# Quality engineering of a traction alternator by robust design

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**Abstract:** Robust design is an engineering methodology for improving productivity during research and development so that high-quality products can be developed and produced quickly and at low cost. A large electrical company was developing traction alternators for a diesel electrical engine. Customer requirement was to obtain very high efficiency which, in turn, was influenced by several design parameters. The usual approach of the 'design–build–test' cycle was considered time-consuming and costly; it used to take anywhere from 4 months to 1 year before finalizing the product design parameters as it involved physical assembly and also testing. Instead, the authors used Taguchi's parameter design approach. This approach took about 8 weeks to arrive at optimum design parameter values; clearly demonstrating the cutting edge of this methodology over the traditional design–build–test approach. The prototype built and tested accordingly gave satisfactory overall performance, meeting and even exceeding customer requirements.

**Keywords:** factor, level, response, quality engineering, parameter design, robust design, noise factors, signal-to-noise ratio

## 1 THE PRODUCT: ALTERNATOR

Alternators, also known as alternating current (a.c.) generators (Fig. 1), operate on the fundamental principle of electromagnetic induction to convert mechanical energy into a.c. electrical energy. The standard construction consists of armature windings mounted on a stationary element called a stator (Fig. 2) and field windings on a rotating element called a rotor. The stator consists of a cast iron frame, which supports the laminated armature core having slots on its periphery for housing the three-phase winding. The rotor is like a flywheel, and has a large number of alternate north and south poles bolted to it. The magnetic wheel is made of cast iron or steel of good magnetic quality. In the alternator, the rotor uses current supplied through slip rings to generate a moving field. Power is extracted from the stationary field coils. The dimensions of stator, rotor, pole, and air gap between rotor and stator impact the value of efficiency of the alternator.

## 2 CUSTOMER REQUIREMENTS

The customer for this product had specified overall performance measures for the alternator in terms of different functional parameters in which efficiency was the most important (see Table 1). The efficiency of an alternator is defined as the ratio of the watts available in the load circuit to the mechanical power supplied. The specification for efficiency was given as minimum 90 per cent, whereas the current product was giving an efficiency of about 65 to 74 per cent, which was leading to customer complaints. The company perceived this as a threat of losing their market in the future to competitors, who could claim an efficiency of at least 90 per cent. The issue with the design department was to arrive at the best parameter values so as to achieve the customer requirements in the shortest possible time.

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## 3   THE CLASSICAL APPROACH

While designing a product, the objective of the design engineer is to maximize the performance of the product and reduce the variability in performance from product to product. The methods like 'design–build–test' and 'optimization' do not deal with the reduction of variability in performance and do not directly give information regarding the contribution of each component to performance. Parameter design – a technique developed by Dr G. Taguchi of Japan – aims at maximizing the performance values of any product, while simultaneously reducing the variability in performance. Hence this approach of robustness in design was adopted in the present study.

## 4   THE TAGUCHI METHODOLOGY

Taguchi proposed a three-step strategy for the development of products. The steps are system design, parameter design, and tolerance design, with an emphasis on the use of experimental methods in the latter two steps. In 1979, Taguchi's ideas were translated in a publication [1] that was followed by many others on the subject (see e.g. references [2] to [4]).

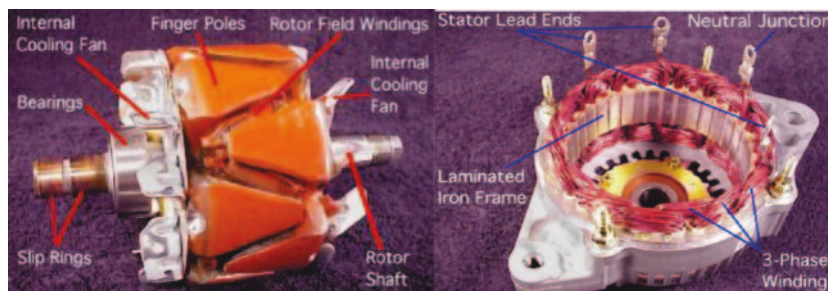The papers by Hunter [5] and Kackar [6] explain the essence of Taguchi's ideas in an understandable and comprehensive manner. In the late 1980s and beginning of the 1990s, there was discussion on the appropriateness of the statistical methods proposed by Taguchi. Publications contributing to this discussion were those of Léon *et al.* [7], Box *et al.* [8], Shainin and Shainin [9], Welch *et al.* [10], Shoemaker *et al.* [11], Box and Jones [12], Nair [13], Lucas [14], and Grize [15]. There are fewer publications that focus mainly on non-statistical issues such as principles, procedures, and objectives.

