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IMPROVEMENT OF PERFORMANCE PREDICTION BY AUTOMATED ASSIMILATION OF GAS TURBINE COMPONENT MAPS

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ABSTRACT

The performance data of most Siemens heavy-duty gas turbines which have been built in the last 20 years are stored in so-called typefiles. These typefiles contain the description of the thermodynamic operating behavior for each gas turbine type using several component maps, e.g., for the compressor, the turbine and the combustion chamber. In addition to all available high-accuracy performance test results, modern IT technology enables the user to handle a tremendous volume of measured data via remote access. This allows the user to determine and to guarantee the performance of modifications and upgrades with sufficient precision, even for older gas turbine types.

The method for automated generation of typefiles based on the entire volume of available data and its corresponding Matlab® based software solution are the focus of this contribution. Although this method offers a very promising source of data from various sites, the obtainable data sets usually do not cover the entire temperature and rotational speed range that is necessary to create a map suitable for all requisite operating conditions. Thus, theoretically-based additional information combined with special extrapolation methods are necessary.

Keywords: gas turbine, component maps, performance simulation

INTRODUCTION

An essential part of the Siemens Gas Turbine Service Business is the calculation of so-called delta performances that are then used in negotiations. A delta performance is defined as the change in gas turbine performance due to the possible implementation of upgraded hardware, such as new turbine stages or a compressor mass flow increase. The delta performance is often calculated and guaranteed at standard day conditions. Standard day conditions are defined by ISO 2314 and are represented by an ambient humidity of 60%, an ambient pressure of 1013mbar and an ambient temperature of 15°C.

The theoretical performance of a gas turbine before and after the upgrading measure(s) is calculated with KreisPR, a special Siemens proprietary software for simple-cycle GT calculations. In order to simulate the performance as accurately as possible, KreisPR requires two typefiles for the calculation. These typefiles have to describe the operating behavior of the current and the upgraded gas turbine with the highest possible level of detail. Due to the numerous Siemens gas turbine models and upgrade combinations, a large number of typefiles is required. Furthermore, in principle two typefiles would be necessary for comparative testing, i.e., the typefile describing the upgraded gas turbine is used to calculate the new correction curves [2], and the initial typefile would have to be applied to the correction curves for the tests before the upgrade outage.

Since some of the typefiles are quite old, they do not always correspond to current knowledge. An update of the typefile by new performance tests at the test bed in Berlin is not possible because these gas turbine types are no longer built. Using data from performance tests, as presented in [3] constitutes a first attempt to obtain an adequate database for the component map generation, but mostly these data sets are quite small and generally represent only a narrow ambient temperature and load range. In addition, the generation of site-specific component maps is not possible. Therefore the most promising way to update these old typefiles lies in the use of operating performance data. Most Siemens gas turbines are equipped with an operating data recording unit. The operating data sets measured by this system are available on-line. Thus, data sets from sites all over the world can be used for updating typefiles. This paper reports how typefiles can be updated using operational measurements and which extrapolation methods are used. Additionally, several results comparing updated and non updated typefiles are presented.

NOMENCLATURE

eta	[%]	Isentropic efficiency
m	[kg/s]	Mass flow
n	[Hz]	Rotational speed
pi	[-]	Pressure ratio
A	[m^2]	Area
B	[-]	Bernstein polynomial
C	[-]	Bezier function
IGV	[%- Mass flow]	Inlet guide vanes
kEOH	[kh]	Equivalent operating hours
P	[-]	Bezier point
PB	[mbar]	Ambient pressure
PHI	[%]	Ambient relative humidity
R	[kJ/(kgK)]	Gas constant
TEB	[°C]	Ambient temperature
TIT	[°C]	Turbine inlet temperature
TVI	[°C]	Compressor inlet temperature
<u>Subscripts</u>		
i,n,a,b,c		Counter / variables
Data		Data set
Reg		Regression
T		Turbine
V		Compressor
0		Design parameter
I		Inlet
II		Outlet
<u>Superscripts</u>		
*		Reduced / dimensionless variables

TYPEFILE STRUCTURE

A Siemens KreisPR typefile has two main parts. The first part comprises the header data. These are the design parameters of the gas turbine at standard day conditions. Thus, the header data need to be very accurate. The second part consists of several component maps for turbine and compressor such as isentropic efficiency of the turbine (eta_T*) and compressor (eta_V*) or the compressor inlet mass flow (m_{VI}*). These maps are built up using reduced dimensionless variables.

The compressor mass flow map is very well suited as an example of the use of reduced dimensionless variables for the component map generation. As well as the IGV, the parameters TEB, PHI, PB, and n also have a direct influence on the mass flow, so that by using all these variables, the compressor mass flow map would have a very intricate multidimensional structure.

By using the reduced compressor speed [3], (equ. 1), which merges TEB, n, PHI, and PB into a single variable, the compressor mass flow map can be reduced to an easy to handle 3-dimensional map.

$$n_v * = \frac{n_v}{n_{v,0}} \cdot \sqrt{\frac{R_{V,I,0} \cdot T_{V,I,0}}{R_{V,I} \cdot T_{V,I}}} \tag{1}$$

By assuming a constant rotational speed, which is the case if the gas turbine is operated with nominal grid frequency and constant ambient pressure and humidity, the reduced compressor speed can be understood as a substitute for the ambient temperature.

Figure 1 shows the functional dependency between reduced compressor speed and ambient temperature for a gas turbine operated at nominal grid frequency at standard day conditions for ambient pressure and humidity.

