The optimal design of electric cable conductor and insulator resistance using Taguchi multi-responses method

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Abstract. The quality of the electrical cable can be determined by resistance of insulator and conductor. There are some factors influencing the resistance of insulators and conductor. In this research, design of experiment, based on Taguchi method, is used to improve cable resistance. Because of having two responses, the optimization process uses the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method. The result showed that the combination of levels of these factors could produce average insulator resistance of 95.70 Ω (increasing by 8.90 Ω), and the average resistance of the conductor 11.908 Ω (decreases down by 0.057 Ω). This optimal condition was obtained by combining the levels of factor A1 B1 C1 D2 E2 F1 G1, i.e. the system works at 140 rpm cabling speed, non core extruder speed 2.9 m/s, core extruder speed 2.9 m/s, cooling water temperature 20 °C, copper elongation 150 - 250, temperature for melting PVC 160 °C- 165 °C and PVC density 154,95-155 kg/m3. Sensitivity analysis indicated that weighting of product quality attributes were not sensitive to optimal factor level combinations.

1. Introduction
The power cable is a medium for channelling electrical energy. The electric cable consists of insulators, which are cables wrapping materials that are usually made of rubber or plastic and conductors made of solid copper or copper fibbers. One of the competitive advantages of electrical cables is determined by the quality of products which also must refer to the National Electricity Company (SPLN) and Indonesian National Standard (SNI) standards.

Experiments will be carried out using the Taguchi method [1], so that product meets the expected quality targets, robust performance, with a small number of experiments. Factors that can be controlled and thought to influence the quality involved in this study are the speed of core extruder, speed of non core extruder, cooling water temperature, PVC melting temperature, cabling speed, copper elongation, and PVC density. While the factors that influence but are difficult to control are human error. The quality design introduced by Taguchi is an off line quality control method that has been widely applied in industries both in the field of mechanical engineering [2-4], chemical engineering [5-8], textile engineering [9], flight engineering [10,11], Biotechnological Application [12] and electrical engineering [13].

The difference between this research and the research that has been done lies in the object, the method and the concept of sensitivity. This research is a development from the Kwintanada study [14] using the Technique for Order Preference by Similarity to Ideal Solution method (TOPSIS) method and developing
perceptual influences using sensitivity analysis. TOPSIS is applied to optimize the chosen alternative based on the product quality attributes. The weight value of product quality attributes can be dynamic and subjective, to accommodate the dynamic weighting, in this study an analysis of the effect of weighting on the conductor's durability and insulator resistance on cable product quality simultaneously. The determination of the optimal conditions of the two response variables in this study is not only based on the results of the experiment but also based on the predictions of the value of the response variable of all alternative combinations of factors formed.

2. Literature Review

An experimental design was applied in this research (with each step/action that is truly defined) so that information relating to or needed for the problem being studied can be collected [15,16]. Two types of experimental designs are known, namely conventional experimental design and Taguchi experimental design. Genichi Taguchi designed an experiment with the aim of getting the factors that influence the response and its interaction with the minimum number of experiments and selecting the best factor level with certain criteria as optimal parameters. Taguchi's strategy for minimizing the number of experiments. S/N ratio is the logarithm of a quadratic loss function and is used to evaluate the quality of a product. There are several types of S/N ratios [1, 18-20] Smaller-the-Better (STB), Larger-the-Better (LTB) and Nominal-the-Better (NTB).

Taguchi is divided into two, namely Taguchi single response and Taguchi multi-responses. The single Taguchi response involves one response variable so that the optimal combination of the response variables is immediately obtained. Taguchi multi-responses method involves more than one response variable, which allows each response variable to have a different combination of factor levels so that further handling is needed to get the optimal combination of factors to improve the quality of each response variable. One method that can be used to solve Taguchi multi-responses problems is the TOPSIS method [6]. TOPSIS is based on the concept that the best chosen alternative not only has the shortest distance with a positive ideal solution, but also has the longest distance from the negative ideal solution [21].

Sensitivity analysis is intended to determine the effect of changes in production parameters on the performance of the production system [14]. In the TOPSIS method, in determining the chosen alternative it will be influenced by the level of importance or the weight of the quality attributes of each response variable. The weight value of product quality attributes is dynamic and subjective or in other words each individual can have different perceptions that can change from time to time. To accommodate the dynamic and subjective quality attributes of product quality attributes, a sensitivity analysis was carried out in this study to determine the effect of priority attributes of product attributes on the quality of electrical cables.

3. Research Methods

The research was conducted at a company that produces electrical cables, and sample testing was carried out in the laboratory. This experimental research is done in three steps, namely:

1. Experimental planning
   In this step, some quality characteristics are identified. Then, based on these characteristics, some factors influencing the quality are identified. This research, quality characteristics are identified based on the safety and durability of the cable which can be measured based on the resistance of the conductor using a double bridge and insulator resistance using an insulation tester. Based on literature reviews, some value of the factors are determined.