### 4.1   Taguchi's three-step procedure

The design process described in Taguchi and Wu [1] and Taguchi [2] is strongly associated with the concept of quality engineering (see e.g. reference [16]). According to the description in Taguchi [2], system design is the stage in which different concepts and choices of technology are considered at different levels, e.g. the system level and the component level. The aim in parameter design is to decide on appropriate levels of individual system parameters. What is an appropriate level for a parameter or an appropriate combination of parameter levels is determined by what reduces the effect of noise on the output characteristic. Finally, in the last step, tolerances are set in a way that further minimizes the effect of noise, e.g. narrower tolerances for noise factors that have the greatest influence. Taguchi [2] emphasizes, however, that this is not the most efficient way to reduce variation caused by noise and that it should be seen as a last resort after parameter design.

The core of Taguchi's parameter design is based on experimental methods. Since the beginning of the 1980s there has been ongoing research to suggest alternatives and improvements of the methods he



**Fig. 1**   The alternator

**Table 1**   Values of functional requirements

| Sl. no. | Characteristic | Requirement |
| --- | --- | --- |
| 1 | Efficiency | Min. 90% |
| 2 | Air gap flux density | Min. 0.63 |
| 3 | Full load field current | Max. 31.00 |
| 4 | Transient voltage dip | Max. 30.00 |
| 5 | Short circuit field current | Max. 21.70 |



**Fig. 2**   Exploded view of the rotor (left) and stator (right)

proposed. Useful references to obtain a picture of the current status of robust parameter design (RPD) are Wu and Hamada [17], Myers and Montgomery [18], Robinson *et al.* [19], and Myers *et al.* [20].

The Taguchi method relies on crossed array designs that require a large number of runs. These designs are intended for estimating interactions between control and noise factors [11, 18].

Robust design makes heavy use of orthogonal arrays, whose use for planning experiments was first proposed by Rao [21]. Orthogonal arrays are useful for studying a large number of decision variables in a small number of experiments.

The basic idea of RPD experiments is to vary control factors and noise factors in the same experiment and seek possible control–noise factor interactions. The combined array approach suggested by Welch *et al.* [10] and Shoemaker *et al.* [11] includes noise factors and control factors in the same design matrix, which often results in cost-efficient experiments.

### 4.2 Different approaches to analysis

An important concept in the Taguchi method is the signal-to-noise (S/N) ratio. The S/N ratio is one of Taguchi's techniques that allows analysis which takes into account the variability caused by a factor or independent variable. In conventional statistics, factors are usually analysed to determine their effect on the mean performance of some quality characteristic or functional parameter. The Taguchi method demonstrates, however, that some factors have an effect on changing the mean, while others have an effect on changing the variability. The role of factors affecting variability is simply missed by conventional experimental methods.

Thus robust design methodology means systematic efforts to achieve insensitivity to noise factors. These efforts are founded on an awareness of variation and can be applied in all stages of product design. An application of parameter design is discussed here.

## 5 EFFICIENCY IMPROVEMENT OF THE TRACTION ALTERNATOR

### 5.1 Selection of factors and levels

After a series of brainstorming sessions, 13 control factors (components) that influence efficiency were selected. In order to identify the best value of each factor (component), it was decided to vary each factor at three levels. In quality engineering it is recommended to select three levels for each factor unless it is known to be linearly related with the response. (Two levels may be adequate in such cases.) Table 2 gives a list of the control factors selected and the corresponding levels of each factor.

In order to consider the effect of inner noise, Taguchi recommends identification of two levels: one above and the other below the existing level for experimentation. During a series of meetings with the design and manufacturing team, four factors each at three levels were selected as noise factors, and levels of the noise factors were chosen with ±5 per cent variation from the nominal value based on the knowledge and experience of the designers. Table 3 gives the list of noise factors and their respective levels.