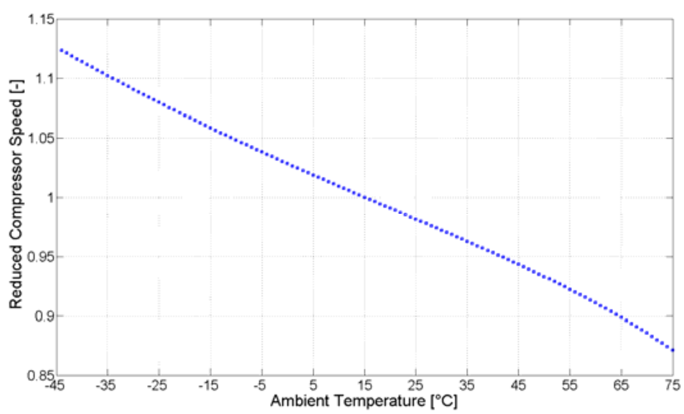

Figure 1: Reduced Compressor Speed vs. TEB

The other reduced variables such as isentropic efficiency or pressure ratio for the compressor and turbine are calculated as ratios using the gas turbine type specific design values and the actual value, as can be seen in equ. (2, 3):

$$pi_v * = \frac{pi_v}{pi_{v,0}} \quad pi_t * = \frac{pi_t}{pi_{t,0}} \tag{2}$$

$$eta_{vi}* = \frac{eta_{vi}}{eta_{vi,0}} \quad eta_{ti}* = \frac{eta_{ti}}{eta_{ti,0}} \tag{3}$$

UPDATING THE HEADER DATA (STEP 1)

When updating a typefile, the header data are the most sensitive aspect, because they constitute the design parameters of the gas turbine. Due to this fact, operating data should not be used exclusively for updating the header data due to the slight inaccuracy of operating instrumentation. Instead, in most cases the fleet analysis database is used for updating the header data. This database is stored in an Excel® worksheet and includes all of the available high-accuracy performance tests for each gas turbine type ever measured. Thus, this database is perfectly suited for generating high-accuracy fleet average performance data. All data points in the fleet analysis have already been converted to standard day conditions for ambient pressure and humidity in order to increase the direct comparability of the measurements.

Figure 2 depicts the main process flow for updating the header data of a typefile. This step (updating header data) constitutes pre-processing for updating the component maps. At first, the old typefile and the corresponding fleet database must be selected using a “pick-a-file” routine. Afterwards, the required measured variables from the fleet analysis are loaded into the program. After the data set has been loaded, a second-order regression determined with least square methods is used to describe the measured data and thus to calculate a theoretical operating point at 15°C ambient temperature. Due to the former conversions in the fleet analysis database, this mathematically-generated point represents a theoretical measurement for an operating point at full standard day conditions.

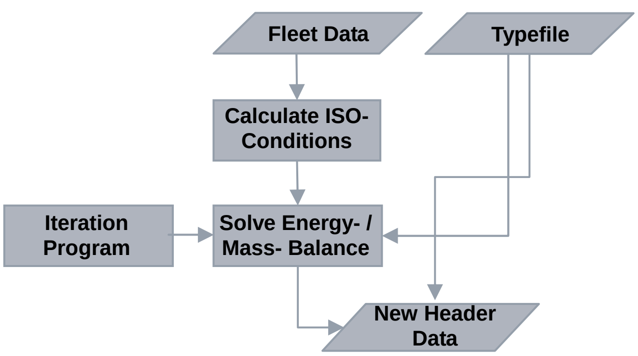

Figure 2: Process Flow for Updating Header Data

Figure 3 depicts the normalized measured generator power output and the applied regression. This regression, describing the blue operating points, is used to calculate the large red theoretical operating point. Each blue dot represents a high-accuracy performance test measurement of a gas turbine while the red dot corresponds to the required full standard day conditions. The high accuracy of the measured data resulting from the narrow scatter bands and the good fit of the applied regression are remarkable.

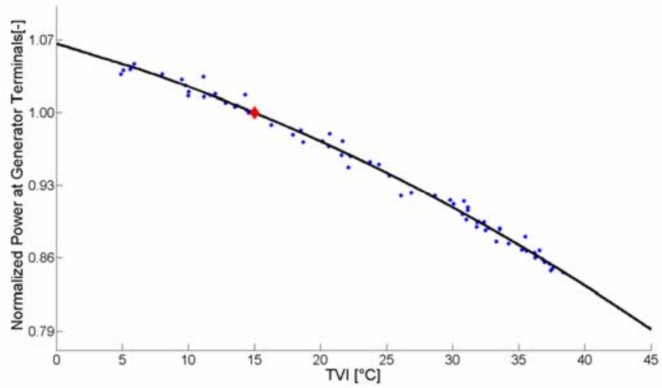

Figure 3: Results from Acceptance Test Measurements

This regression routine is applied for every required parameter. After these calculations have been completed, a set of theoretically-determined high-accuracy parameters for complete standard day conditions is available. These converted parameters represent a complete set of theoretical measurements at full standard day conditions. The next step, which is a subsequent iteration routine, closes the thermodynamic energy and mass flow balance by means of an iterative adjustment of the theoretically-determined parameters to ensure that the mathematically-simulated measurement is thermodynamically correct. Therefore, the pre-processing routine includes the implementation of an interface to a special Siemens iteration program, which in turn is linked to KreisPR. After completing this iteration routine, the adjusted theoretical measurement represents an ideal operating point and is thus perfectly suited for use as header data.

In the final step of pre-processing, the new typefile with the adjusted header data is automatically generated. Furthermore, two standard day conditions base load calculations are calculated by KreisPR using the current and the updated typefile and an overview of the absolute and relative changes yielded in the header data is printed. This entire pre-processing procedure takes only a few minutes.

