_{df=1}$ %	231	193	75.8	26.0
System Δfuel kW	24816	15415	10494	-139
System Δfuel/fuel$_{df=1}$ %	12.15	7.55	5.14	-0.07
System Δfirst-law eff	0.0424	0.0275	0.0191	-.0003
System Δfirst law eff/eff$_{df=1}$ %	10.83	7.02	4.88	-0.07
System Δsecond law eff	0.0438	0.0411	0.0209	0.0007
System Δsecond law eff/eff$_{df=1}$ %	9.94	9.32	4.74	0.17
Device Indicators P kPa, T C	P_2, T_2	T_4, T_{14}	T_7	T_{17}
Computed at *df*=1	586, 256	495, 148	38	37
Computed at *df*=0.8	793, 366	559, 53	82	34

TABLE II. LOAD FRACTION = 0.6, DEGREE OF DEGRADATION 0.7
(SINGLE-INEFFICIENCY FINGERPRINTS)

Fingerprint	Device			
	1	2	3	10
	compressor	gas turbine	steam turbine	condenser
Iterations load & malfunction	4, 4	4, 4	4, 4	4, 4
Device design efficiency	0.8660	0.8967	0.8190	0.8654
Device efficiency at load fraction	0.7819	0.8706	0.7733	0.9147
Degraded device efficiency	0.6030	0.5792	0.5481	0.5285
Device Δfuel kW	17659	15231	6755	621
Device Δfuel/fuel$_{df=1}$ %	291	326	89.9	41.67
System Δfuel kW	26569	30571	14450	-244
System Δfuel/fuel$_{df=1}$ %	15.93	18.33	8.66	-0.15
System Δfirst-law eff	0.0494	0.0557	0.0286	-.0006
System Δfirst law eff/eff$_{df=1}$ %	13.74	15.49	7.97	-0.15
System Δsecond law eff	0.0507	0.0692	0.0314	0.0011
System Δsecond law eff/eff$_{df=1}$ %	12.57	17.15	7.78	0.29
Device Indicators P kPa, T C	P_2, T_2	T_4, T_{14}	T_7	T_{17}
Computed at *df*=1	462, 233	547, 134	38	37.7
Computed at *df*=0.8	690, 381	634, 57	159	33

The control strategy is described on page 123 and figure 7.9.b of the book by El-Sayed 2003. The driving shaft speed, the pressure at the exit of the gas turbine, the condenser pressure, saturated liquid at exit of condenser and saturated vapor at exit of boiler section are set at the full load values (design point). A shaft speed sensor adjusts the compressor inlet guide vanes. A firing temperature sensor adjusts the fuel flow to the combustor. The set value of the firing temperature may deviate from that of the design point to match the turbine speed with that of the compressor. The water level in the separating drum of the boiler controls the steam flow to the bottoming cycle. The condensate level controls the rate of condenser cooling water.

3. Computation and the System's Convergence to a New State

Rounds of computations go through the system states looking for computable states, then through the performance equations of devices looking for computable efficiency parameters, and then through the processes of the system looking for computable processes until a solution is obtained. Tearing at certain stream variables where the variable on the two sides of a tear converge to the same value is essential. The number of tears often equals the number of major mass rate streams, but the locations and the parameters of the tears are not unique. They depend to some extent on the computational algorithm. The stream masses are assumed and adjusted until the torn variables converge. In this problem, 4 stream masses are considered and 4 tears are introduced as shown in figure 1. Convergence to a system state matching the load fraction required 3 to 6 iteration loops, each taking less than one minute to go through the system states performance equations and processes 20 to 40 times until all the states and processes are computed.

For the design point (load fraction =1), any degradation will produce less power. This is because a limit is imposed on the firing temperature. The lower the degrading factor, the lower the power produced for the same fuel consumption without degradation is. For load fractions <1, the power output can meet the load if the degrading factor is not below the value that increases the allowed firing temperature. Otherwise less power is produced while using the fuel of the load fraction without degradation. Table 3 shows examples of device degradations that could not meet the load because of constraint on the firing temperature. For example, for load fraction 0.8 and degrading factor 0.8 for the compressor, the required power meeting the load (80 MW) could be obtained. For degrading factor 0.7, 80 MW could not be obtained and convergence failed. The fuel consumption at 0.8 load fraction without degradation is 204.133 MW but produced only 62.441 MW, not the load of 80 MW.