### 5.2 Conduct of the study

A robust design is a product or process design that performs consistently as intended, under a wide range of noise conditions, throughout its life cycle. The three major sources of noises that affect the performance of the product are: inner noise, outer noise (customer usage conditions), and product-to-product variation. Inner noise was taken into account by considering the noise factors during the

**Table 2** Different control factors and their levels

| Sl. no. | Control factor | Code | Level (in mm) | | |
|---|---|---|---|---|---|
| | | | 1 | 2 | 3 |
| 1 | Stator o.d. | A | 740 | 730 | 720 |
| 2 | Stator i.d. | B | 575 | 565 | 555 |
| 3 | Stator core length | C | 320 | 310 | 300 |
| 4 | Coil span | D | 4 | 5 | 6 |
| 5 | Slot width | E | 17.5 | 16.5 | 15.5 |
| 6 | Slot height | F | 38 | 36 | 34 |
| 7 | Rotor i.d. | G | 395 | 385 | 375 |
| 8 | Pole length | H | 345 | 335 | 325 |
| 9 | Pole body width | I | 93 | 90 | 87 |
| 10 | Pole shoe width | J | 166 | 162 | 158 |
| 11 | Pole shoe height | K | 27 | 25 | 23 |
| 12 | Min. air gap | L | 3.5 | 3 | 2.5 |
| 13 | Max. air gap | M | 5.0 | 4.5 | 4.0 |

**Table 3** Noise factors and their levels

| Control factor level | Noise factor | Level | | |
|---|---|---|---|---|
| | | +5% | Nominal value | −5% |
| 1 | Stator core length | 336 | 320 | 304 |
| | Pole length | 362 | 345 | 328 |
| | Min. air gap | 3.67 | 3.5 | 3.32 |
| | Max. air gap | 5.25 | 5.0 | 4.75 |
| 2 | Stator core length | 325 | 310 | 295 |
| | Pole length | 352 | 335 | 318 |
| | Min. air gap | 3.15 | 3.0 | 2.85 |
| | Max. air gap | 4.72 | 4.5 | 4.27 |
| 3 | Stator core length | 315 | 300 | 285 |
| | Pole length | 341 | 325 | 309 |
| | Min. air gap | 2.62 | 2.5 | 2.37 |
| | Max. air gap | 4.2 | 4.0 | 3.8 |

design stage. The outer noises were chosen by considering different customer usage conditions like variable voltage and variable frequency. For this purpose it was decided to try four combinations of voltage and current: (440 KVA, 220 V), (440 KVA, 627 V), (525 KVA, 540 V), and (525 KVA, 384 V). The product-to-product variation could be considered only during the manufacturing stage and hence was not studied. The response of the experiment was taken as the efficiency of the alternator.

The 13 control factors were allocated in an orthogonal array (OA) table $L_{36}$ ($2^3 \times 3^{13}$) called the inner array. The $L_{36}$ array was preferred (no interactions were considered for estimation by the management) to other three-level OA designs in view of its superiority in estimation of main effects. Interactions between any two columns of this array are confounded with the remaining columns, thus making this array fit for main effect estimation only [3]. Thus there were 36 combinations of control factors. The noise factors were allocated in an OA table $L_9$ ($3^4$) called the outer array. For each combination in the inner array there were nine combinations in the outer array. Thus there were $36 \times 9 = 324$ experimental combinations. Each of these 324 combinations was evaluated at four combinations of voltage and current. Thus the total number of simulations became $324 \times 4 = 1296$.

For conducting the experiment through computer simulation, a program was made with the transfer function. (The transfer function is confidential to the company, so it is not disclosed here.) The transfer function is a mathematical model mapping the input variables considered in the study with the output variable: efficiency of the alternator. An Excel program was prepared for the transfer function. The responses were obtained by running the program for various values of the parameters, as per the master plan of the experiment given in Fig. 3.