EVALUATION OF OPERATING DATA (STEP 2)

Nearly every modern Siemens gas turbine is equipped with an operating data monitoring and storing system. This system makes the operating data available on-line within a maximum delay of 24 hours. Due to this, the user is able to handle a tremendous volume of actual operating data on-line via remote access. Thus, these data sets from different sites form the basis for updating the component maps with respect to the latest technical expertise gathered from field experience.

For a high-quality long-term performance analysis, perhaps over a period of several years, some 20 different signals are sufficient. Most of the key signals are implemented redundantly in the data monitoring system to reduce the error rate. These signals must be filtered in order to ensure complete steady-state base load operation. Thus, only slight changes, less than 0.25% in the key signals for 30 minutes, are allowed in order to ensure that the gas turbine has fully warmed up and is in steady-state base load operation. If this is the case, the data sets for these 30 minutes are averaged and afterwards they represent a single measured operating point. After the data have been filtered and averaged in this way for a user-specified time span, in most cases an entire year, the data sets generated in this manner form the basis for the next step. In this subsequent step, the averaged data sets are used as input for KreisPR, which performs a simple-cycle GT calculation to determine the non-measurable variables such as efficiencies for the turbine or compressor. During this step, several conversions are applied in order to, on the one hand, exclude the impact of some variables, and, on the other hand, reduce the complexity of the problem. Therefore, the fuel is converted to methane, pressure losses at the compressor inlet (total) and turbine outlet (static) are corrected to standard values and the TIT is corrected to its design value. The IGV is slightly corrected to its base load setting since this is the most interesting operating point. This correction is necessary due to the small deviations caused by the filter bandwidth.

Of course, the data quality of operating data is below the data quality obtained from acceptance test equipment. For example the standard deviation for power output measured with operating instrumentation is about 0.35%. This minor deficiency in measuring accuracy is offset by the wide load range covered by measurements performed during a year using operating instrumentation.

Due to special boundary conditions relating to plant configuration, the data validation and therefore the results from simple-cycle or multi-shaft combined-cycle sites are more reliable than single-shaft combined-cycle sites. Therefore, combined-cycle single-shaft sites require further evaluation steps which are not explained in detail in this paper for the sake of brevity.

If the evaluation range covers an entire year, which is the optimal time span for most applications, the degradation of the turbine is easy to handle because seasonal deviations only have a minor impact. Consequently, the turbine degradation can easily be corrected within the program by a detrend algorithm. Compressor fouling is more difficult to handle, because the seasonal impact on compressor performance is hypostatic by compressor washing events. Thus, a simple detrend algorithm has no effect here. Therefore, the best approach in terms of data quality, is to take only those data sets into account which were recorded shortly after a compressor washing event.

The correction of degradation effects is necessary because it is important to ensure that no time-dependent trends are detectable for the parameters depicted in the component maps in order to obtain high-quality component maps that represent the "new and clean" operating behavior of the gas turbine.

So far, for a sufficient update of a typefile, up to five different sites can be simultaneously evaluated within this routine. When enough data sets have been obtained and prepared, optimization of the typefile component maps can be started.

COMPONENT MAP GENERATION (STEP3)

The main process flow for updating a single typefile using operating data from different sites is shown in figure 4.