With no degradation, load fractions down to 0.4 could be analyzed with no convergence problems. Although the covered range of inputs with successful convergence is adequate, there is no guarantee that all inputs of load fractions and degrading factors for each device will converge successfully to solutions with the current computational algorithm. Also some solutions involve undesired performance. For example, the condenser cooling water pump failed to deliver the appropriate pressure for large mass rates. A pump of different performance equation should have been used.

Each column of Tables 1, 2 and 3 is a result of two system solutions, one without a degrading factor and one with. A system solution consists of all state properties including exergy, all mass and energy rates, all process efficiencies and exergy destructions. The solution sheds light on the complexity of how performances shift among devices due to part load with and without degrading factor. Overall system energy and exergy balances portray the consistency of computation.

4. Application to an Existing Plant

The documents available for a plant should lead to the following information with least filling-in assumptions:

- The design steady state solution of the plant presented as states and processes and efficiency parameters
- The performance curve of each device from design to allowed off-design limits.
- The controlling strategy of load variation.

The above 3 sets of information allow the prediction of off-design system performance at a part-load to compare with document data as a calibration of the predicted values. The prediction is detailed for the simple combined cycle (El-Sayed 2003, pages123-127). The study (El-Sayed 2006) adds the degrading factors and simulates their effects one factor at a time. The simulated effects are used to explain the cause of any noticeable change in measured fuel consumption or power output. The more single inefficiency fingerprints are generated, the higher the probability of finding or understanding the cause of the observed deterioration is.

In the following, the case of simultaneous inefficiencies is added, guided by the baseline fingerprints of single inefficiencies.

TABLE III. DEVICE DEGRADATIONS RESULTING IN POWERS UNABLE TO MEET THE LOADS (SINGLE-INEFFICIENCY FINGERPRINTS)

Fingerprint	Device			
	1 compr	1 compr	2 gas turbine	2 gas turbine
Load fraction & Degrading factor	1, 0.8	0.8, 0.7	1, 0.7	0.9, 0.8
Iterations load & malfunction	2, 6	3, 4	2, 5	3, 4
Device design efficiency	0.8660	0.8660	0.8967	0.8967
Device efficiency at load fraction	0.8660	0.8379	0.8959	0.8984
Degraded device efficiency	0.6806	0.6065	0.6275	0.7186
Device Δfuel kW	18277	20222	18915	10829
Device Δfuel/fuel$_{df=1}$ %	272.7	333.7	227	161
System Δfirst-law eff	0.0347	0.086	0.0951	0.0676
System Δfirst law eff/eff$_{df=1}$ %	8.5	21.9	23.3	16.8
System Δsecond law eff	0.052	0.0922	0.1173	0.0787
System Δsecond law eff/eff$_{df=1}$ %	11.29	20.9	25.4	17.4
Power delivered MW	91.492	62.441	76.715	74.878
Fuel rate MW	244.643	204.133	244.643	233.47
Device Indicators P kPa, T C	P_2, T_2	P_2, T_2	T_4	T_4
Computed at df=1	737, 288	604, 261	456	474
Computed at df<1	896, 397	752, 398	584	557

5. Simultaneous Multiple-Inefficiency Degrading Factors

The methodology remains the same for cases having two or more inefficiencies acting in the same time. All the degrading factors are entered to simulate their combined effect and to compare with their individual effects.

Because the number of efficiency parameters in a system is large (about 20 for the considered combined cycle), the number of possible combinations of degrading factors at a number of desired loads can lead to an explosive increase of the number of fingerprints; relevant and irrelevant. Therefore it is important to consider only the meaningful and the most probable inefficiency combination guided by the single inefficiencies. Single inefficiency fingerprints can give insight into the interpretation of an actually occurring combined effect. Table 4 addresses the case of simultaneous inefficiencies. The table shows the fingerprints of three single inefficiencies and their simultaneous effect. The combined cycle considered in Table 4 happens to differ slightly in its design point only, otherwise identical to the one used in Tables 1, 2 and 3. Two useful indicators are noted from Table 4 as to the source of the malfunction:

- The change in the exergy destructions of devices converted to fuel consumptions. This is a fuel consumption assigned to devices in proportion of their exergy destructions to the exergy of the system's fuel.
- Certain pressure and temperature measurements

A change in a system's fuel consumption appreciably higher than those of the single devices indicates more than one device is responsible for the malfunction. The table shows device fuels of about 4000 kW, system fuels of about 6000 kW for single inefficiencies and of about 14000 kW for combined inefficiencies. Unusual pressure and temperature measurements can also be indirect indicators of the sources of the malfunction (e.g. a temperature rise from 258°C to 305°C at compressor exit). The use of the information of single inefficiencies is therefore helpful to direct to the probable simultaneous inefficiencies that need to be simulated for their fingerprints in order to ultimately pinpoint the sources of the malfunction.