### 5.3 Analysis and conclusions

As the aim of the study was to improve the efficiency of the traction alternator and simultaneously minimize its variation, it was necessary to account for the variation in the performance characteristics for each combination of control factors in $L_{36}$ over the range of noise factors considered in $L_9$. This was achieved by expressing these varying data in a single measure, the S/N ratio. The S/N ratio measures the level of performance and the effect of noise factors on performance. The higher this ratio, the more the system is doing what it is intended to do regardless of noise factors. The S/N ratio formula for 'higher the better' (HB) response assumes the characteristics can take any value up to infinity, whereas in this case the upper limit on efficiency was 100 per cent. Thus the HB S/N ratio formula was not suitable. Hence, the S/N ratio formula for 'lower the better' (LB) type of characteristics was used

$$\text{LB}: \quad \text{S/N} = -10\log_{10}\left(\frac{1}{n}\sum x_i^2\right)$$

| Outer array (noise factors) | | | | |
|---|---|---|---|---|
| Sl. no. | 1 | 2 | 3 | 4 |
| 1 | | | | |
| 2 | | | | |
| 3 | | | | |
| . | | | | |
| . | | | | |
| . | | | | |
| 8 | | | | |
| 9 | | | | |

| Inner array (control factors) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Expt no. | A | B | C | D | E | F | G | H | I | J | K | L | M |
| 1 | | | | | | | | | | | | | |
| 2 | | | | | | | | | | | | | |
| 3 | | | | | | | | | | | | | |
| 4 | | | | | | | | | | | | | |
| 5 | | | | | | | | | | | | | |
| . | | | | | | | | | | | | | |
| . | | | | | | | | | | | | | |
| . | | | | | | | | | | | | | |
| 36 | | | | | | | | | | | | | |

**Fig. 3** Typical master plan of experimentation

where $x_i = 1-$ efficiency for the $i$th combination in the $L_9$ OA. For each experiment, 36 such losses in efficiency values ($x_i$) were obtained. Hence the optimization problem reduces to minimizing the $x_i$ values (note that minimizing $x_i$ maximizes the efficiency as well as minimizes the variation).

Consider a typical set of experiments, say Expt no. 1 as shown in Fig. 3 which, in turn, is obtained from Tables 2 and 3. It is a combination of 13 inner array design values with nine outer array design values. The first experimental combination for the inner array is A = 740, B = 575, C = 320, D = 4, E = 17.5, F = 38, G = 395, H = 345, I = 93, J = 166, K = 27, L = 3.5, and M = 5.0. For this main experiment, using nine outer array combinations with four replications, 36 observations were obtained. These data are shown in Table 4. The S/N ratio for this set of values was calculated as follows

$$
\begin{aligned}
\text{S/N} &= -10\log_{10}\left(\frac{1}{n}\sum x_i^2\right), \text{ where } x_i = 1 - \text{efficiency} \\
&= -10\log_{10}\left(\frac{1}{36}\times[(1-0.9409)^2 + (1-0.9402)^2 \right. \\
&\quad + (1-0.9381)^2 + \ldots + (1-0.9524)^2 \\
&\quad \left. + (1-0.9527)^2]\right) \\
&= 24.028\,17
\end{aligned}
$$

Similarly, all 36 S/N ratios were calculated. Analysis of variance (ANOVA) was performed on the S/N ratios to obtain the contribution of each of the factors to the variability in performance of the product. For identifying the significant factors, contribution percentages for each factor were calculated. The average response for each level of the factors was calculated from the S/N ratios and is given in Table 5.

From the ANOVA table obtained as the output of ATM (Analysis by Taguchi Methods) software (Table 6), it was found that factors A, D, F, H, L, and M were those having a significant effect on efficiency by considering the contribution percentage of these factors on the total variation. Hence the best levels for these factors were determined from the average response curve (Fig. 4) of these factors so as to maximize the S/N ratio. The best levels were thus identified for these factors as $A_1$, $D_2$, $F_3$, $H_2$, $L_3$, and $M_1$. Since the other factors did not have a significant impact on efficiency, their best levels were decided as per manufacturing feasibility, cost, etc. The best factor level combination thus arrived at was

$$A_1, B_3, C_3, D_2, E_3, F_3, G_2, H_2, I_1, J_3, K_3, L_3, M_1$$

Prediction was done with respect to the significant factors of the best combination.

