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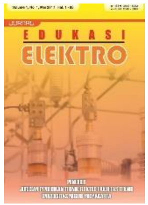


# Voltage THD Analysis on the Use of DC Motors in the Steel Milling Process

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**Abstract—**A milling process utilize DC motors and rectifier circuits. Semiconductor components in the rectifier circuit could cause harmonic distortion. At PT X, the voltage THD generated at the 6KV feeder panel has exceeded the standards set by the IEEE. This study aims to analyze the voltage THD caused by a controlled rectifier circuit and DC motors, and to design a filter to mitigate it. MATLAB software is used to analyze the THD voltage. From the simulation results, it is known that the 400KW, 450KW, and 600KW DC motors produce voltage THD values of 9.35%, 14.23%, and 12.28% respectively which exceed the set standards of 8%. A single-tuned passive filter is designed to reduce the THD voltage value on each motor. The installation of the filter effectively reduces the THD voltage value in the 400KW, 450KW, and 600KW DC motors to 4.34%, 5.38%, and 6.35% respectively.

**Keywords:** DC motor, rolling mill, total harmonic distortion (THD), passive filter

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## 1 Introduction

In the current era, technology developments have assisted the industrial sector in carrying out manufacturing processes that have undergone changes towards a better and more advanced stage. These changes have contributed to increased productivity. Especially in the current era, industrial competitiveness is determined by the existence of innovative changes that can produce high added value products [1], [2]. One sector that relies heavily on technological advances is steel manufacturing. In the steel manufacturing process, there are at least two main processes, namely the steel melting process and the rolling mill process.

Steel production is one of the industries with massive use of materials and energy. One of the processes in steel production is the milling process, namely the process of forming steel into linear elements by inserting steel blades or billets into two rollers that rotate on a stand which causes permanent deformation in the billet. The rolling mills production field consists of several roller booths depending on the type and size of the product, where each roller is driven by a DC motor [3], [4].

DC motors are still often used as main drivers in steel mills. One of the advantages is the ease of constant motor speed regulation when compared to AC motors. The braking system on a DC motor is also much more simple than an AC motor, so that the operator's safety factor when the milling process experiences an error can be considered. However, the use of DC motors still has drawbacks such as more complicated maintenance, relatively expensive unit prices, and the need for additional circuits such as rectifiers for power supply. A converter or rectifier circuit is needed to convert AC voltage to DC voltage. The rectifier circuit usually uses semiconductor components such as diodes, thyristors, and transistors [5]. Semiconductor components such as thyristors are very commonly used for a full wave controlled rectifier circuits. The ability to regulate the output voltage through setting the duty cycle (α) on the gate can be used to adjust the speed of a DC motor [6]. Especially in this modern era, there are also many DC Drive devices available that are capable of operating DC motors with a reliable, stable and safer system [7].

Steel milling process requires high precision and the ability to handle heavy loads efficiently. Characteristics of loads that tend to change rapidly, changes in the process from acceleration to deceleration, and constant torque with various speed ranges are the parameters that must be controlled by an electric motor as the main drivers. Motor drives with good accuracy and efficiency are the main choice in the steel milling process. The use of motor drives that are right on target can optimize production costs, minimize repairs, increase system reliability, and maintain the quality of the final product [8].

However, the use of semiconductor equipment runs the risk of causing the load to become non-linear [9]. Loads that are not linear have the risk of producing harmonic waves in the power system. Harmonics can be defined as the sinusoidal component of a periodic wave which has frequency of many times than its fundamental frequency. A rectifier circuit is a component that has the potential to cause harmonics in the electric power system. In the case of a controlled rectifier, the greater the trigger angle used, the more non-linear of the load will be, so that the waveforms of the output voltage and input current become not sinusoidal or distorted. [10]. The amount of voltage harmonic distortion set in the standard is usually a percentage of the ratio between the harmonic rms voltage value and the fundamental rms voltage value. This quantity is also known as Total Harmonic Distortion (THD).

$$THDv = \frac{V_H}{V_F}\, x\, 100\% \quad (1)$$

$$V_H = \sqrt{V_2^2 + V_3^2 + \cdots + V_n^2} \quad (2)$$

Explanation:
$V_H$ = harmonic voltage
$V_n$ = rms voltage of the nth-order individual harmonics
$V_F$ = rms fundamental voltage

The emergence of harmonic waves is an abnormal symptom in the electric power installation system. Abnormal voltage and current waveforms, as well as frequencies that do not match the nominal frequency. This kind of condition will cause a negative effect on the electrical system itself. Some of the resulting impacts include; high temperature of the neutral conductor, failure of conductor insulation, large leakage voltage that occurs on the ground-neutral wire, distortion of the voltage waveform, and poor power factor [11]. This condition will cause an excess heat in the transformer used, and can reduce efficiency due to a decrease in the installed power (derating) of the transformer. [12].