A baseline of single inefficiency fingerprints evolving to multi-inefficiency fingerprints may serve as one possible malfunction identification strategy. The strategy may be called "*Single Inefficiencies* G*uided Strategy*". For a plant of 20 efficiency parameters considering high, medium and low values for load fractions and degrading factors, a baseline of 200 to 250 fingerprints is expected. When a suspicious increase in the plant fuel consumption is noticed at a particular load fraction, the increase is compared with the fingerprints of the nearest simulated load fraction. If the increase is higher than the highest simulated degrading factor, then more than one efficiency parameter is expected to be deteriorating at the same time. Few combined two inefficiencies are simulated to match the increase in fuel consumption. Otherwise a single inefficiency and its degrading factor are likely to be identified with the help of the available pressure and temperature measurements.

It may be noted that as the number of combined inefficiencies increases, one expects weaker degrading factors that would not simulate catastrophic plant failure. For example, convergence failed when using a degrading factor of 0.7 instead of 0.85 for the simultaneous case of Table 4.

It may also be noted that a baseline may be expanded to contain very mild degradations applied to all efficiency parameters to simulate plant ageing with time.

A different approach to handling simultaneous in-efficiencies has been proposed recently by Toffolo and Lazzaretto, 2006. An evolutional optimization approach is sought. The approach minimizes the difference between real measurement and their simulated values by adjusting the degradation factors of the considered parameters.

Obviously, more competitive strategies than the single inefficiencies guided strategy and the evolutional optimization strategy are still needed.

Finally, a major problem with simulating off-design performance from design information is the convergence to a solution. Improved computational algorithms improve the reliability of convergence.

TABLE IV. THE FINGERPRINTS OF 3 SINGLE AND SIMULTANEOUS INEFFICIENCIES AT LOAD FRACTION 0.8 (MULTIPLE-INEFFICIENCY FINGERPRINTS)

Fingerprint	Single Inefficiencies 1 compressor	2 stm trbn	3 feed pmp	Combined Inefficiencies 1 compressor +	2 stm trbn +	3 feed pmp
Considered efficiency	Ad. Eff	Ad. Eff	Ad. Eff	Ad. Eff	Ad. Eff	Ad. Eff
Design efficiency	0.892	0.930	0.940	0.892	0.930	0.940
Efficiency at partload	0.828	0.917	0.899	0.828	0.917	0.899
Degrading factor	0.850	0.850	0.850	0.850	0.850	0.850
Degraded efficiency	0.756	0.793	0.764	0.756	0.793	0.782
FINGERPRINTS						
Device fuel kW, no degrading	4983	2355	18	4983	2355	18
Device fuel kW, degrading	9459	6244	50	9721	6094	48
Device Δ fuel kW	4476	3889	32	4737	3738	30
Device Δ fuel %	90%	165%	172%	95.1%	159%	159%
System fuel kW, no degrading	155994	155994	155994		155994	
System fuel kW, degrading	162281	162589	156047		170639	
System Δfuel in kW	6286	6594	51		14644	
System Δfuel %	4.03%	4.22%	0.03%		9.38%	
Δ first law efficiency	0.0165	0.0173	0.0001		0.0366	
Δ first law efficiency %	3.87%	4.05%	0.03%		8.58%	
Δ second law efficiency	0.0163	0.019	0.0001		0.0382	
Δ second law efficiency %	3.43%	4.00%	0.02%		8.05%	
Pressure kPa and temp C indicators						
P,T off compr,, no degrading	582,258	582,258	582,258		582, 258	
P,T off compr., degrading	652,305	608,260	582,258		695, 312	
Toff gas trbn., no degrading	493	493	493		493	
Toff gas trbn., degrading	472	484	493		462	
Texht gas, no degrading	150	150	150		150	
Texht gas, degrading	155	152	150		158	
Texit clg water, no degrading	35.7	35.7	35.7		35.7	
Texit clg water, degrading	35.4	35.0	35.7		34.7	

6. Conclusion

A baseline of single inefficiency fingerprints evolving to multi-inefficiency fingerprints offers an alternative method to the pinpointing of the sources of inefficiency malfunctions of energy systems. The simulation of the fingerprints that would match or guide to the actual malfunction is fast. However, reaching the matching fingerprints for the case of multiple inefficiencies still needs enhancing.

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