The expected average efficiency at the best combination was evaluated based on the additive linear model of effects on efficiency [3]

**Table 4** Data for the first experiment of $L_{36}$

| Expt | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 1 | 94.09 | 94.02 | 93.81 | 93.71 | 93.77 | 92.98 | 93.38 | 92.57 | 92.49 |
|      | 91.40 | 91.43 | 91.46 | 91.60 | 91.63 | 91.64 | 91.80 | 91.82 | 91.84 |
|      | 95.49 | 95.51 | 95.51 | 95.39 | 95.44 | 95.27 | 95.28 | 95.10 | 95.16 |
|      | 95.16 | 95.18 | 95.21 | 95.21 | 95.24 | 95.22 | 95.27 | 95.24 | 95.27 |

**Table 5** Average response table

| | S/N ratio | | | Raw data | | |
|--------|-----------|-----------|-----------|----------|----------|----------|
| | Factor level | | | Factor level | | |
| Factor | 1 | 2 | 3 | 1 | 2 | 3 |
| A | 24.048 18 | 23.849 64 | 23.779 35 | 0.059 06 | 0.060 60 | 0.061 39 |
| B | 23.881 94 | 23.880 44 | 23.914 79 | 0.060 68 | 0.060 32 | 0.060 05 |
| C | 23.854 95 | 23.892 27 | 23.929 95 | 0.060 42 | 0.060 34 | 0.060 29 |
| D | 23.958 23 | 24.009 92 | 23.709 02 | 0.061 34 | 0.059 41 | 0.060 30 |
| E | 23.881 85 | 23.889 85 | 23.905 46 | 0.060 45 | 0.060 42 | 0.060 17 |
| F | 23.773 43 | 23.935 82 | 23.967 91 | 0.061 22 | 0.060 08 | 0.059 74 |
| G | 23.895 52 | 23.843 77 | 23.937 88 | 0.060 34 | 0.060 68 | 0.060 03 |
| H | 23.896 08 | 23.995 27 | 23.785 81 | 0.060 35 | 0.059 65 | 0.061 04 |
| I | 23.898 70 | 23.905 70 | 23.872 77 | 0.060 28 | 0.060 23 | 0.060 53 |
| J | 23.905 44 | 23.833 22 | 23.938 51 | 0.060 28 | 0.060 76 | 0.060 00 |
| K | 23.896 81 | 23.879 67 | 23.900 69 | 0.060 36 | 0.060 40 | 0.060 29 |
| L | 23.820 80 | 23.874 61 | 23.981 76 | 0.061 01 | 0.060 51 | 0.059 53 |
| M | 23.990 35 | 23.829 46 | 23.857 36 | 0.059 62 | 0.060 80 | 0.060 63 |

$$\mu_{\text{Expected}} = \bar{T} + (\bar{A}_1 - \bar{T}) + (\bar{D}_2 - \bar{T}) + (\bar{F}_3 - \bar{T})$$
$$+ (\bar{H}_2 - \bar{T}) + (\bar{L}_3 - \bar{T}) + (\bar{M}_1 - \bar{T})$$

where $\bar{T}$ is the overall average and $\bar{A}_1$, $\bar{D}_2$, $\bar{F}_3$, $\bar{H}_2$, $\bar{L}_3$, and $\bar{M}_1$ are the respective level averages of efficiency in the experiment. Thus

$$\mu_{\text{Expected}} = \bar{A}_1 + \bar{D}_2 + \bar{F}_3 + \bar{H}_2 + \bar{L}_3 + \bar{M}_1 - 5\bar{T}$$
$$= 94.474\%$$

This value is much higher than the customer's requirement. The 95 per cent confidence interval was computed as 94.222 to 94.726 per cent, indicating that the requirement of minimum 90 per cent efficiency will be certainly met.