Several negative effects caused by the emergence of harmonics that exceed standards such as reduced life of conductor insulation, generation of voltage on the ground wire, and low power factor values have also begun to appear in the electricity system. Several electronic components such as PLC, UPS, computers in the rolling mills plant at PT X have also experienced abnormal conditions several times which surely have disrupted the production process.

An initial observation was made on the side of the medium voltage sub-station (6,000 V) using a power quality meter. From these observations it is known that the harmonic distortion generated in the network reaches 7.2% at full load, while the maximum THD voltage allowed according to IEEE 519-2014 is only 5% for the 1kV to 69kV bus voltage category. The main load on the network is a DC motor equipped with a thyristor-based 3-phase rectifier circuit.


**Fig. 1.** Voltage THD on incoming 6KV panel

Several studies have been conducted to determine the harmonic distortion caused by non-linear loads such as semiconductor components. One of the studies in 2020 found that the results of using SCR components used in rectifier circuits with DC motor loads are known to produce THD values that are greater than ordinary diodes [13]. In addition, the steel production process at a factory in Myanmar is known to produce voltage harmonic distortion that exceeds the standards set out in IEEE 514-2014, a passive filter circuit is needed to reduce the resulting harmonic distortion. [14]. Several studies have been carried out to determine the impact of the use of semiconductor components on the emergence of harmonic waves in an electrical installation. Research on the specific harmonic waves generated by DC motors in the steel milling process is still hard to find due to the limited availability of data. The production process parameters such as motor speed and motor current when supplying the load are also considered in this study. So it is necessary to carry out further analysis considering the amount of energy consumed in the production process, due to the large capacity of the electricity resources used. Appropriate mitigation efforts are also expected to help reduce or even prevent the negative effects that can be generated by harmonic distortion through an appropriate procedure or method.

## 2 Research Method

This study utilizes SIMULINK to simulate a full-wave controlled 3-phase rectifier circuit with a DC motor load. This rectifier circuit uses 6 thyristors arranged in parallel. In this configuration, the output voltage of the 3-phase full-wave controlled rectifier is affected by the trigger angle value at the thyristor gate. Where the smaller the value of the trigger angle ($\alpha$), the greater the resulting average output voltage value [6]. In this study the type of rectifier used was a 3-phase full-wave controlled rectifier using 6 thyristors which were divided into 2 groups, namely the positive group and the negative group. The positive group will be active when the source voltage is positive, and the negative group will be active when the source voltage is negative. There are two trigger angle adjustment processes, namely conducting operation when $0° < \alpha < 60°$, and discontinuous operation when $60° < \alpha < 120°$ [15].