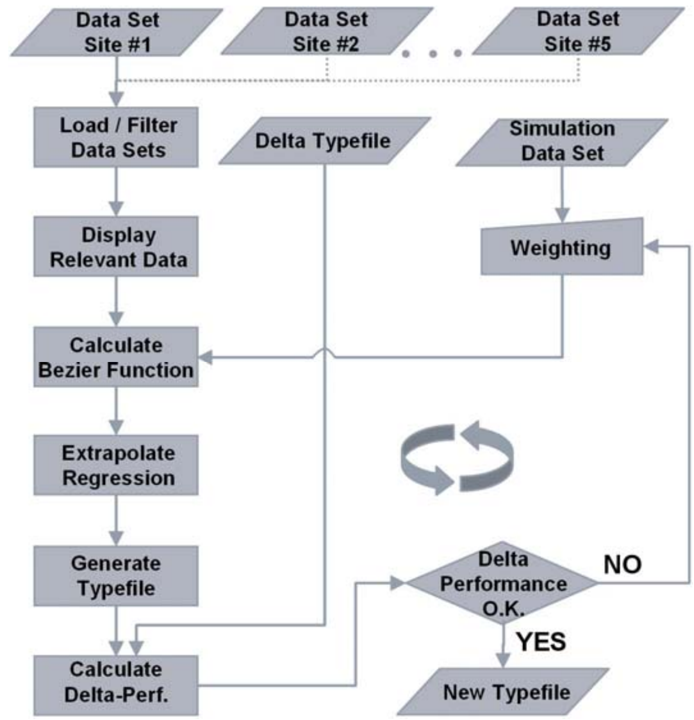

Figure 4: Process Flow for Map Generation

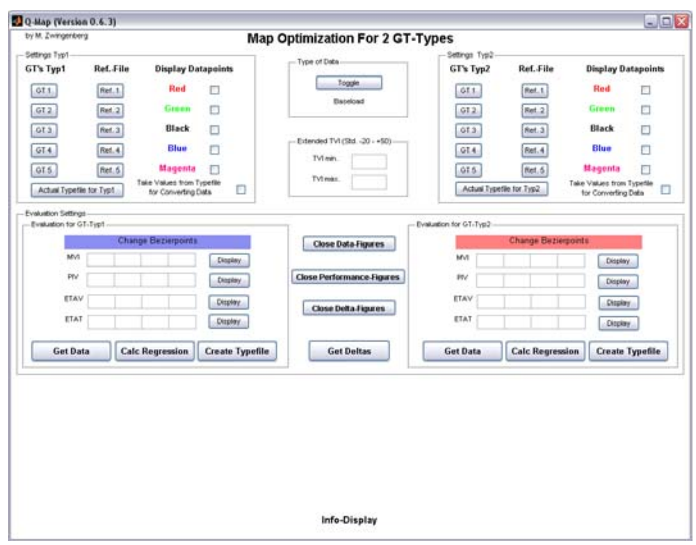

Figure 5: GUI for Dual Typefile Updating

The GUI (fig. 5) used for generating the component maps is subdivided into three main parts. The upper third of the GUI contains all the control buttons for finding and loading the required data sets via “pick-a-file” routines. These data sets include up to five different long-term operating data evaluations, the corresponding performance test results and the current (to be updated) typefile.

The middle third of the GUI unites the control buttons for the four main functionalities and the optimization input fields. The lower third of the GUI is reserved for displaying the numeric results of the regression calculations. Since the program was developed at the thermodynamic service department, the primary objective of this program is to update and optimize the delta performance. Therefore it must be possible to update two typefiles simultaneously. Thus, the program has a dual structure: the left part of the GUI is for one GT type and the right part is reserved for another GT type. Of course, it is also possible to update a single typefile by using just one side of the GUI.

LOADING THE DATA (STEP3A)

The evaluation input data must be stored in an Excel® worksheet. The files can be picked in a dialog window to reduce application errors caused by typing errors. The data is stored in an Excel® worksheet because this allows further evaluations with more commonly used software; this means that no Matlab®-specific dataset must be generated.

After reading the evaluation data from the Excel® worksheets, the absolute values of the required variables are converted to reduced thermodynamic variables to eliminate various influencing parameters such as ambient pressure or ambient relative humidity. For these conversions, the results of the site-specific high-quality performance tests are required to perform the conversion to the individual design point for each gas turbine while calculating the reduced thermodynamic variables. The use of individual performance tests for this step eliminates minor differences in design point performance.

If no specific performance test measurements are available, conversion can be performed using the design point which is stored in the typefile. When doing this, the site specific operating performance deviations cannot be reduced, but it is a good opportunity to compare different sites to the values in the typefile in terms of degradation effects.

As the values have already been corrected to the same reference conditions, an ideal curve would be a horizontal line. Due to aging [4], measurement and correction uncertainties, scatter bands occur. To eliminate the degradation effect, as next step, a linear detrend function is applied to the turbine efficiency. Figure 6 shows the effect of the detrending for an entire year with an extended scale for the ordinate. The blue circles represent the original turbine efficiency whereas the green plus signs represent the detrended turbine efficiency.

The detrended data are shifted to the mean value of the non-detrended data. In most cases, degradation is below 0.1%-pt. during a given year and thus within a narrow range that can be neglected. When detrending the data, one must bear in mind that the absolute value is represented by the header data. So in this step, only the progression of the data is of interest and so there is no problem in shifting the detrended data to the mean value of the original data.

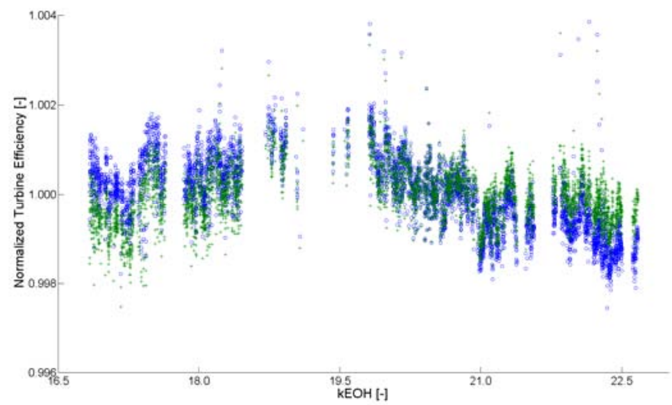

Figure 6: Detrended Turbine Efficiency

Despite the conversion of the performance data to the site-specific design operating point and although the data sets from various sites all represent the same gas turbine type, there are still some minor differences in operating performance. If these differences are not consolidated, the measured data point distribution of the various sites will have a major impact on the regression function applied later. Due to this fact, consolidation of the data sets is necessary. Consolidation is performed by a special filter function (see equ. 4). The main reason for using this function is the elimination of extreme data points of the dataset with length n, which the user may have inadvertently not removed. For this reason, the key advantage of this filter function is that the sparsely occupied peripheral areas of the data sets have greater influence on this regression function than by using a normal regression of second order.

$$F_{\mathrm{Reg}}(x_i) = \frac{A_{DATA}}{(x_n - x_i)} + b \cdot \left(x_i - \frac{x_n + x_1}{2} \right) + \\ + c \cdot \left(x_i^2 - \frac{x_n^2 + x_n x_1 + x_1^2}{3} \right) \quad (4)$$

This is achieved by calculating the area below the data points after the data set has been sorted, and taking this area into account as an additional constraint to the regression function. Thus, this function (Equ. 4) ensures that the peripheral data points are not filtered due to poor performance of the regression at the peripheral areas. Depending on the quality of the data sets, the user can choose the percentile filter effectiveness during the procedure. Once this function has been developed within the program, it can also be used for consolidation. This means that the data sets are consolidated to the mean value of all data sets at design point regarding the reduced compressor or turbine speed.