2. Experimental implementation
   The experiment is a phase of collecting experimental data based on the selected orthogonal array matrix. Experiments were carried out directly in the production department and the quality control department. Insulator resistance testing is done by using an insulation tester to determine the condition
of cable insulation. The test was carried out using a combination of L8 27 and L4 23 orthogonal arrays with 4 replications. Conductor durability testing is done by using a double bridge to check the conductor whether it has the properties of standard requirements.

3. Experimental analysis
   Multiple linear regression models are used to help predict the resistance of the insulator and the resistance of the conductor. Because the optimum conditions for insulator resistance and conductor resistance are obtained from different factor level combinations, analysis is needed to optimize these different conditions simultaneously. For this purpose, research uses the TOPSIS method

4. Research Results and Discussion
   4.1 Experimental Planning
   In this research, a system will be designed that can improve the quality of the electricity cables produced. Two response variables were chosen as a measure of quality, namely the resistance of conductors in Ohm units (Ω) and the characteristics of STB (smaller the better), and resistance of insulators with units of Ohm (Ω) and characteristics of LTB (larger the better)

   Factors that are thought to influence the quality involved in this study are core extruder speed, non core extruder speed, cooling water temperature, PVC melting temperature, cabling speed, copper elongation, and PVC density as a control factor, and human error as a noise factor. Control factors and noise factors that are thought to affect the quality characteristics of the electricity cables produced can be tabulated in Table 1.

   | No | Controllable Factors       | Code | Level 1        | Level 2        |
   |----|---------------------------|------|----------------|----------------|
   | 1  | Cabling speed             | A    | 140 rpm        | 160 rpm        |
   | 2  | Non core extruder speed   | B    | 2.9 m/s        | 3.2 m/s        |
   | 3  | Core extruder speed       | C    | 2.9 m/s        | 3.2 m/s        |
   | 4  | Cooling water temperature | D    | 25 °C          | 20 °C          |
   | 5  | Copper elongation         | E    | 250 – 350      | 150 – 250      |
   | 6  | PVC melting temperature   | F    | 160 °C -165 °C | 165 °C -170 °C |
   | 7  | Density PVC               | G    | 154.95-155     | 155-155.05     |
   | 8  | Human error               | H    | No             | Yes            |

   4.2 Experiment Implementation
   To identify the resistance of the conductor and the resistance of the insulator, the experiment was performed using the inner array L8 27 and the L4 outer array 23. The result of experiment for conductor resistance is shown in Table 2. For isolator experiment was done as well.

   4.3 Experimental analysis
   Based on experimental data, to determine the combination of level factors that produce optimal cable quality.Determination of S / N Ratio for conductor resistance response variables is based on the objective function of the STB, while the insulator resistance response variable is based on the objective function of
Table 2 Data on Conductor Resistance Measurements in Ohm (Ω).

| Trial | A | B | C | D | E | F | G | Experiment result | Experiment result |
|-------|---|---|---|---|---|---|---|-------------------|-------------------|
| 1     | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 11.942           | 11.956           |
| 2     | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 11.919           | 11.916           |
| 3     | 1 | 2 | 1 | 1 | 2 | 2 | 2 | 11.994           | 11.995           |
| 4     | 1 | 2 | 2 | 1 | 2 | 1 | 1 | 11.938           | 11.936           |
| 5     | 2 | 1 | 2 | 1 | 1 | 2 | 1 | 11.930           | 11.924           |
| 6     | 2 | 1 | 2 | 2 | 1 | 2 | 1 | 11.970           | 11.975           |
| 7     | 2 | 2 | 1 | 1 | 2 | 2 | 1 | 11.941           | 11.934           |
| 8     | 2 | 2 | 1 | 2 | 1 | 1 | 2 | 11.968           | 11.966           |

LTB. The effect of each factor is intended to find out the formulation that will produce the best combination of level factors for each response variable. The combination of the best factor levels of conductor and insulator resistance response variables are A1, B1, C1, D2, E1, F2, G1.

Table 3 Multiple Linear Regression Models of Conductor Resistance.