**Table 6**  ANOVA table for S/N ratios

| Source of variation | Degrees of freedom | Sum of squares | Mean square | Contribution (%) |
|---|---|---|---|---|
| A | 2 | 0.466 50 | 0.233 25 | 16.25 |
| B | 2 | 0.009 05 | 0.004 52 | |
| C | 2 | 0.033 75 | 0.016 87 | |
| D | 2 | 0.621 28 | 0.310 64 | 22.32 |
| E | 2 | 0.003 46 | 0.001 73 | |
| F | 2 | 0.260 90 | 0.130 45 | 8.19 |
| G | 2 | 0.053 32 | 0.026 66 | |
| H | 2 | 0.263 49 | 0.131 74 | 8.29 |
| I | 2 | 0.007 22 | 0.003 61 | |
| J | 2 | 0.069 58 | 0.034 79 | |
| K | 2 | 0.003 00 | 0.001 50 | |
| L | 2 | 0.161 15 | 0.080 57 | 4.28 |
| M | 2 | 0.177 39 | 0.088 69 | 4.91 |
| Pooled error | 23 | 0.599 32 | 0.026 06 | |
| Total | 35 | 2.550 03 | | |

## 5.4 Confirmatory trials

During experimentation, no physical assembly was carried out; however, with this optimum combination, five assemblies were made and tested in the design laboratory of the company as per the standard test procedures for various functional performances. The efficiency obtained from the best combination was found to be very satisfactory (more than the customer's requirement). At this factor level combination, the other functional requirements such as air gap flux density, full load field current, transient voltage dip, and short circuit field current of the alternator were also found to be satisfactorily meeting the customer requirements (Table 7).

## 5.5 Benefits

With the design–build–test approach this type of exercise was usually taking a cycle time of 8 to 12 months, whereas by this robust design approach, the best design could be identified in merely 8 weeks: a remarkable reduction in development cycle time. The company could clearly see the advantage of Taguchi methods.

**Table 7**  Values of functional requirements

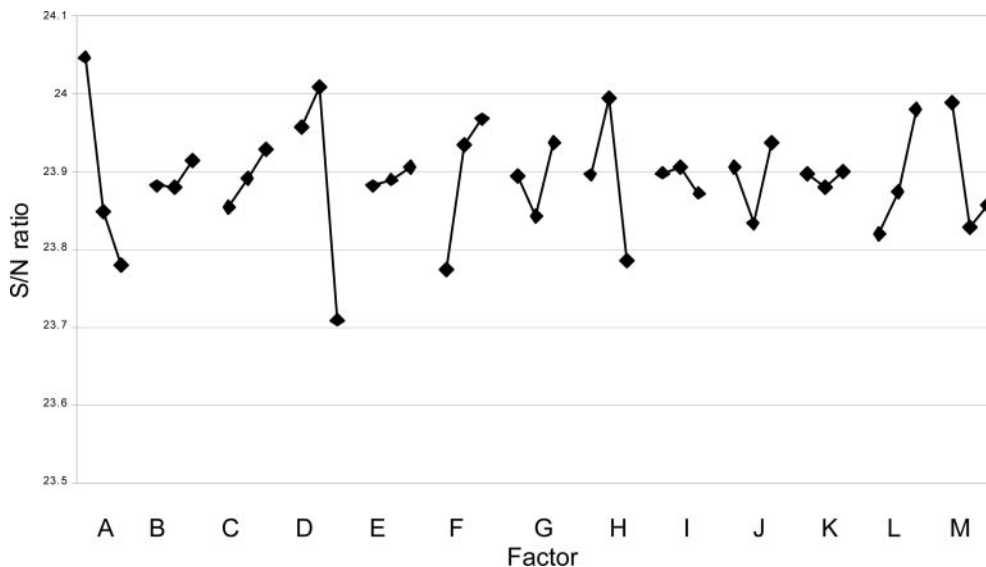| Sl. no. | Characteristic | Requirement | Average achieved |
|---|---|---|---|
| 1 | Efficiency | Min. 90% | 94.33% |
| 2 | Air gap flux density | Min. 0.63 | 0.6463 |
| 3 | Full load field current | Max. 31.00 | 28.1919 |
| 4 | Transient voltage dip | Max. 30.00 | 29.52 |
| 5 | Short circuit field current | Max. 21.70 | 21.5446 |



**Fig. 4**  Average response curve for S/N ratios

This study demonstrated the design of a product to perform at the indented value under all operating conditions. The fundamental principle of robust design, i.e. improving quality by minimizing effect of causes of variability in performance without eliminating them, was demonstrated through this project and the company's research and development department has embarked on several such iterations on new products. The two major tools, the S/N ratio and the orthogonal array, are being taught across the management.

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