As the final step of this subfunction, the data sets for isentropic compressor, turbine efficiency, compressor mass flow and compressor pressure ratio are displayed for information purposes. At this stage, the user is able to readily compare various sites using the check boxes in the upper third of the main control GUI.

CALCULATING THE REGRESSION (STEP3B)

The function used for calculating the regression is of third order and is displayed in an equidistant four point Bernstein-Bezier representation, as shown in equ. (5):

$$C(t) = \sum_{i=0}^{n} P_i \cdot B_{i,n}(t) \qquad (5)$$

The function stated here consists of four Bezier Points P_i weighted by four corresponding Bernstein Polynomials $B_{i,n}$. Equ. (6) states the definition of a Bernstein polynomial for the standard case.

$$B_{i,n}(t) = \sum_{i=0}^{n} \binom{n}{i} \cdot t^i \cdot (1-t)^{n-1} \quad t \in [0,1] \qquad (6)$$

Since the standard Bernstein polynomials (equ. 6) are only defined for the interval from zero to one, they must be linearly transformed to the required interval [a b]. In most cases this interval is similarly fixed for all typefiles and represents the most common temperature ranges for all sites. An unnecessary increase in the [a b] interval would lead to a reduced regression performance, therefore the [a b] interval should be as small as possible and only as wide as necessary.

$$B_{i,n}(t) = \binom{n}{i} \cdot \frac{1}{(b-a)^n} \cdot (t-a)^i \cdot (b-t)^{n-i} \qquad (7)$$

One of the great advantages of the Bernstein-Bezier-Representation takes place during the calculation of the derivations. The first and second derivations are used to express some physical implausibilities by mathematical constraints. Thus the first and second derivation can be calculated simply by means of knowledge on the position of the four Bezier points. For example, as long as the second Bezier point is above the straight line from Bezier point 1 to Bezier point 3 the second derivation in Bezier point 1 is less than zero. Another important attribute is that the first and the last Bezier point are hit directly whereas the Bezier points between them are weighting points which are not hit directly in most cases.

Figure 7 shows two one-year evaluations of compressor efficiency for one gas turbine type after conversion to reduced thermodynamic variables and consolidation of the data sets. Besides the data points, the corresponding black Bernstein-Bezier curve and the four connected red Bezier points are also displayed.

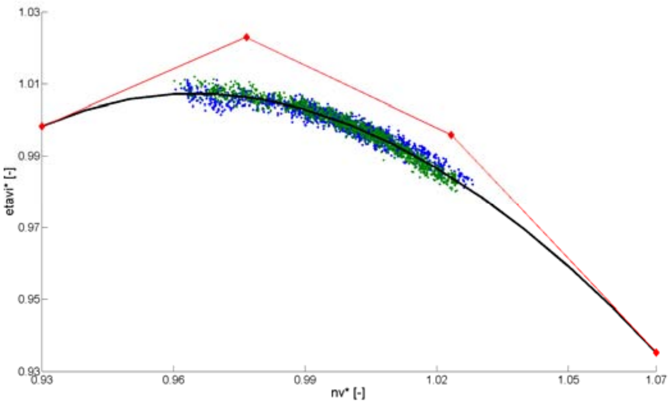

Figure 7: Bezier Curve for Compressor Efficiency

Each relevant parameter such as eta_T*, eta_V*, m_{VI}*, pi_V* is displayed in a similar manner. Up to this point, extrapolation of the data sets only takes place in line with mathematical constraints. To optimize the quality of the extrapolation, the user is enabled due to the controls in the middle third of the GUI to manually manipulate the regression function by shifting the Bezier points along the ordinate. At this point the high user-friendliness of the function afforded by the Bernstein-Bezier representation becomes evident. This makes it possible to input knowledge from simulation tools for the turbine or compressor into the operating data sets by appropriate weighting. If the distribution of the operating data, the simulated data, and the peculiarities of the Bernstein-Bezier curve are known, the user can readily adapt the regression function to the comprehensive knowledge for particular gas turbine types and by doing this, harmonize all available knowledge and thus generate high-quality typefiles.

Because data filtering and complexity reduction steps were performed previously, the compressor operating behavior can be displayed in a two-dimensional manner, for example. This is ideal for user-friendly depiction of the most interesting curves, but for the typefile in combination with KreisPR, the complete 4-dimensional map is required. Therefore, certain extrapolation methods must be applied. Consideration of the following topics can reduce risks associated with extrapolation from a 2-dimensional curve to a 4-dimensional function.

The typefiles are primarily generated for delta performance calculations. Usually these performance calculations are for base load versus the ambient temperature, which is the case for two-dimensional depiction. Consequently, a superior quality can be ensured in such cases.

The second factor is the operating behavior of a modern gas turbine. Figure 8 is a schematic view of a compressor efficiency map.

It is obvious that the compressor is operated within a relatively narrow range, hence the extrapolation routines for

IGV and pi_V* must only be valid and superior in quality for this narrow range. The outer regions also have to be covered, but they are less frequently used in daily business, and thus extrapolation is acceptable for these ranges.