| Level Noise Factor | Replication | Regression Model                                                                 |
|--------------------|-------------|-----------------------------------------------------------------------------------|
| 1                  | 1           | \( Y = 11.9255 + 4.0002 \times 10^{-7} A + 2.0000 \times 10^{-2} B + 1.5500 \times 10^{-2} C - 3.0003 \times 10^{-3} D - 3.6500 \times 10^{-2} E + 1.1500 \times 10^{-2} F + 5.0001 \times 10^{-3} G \) |
| 1                  | 2           | \( Y = 11.9675 - 1.0002 \times 10^{-3} A + 1.5000 \times 10^{-2} B + 1.4500 \times 10^{-2} C - 3.9999 \times 10^{-3} D - 4.5500 \times 10^{-2} E + 9.5003 \times 10^{-2} F - 2.3842 \times 10^{-3} G \) |
| 1                  | 3           | \( Y = 11.9365 - 2.5001 \times 10^{-3} A + 1.6500 \times 10^{-2} B + 1.2500 \times 10^{-2} C - 1.5001 \times 10^{-3} D - 3.7500 \times 10^{-2} E + 1.4500 \times 10^{-2} F + 4.5004 \times 10^{-3} G \) |
| 1                  | 4           | \( Y = 11.9763 - 7.5030 \times 10^{-4} A + 7.7498 \times 10^{-3} B + 6.7499 \times 10^{-3} C - 1.0750 \times 10^{-2} D - 3.9750 \times 10^{-2} E + 1.0750 \times 10^{-2} F + 9.7501 \times 10^{-3} G \) |
| 2                  | 1           | \( Y = 11.9643 - 2.2500 \times 10^{-3} A + 8.2500 \times 10^{-3} B + 1.7750 \times 10^{-2} C - 8.2500 \times 10^{-3} D - 3.7750 \times 10^{-2} E + 1.1750 \times 10^{-2} F + 2.2500 \times 10^{-3} G \) |
| 2                  | 2           | \( Y = 11.9653 + 5.7502 \times 10^{-3} A + 7.2498 \times 10^{-3} B + 9.7499 \times 10^{-3} C - 6.2500 \times 10^{-3} D - 4.2750 \times 10^{-2} E + 9.7499 \times 10^{-3} F + 7.2498 \times 10^{-3} G \) |
| 2                  | 3           | \( Y = 11.9435 + 5.5006 \times 10^{-3} A + 1.3500 \times 10^{-3} B + 7.5000 \times 10^{-3} C - 3.5002 \times 10^{-3} D - 3.9500 \times 10^{-2} E + 1.4500 \times 10^{-2} F + 6.5000 \times 10^{-3} G \) |
| 2                  | 4           | \( Y = 11.9813 - 2.5010 \times 10^{-3} A + 5.7499 \times 10^{-3} B + 7.2501 \times 10^{-3} C - 6.2497 \times 10^{-3} D - 4.0750 \times 10^{-2} E + 1.2500 \times 10^{-2} F + 3.7501 \times 10^{-3} G \) |

Because the optimal factor level combination in each response variable is different, a multi-response analysis is needed. The factors that influence the conductor resistance and isolator resistance simultaneously are B, C, D, E, F and G so that the analysis of 26 alternative combinations and their slices with L8 AO obtained 64 alternatives. Multiple linear regression analysis can be developed for estimating conductor and...
isolator resistance. The multiple linear regression model for the conductor resistance can be seen in Table 3. With the same method, isolator resistance multiple linear regression estimation model can be develop.

4.3.1 Determination of Optimal Factor Levels Using TOPSIS. Because the optimum conditions for conductor resistance and insulator resistance are obtained from a combination of different level factors, analysis is needed to optimize the different conditions simultaneously using Taguchi multi-responses.

Based on the fuzzy number conversion, the weight is calculated. For high scale conductor resistance and low scale for insulator resistance, the weight will be \( w_1 = 0.56264 \) and \( w_2 = 0.43736 \).

| Trial | TOPSIS | Trial | TOPSIS | Trial | TOPSIS | Trial | TOPSIS |
|-------|--------|-------|--------|-------|--------|-------|--------|
| 1     | 0.4622 | 17    | 0.3284 | 33    | 0.3247 | 49    | 0.1916 |
| 13    | 1.0000 | 29    | 0.8637 | 45    | 0.8599 | 61    | 0.7243 |
| 16    | 0.8028 | 32    | 0.6674 | 48    | 0.6637 | 64    | 0.5290 |

Based on TOPSIS calculation Table 12, it was found that the optimal conditions were obtained in the 13th trial with a combination of factor levels A1 B1 C1 D2 E2 F1 G1. This combination results in an average can decrease conductor resistance of 11.908 \( \Omega \) (0.48%) and increase insulator resistance 95.70 \( \Omega \) (9.30%).

4.3.2 Analysis of Sensitivity. The combination of level factors that produce the optimal response above is obtained on a formal scale system to convert linguistic forms into a corresponding fuzzy number which is high for conductor and medium (medium) resistance for insulator resistance or corresponding to conductor endurance attribute weights 0.56264 and endurance attributes of insulator 0.437359. Based on the sensitivity analysis, the results show that the formal scale system changes used to convert linguistic forms into fuzzy numbers are not sensitive to optimal factor level combinations.

5. Conclusion
Based on the results of the analysis above, it can be concluded that the combination of level factors that produce the optimal quality of NYM 2x1.5mm2 cable is A1 B1 C1 D2 E2 F1 G1. This means the system works at 140 rpm cabling speed, non core extruder speed of 2.9 m / s, core extruder speed of 2.9 m / s, 20 \( ^\circ \)C cooling water temperature, 150 - 250 copper elongation, temperature for PVC 160 \( ^\circ \)C melting -165 \( ^\circ \)C and PVC density 154.95–155. This optimal combination can improve cable quality both from conductor resistance and insulator resistance, average conductor resistance of 11.908 \( \Omega \) decreases (11.965 \( \Omega \) - 11.908 \( \Omega \) = 0.057 \( \Omega \)) and insulator resistance is 95.70 \( \Omega \), increasing by (95.70 \( \Omega \) - 86.80 \( \Omega \) = 8.90). Based on the sensitivity analysis, the results show that changes in the order of priority attribute weights on a formal scale system used to convert linguistic forms into fuzzy numbers are not sensitive to the optimal combination of factor levels.

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