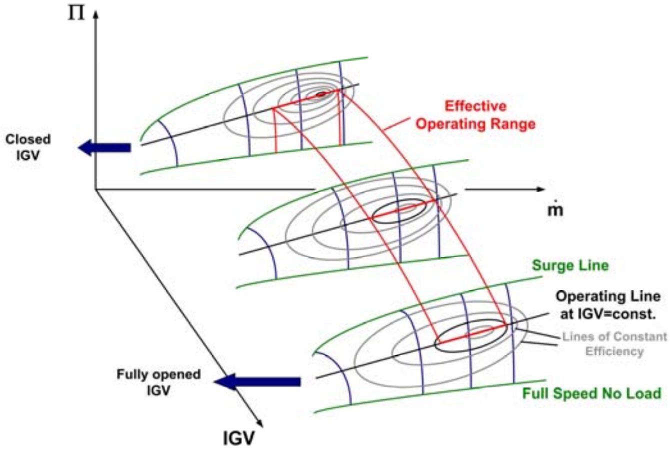

Figure 8: Generic Compressor Map

In order to ensure a high quality extrapolation even for these areas of minor interest, polynomial models are used for eta_T*, eta_V*, m_{VI}*, and pi_V*. These polynomial models can be adapted to the results of the simulation tools, test bed performance test or operational part load data. After they have been developed they can be integrated into the main program. Consequently, one has to develop and implement several new polynomial models at this point when evaluating a gas turbine type for the first time. After completing this step, the program allows the user to select the correct extrapolation polynomial for a specific gas turbine type. In most cases a 4-dimensional polynomial model with 27 parameters is used for compressor efficiency. For the turbine efficiency polynomial, by contrast, a 3-dimensional polynomial with 9 parameters is typically used.

These model polynomials are adapted to the new base load operation Bezier function yielded by the former steps, using both operating data and theoretical knowledge. The result can be seen in Figure 9. In this figure, the blue dotted lines represent the portions of the polynomial model, the solid green line represents the combination of the eta_V* vs. n_V* and the pi_V* vs. n_V* regressions that have been shifted to the design point. The solid red lines represent the portions of the polynomial model adjusted to the green line. The polynomials are only displayed as extracted lines in the interest of clarity. This adapted polynomial for base load IGV is the basis for subsequent extrapolation of eta_V* in the IGV direction. This extrapolation uses relative changes in efficiency correlated with the IGV position and is applied to the polynomial for eta_V* adapted in the former step at base load IGV. The extrapolation for pi_V*, m_V*, and eta_T* is performed similarly to the extrapolation in pi_V*-direction for eta_V*.

After applying these extrapolation routines, the new typefile with updated header data and optimized component maps is stored.

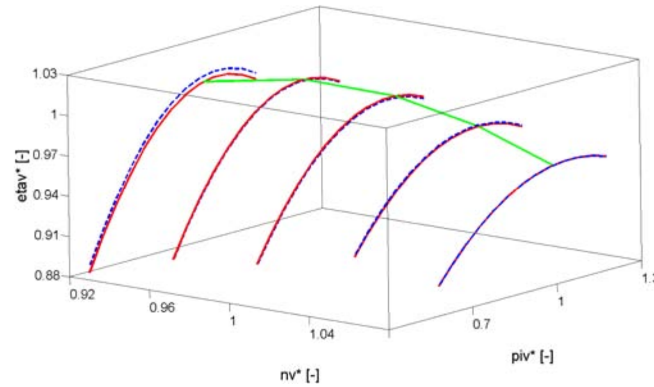

Figure 9: pi_V* Extrapolation

OPTIMIZATION STEPS AND RESULTS (STEP 4)

Since the main objective of the program is an optimized delta performance, the first check after generation of the typefile is to calculate and display the old and the optimized delta performances for the components and the guarantee data. For this reason, the main program is able to control KreisPR. When the calculation is completed, possible discontinuities in the newly-generated typefiles can be readily detected.

As can be seen in figure 10, the red dotted (□) line represents a nearly perfect delta performance, which means that both typefiles were extrapolated very well, whereas the blue dotted (○) line is an example of a poor extrapolation with regards to the extreme low and high temperatures. The temperature range between 5°C and 35°C is covered in both cases by operating data measurements. Thus, in terms of this range the agreement for the red and blue dotted line is very good, but the extrapolation of the blue line exhibits quite poor quality and, especially for temperatures higher than 40°C, an implausible trend.

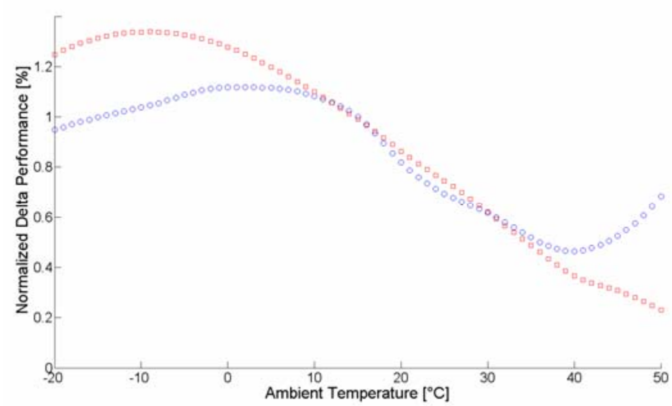

Figure 10: Delta Performance Comparison

In the event that a delta performance such as the blue line was generated after the first optimization step, it is obvious that weighting of operating data and theoretical data must be optimized, especially at high temperatures. If all steps have been performed properly and the latest information and technology have been implemented, the delta performance prediction in the test cases can be significantly improved by more than 20%. This applies especially at low ambient temperatures.

TYPEFILE CHECK (STEP5)

Since the old typefile was used for the evaluation and the conversion to standard day conditions of the operating data, there might be some impact due to the old component maps. In most cases, the impact of the old maps is negligible but it may nonetheless be necessary to launch an iteration process. In such cases, the operating data sets must be reevaluated, using the updated typefile.

To reliably detect possible disharmonies between operating data and the newly generated typefile before a possible subsequent iteration process is launched, the optimized typefile is used for converting the operating data to full standard day conditions, which implies a constant ambient temperature of 15°C. After this step, the values which are relevant for component maps are displayed versus the measured ambient temperature. Since the data set is converted to a constant ambient temperature, no temperature-dependent trend should be detectable and thus the result should be a horizontal line in the ideal case.

Figure 11 shows the normalized compressor mass flow, converted to standard day conditions. The oscillation of the data points can be traced to a phenomenon which is typical for least squares regression functions. If the data could not be described entirely by the regression function, the function is applied to the data set such that the deviation between data points and function begins oscillating around the data points. Applying this knowledge to Figure 11, one can see that in this case, no temperature-dependent trend is detectable and the oscillation which can be seen is a normal regression phenomenon. Furthermore, this oscillation is negligible in terms of its amplitude, so that for this case the compressor mass flow map is now sufficiently adapted.

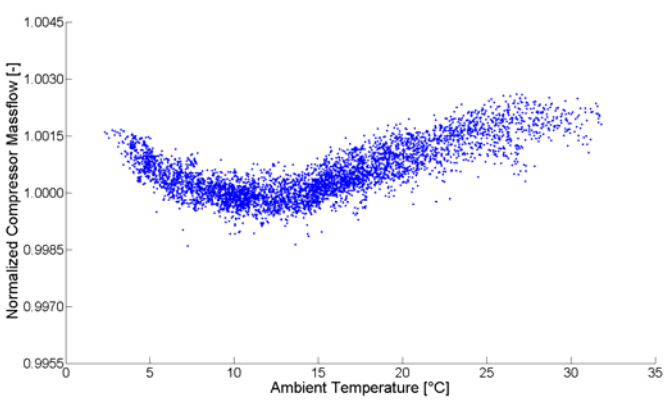

Figure 11: Compressor Mass Flow Check

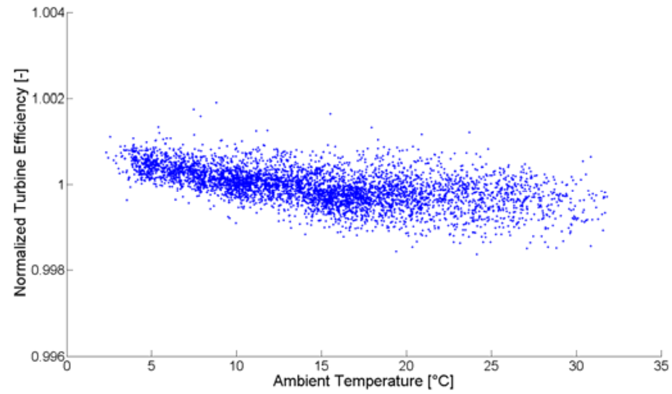

Figure 12: Turbine Efficiency Check

Figure 12 differs strongly from figure 11. The maximum deviation for the normalized turbine efficiency lies within the range of the normalized compressor mass flow, but in this case a linear ambient temperature trend is detectable. Although the absolute deviation is quite small, the extrapolated deviation approaches the extent that is too large to be tolerated. With regard to these facts, in this case optimization of the turbine component map was less than optimal and needs to be repeated.

Before starting the optional iteration process which excludes the impact of the old typefile in the first evaluation step, this conversion method provides an excellent opportunity to quickly check the quality of the component maps generated. This iteration process is normally only necessary if great deviations between old and new typefiles occurred. Despite all these checks, one must bear in mind that the component maps are not adjusted to one single site. Therefore, minor deviations are unavoidable and this leads to a narrow scatter band for the data sets of various sites.

GENERATING PART LOAD TURBINE MAPS

A procedure has been developed for updating the 3-dimensional turbine efficiency map without the requirements for polynomial models for extrapolation for cases in which sufficient part load operating data are obtainable for steady-state operating points. This procedure requires the basic typefile and an Excel® worksheet containing the reduced dimensionless base and part load data points for the turbine map as input. In fact, this procedure does not correct the degradation of the turbine efficiency, which means that this correction must be performed manually, if possible.

This procedure fits a surface to the data points, shifts the surface to the ideal operating point and generates the new typefile with the optimized turbine efficiency map. Additionally, some statistical information about the data set and the quality of the regression are stored in an Excel® worksheet for further information. The surface is represented using an equidistant Bernstein-Bezier function, equ. (8), with 16 (4x4) Bezier points, constrained by 36 mathematical boundaries to avoid physical impossibilities in the surface progression. The

Bernstein Polynomials have been linearly transformed to the required intervals for pi_T* and n_T* in accordance with equ. (7).

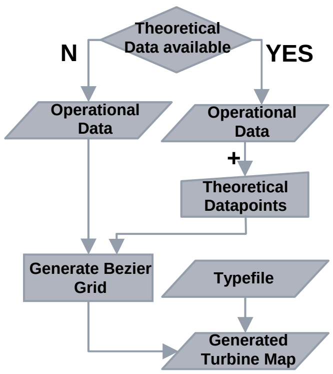

Figure 13: Process Flow for Updating Turbine Map

$$C(u,v)=\sum_{i=0}^{n}\sum_{j=0}^{m}B_{i,n}(u)\cdot B_{j,m}(v)\cdot P_{ij} \qquad (8)$$

Figure 14 shows the result for some exemplary data without the input of additional theoretical knowledge. The black fine-grid surface represents the calculated turbine map, whereas the 4x4 grid represents the equidistant Bezier grid which defines the form of the fine-grid surface.

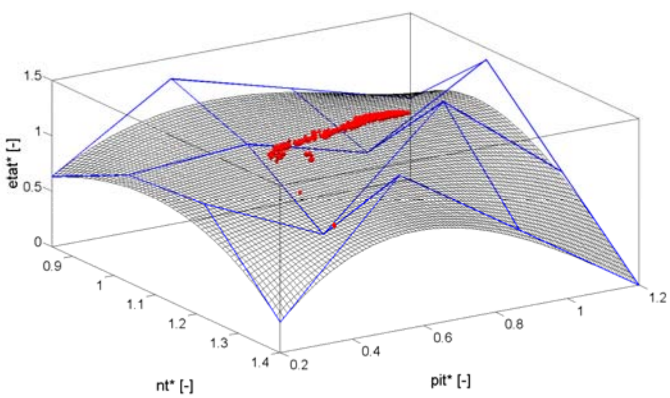

Figure 14: Bezier Grid without Additional Data Points

It is obvious that the main operating area of a gas turbine is described very well with only little optimization potential, whereas the edge points, where no Siemens gas turbine will ever be operated, e.g., for pi_T*=1.2 and n_T*=1.4, the turbine map becomes implausible and needs to be optimized to minimize error potential even in regions of the turbine map that are far from the design point.

For this reason, the procedure offers the possibility to add four theoretically-determined data points. In practice, two or three data points near the most interesting edges of the map provide sufficient results. In Figure 15, the same routine was applied to identical operating data points, however three theoretical data points were added this time. Thus, the quality of the regression was reduced by 0.05% but the overall performance is now much more plausible. Thanks to effective simulation tools in combination with operating data evaluation, it is possible to generate high-quality turbine efficiency component maps even for part load data.

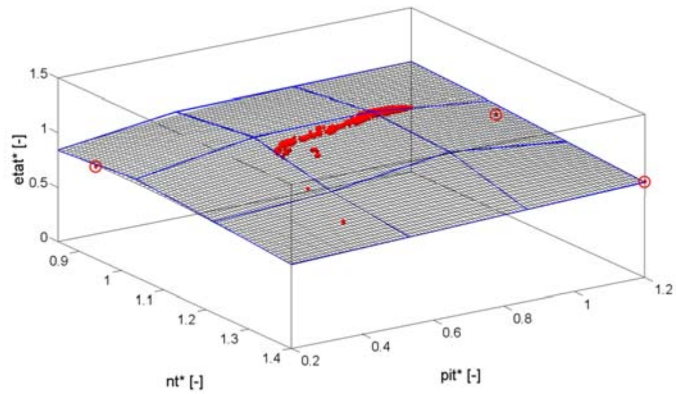

Figure 15: Bezier-Grid with Additional Data Points

In order to visualize the quality of the regression, the operating data (blue dots) and the corresponding theoretical values (red dots) have been projected to the eta_T*-pi_T* plane (fig. 16). Due to projection, the regression and the associated data points seem to smear slightly, but despite this smearing effect, the overall performance of the generated turbine map compared to the operating data is quite good.

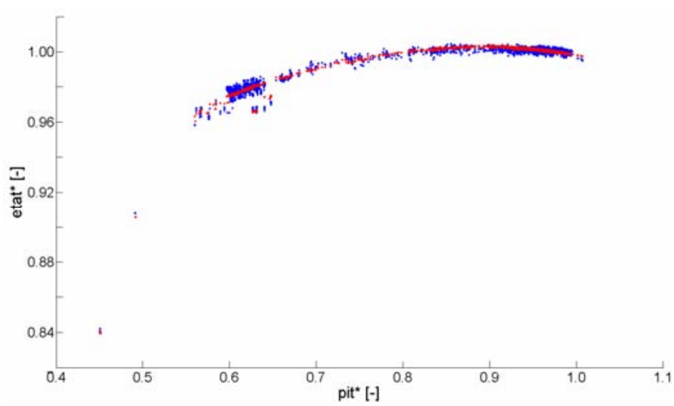

Figure 16: Projection of the generated Turbine Map

CONCLUSION

The benefit of using component maps for performance prediction and component map generation using fleet analysis data from acceptance tests was presented previously in [3]. Building on this, the present paper reports on the use of operating data for map generation, process details of map generation using operating data and the tool which has been developed to handle this great volume of data. In addition, the tool developed is able to update typefiles simultaneously in terms of optimized delta performance. Thus, a control loop for performing the unavoidable extrapolations using parameter delta performance has been implemented at this point.

For updating the design data of a typefile, the combination of existing high-quality acceptance test measurements and the application of several regression functions is used with constraint by certain mathematical boundaries and supported by a thermodynamic iteration program. This results in minimal computing time and trims costs through avoidance of additional tests in a user-friendly GUI-based program environment.

Fast and easy-to-handle component map assimilation methods that use operating data enable the user to quickly respond to the latest field expertise and thus to predict performance at a high level of accuracy. Therefore, the advantages of using operating data for component map improvement have been demonstrated, especially regarding delta performance optimization.

Due to the limited measuring range using operating data, certain extrapolation methods must be applied to generate a fully usable component map. The usage of the combination of Bernstein-Bezier curves and polynomial models supported by numeric simulation tools has proven to be a very efficient and controllable way to perform extrapolations, if some basic knowledge already exists and only steady-state base load data are obtainable.

In the event that no additional knowledge is available for creation of polynomial models for the turbine efficiency map, the use of steady-state part load data is mandatory. Due to the great degree of freedom of the Bernstein-Bezier surface used here, even the use of 36 constraining equations is not sufficient for suppressing implausible solutions. To alleviate this situation, a small number of additional numerically-simulated data points have been implemented in the outer regions of the map. This has yielded very good results.

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