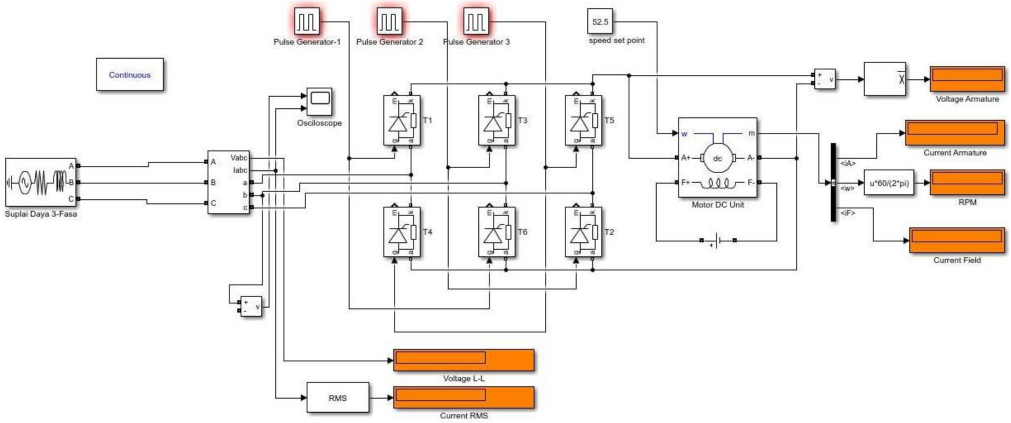


**Fig. 2.** Simulation circuit designed in Simulink MATLAB

This study aims to analyze the distortion of harmonic waves caused by the use of DC motor loads in the steel milling process, as well as to find the right filter design to mitigate this distortion. The circuit was made based on the actual conditions in the plant, where in this study the loads were identified in the form of 3 DC motor units with a capacity of 400KW, 450KW and 600KW respectively. The three motors are used during the steel milling process.

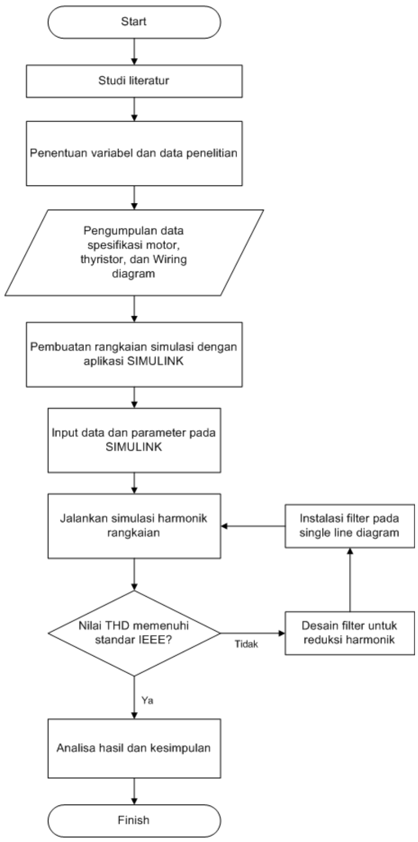


**Fig. 3.** Research flowchart

Some necessary data such as motor and transformer specifications, motor operating characteristics, rectifier circuit configurations are also filled into the application as simulation parameters.

**Table 1.** Simulation Parameter

| Data | 400 KW | 450 KW | 600 KW | Unit |
|---|---|---|---|---|
| **Transformer** | | | | |
| $S_n$ | 667 | 630 | 1.000 | KVA |
| $V_o$ | 740 | 620 | 740 | Volt |
| $Z_{\%}$ | 5,1 | 6,33 | 5,35 | % |
| $S_{sc}$ | 13,076 | 9,959 | 18,688 | MVA |
| **Motor** | | | | |
| $R_{arm.}$ | 0,313 | 0,43 | 0,253 | Ohm |
| $L_{arm.}$ | 7,64 | 8,42 | 7,28 | mH |
| $R_{field}$ | 15,6 | 50,5 | 13,5 | Ohm |
| $L_{field}$ | 380,78 | 988,86 | 388,46 | mH |
| **Speed** | 501 | 850 | 389 | Rpm |
| **alpha** | 51 | 34 | 39 | Deg. |

The circuit that has been made and filled in with its parameters is then simulated, and continued with the application of FFT Analysis on the input voltage to determine the THD value of the voltage produced by the circuit. The THD voltage standard set for the voltage category below 1 KV is 8%, based on IEEE 514-2014.

**Table 2.** THD voltage standard based on IEEE 514-2014

| Line Voltage | $THD_V$ Total Allowed (%) |
|---|---|
| ≤ 1 KV | 8,0 |
| <1 KV ≤ 69 KV | 5,0 |
| >69 KV ≤ 161 KV | 2,5 |
| > 161 KV | 1,5 |

The circuit that does not meet the standard will then be fitted with a single-tuned passive filter circuit based on the most dominant individual harmonic order, so that a THD voltage value that meets the standard is achieved. The components in the passive circuit include capacitors (C), inductors (L), and resistors (R) which are connected in series with ground.

**Fig. 4.** Single-tuned passive filter

Each installed component's value is calculated based on the value of required reactive power ($Q_C$) and actual power factor (Cos $\varphi_1$). The value of the power factor to be achieved (Cos $\varphi_2$) from the filter installation in this study is 0,9. The method used to calculate the QC value is by using equation (3).

$$Q_C = P\,[tan(cos^{-1}\varphi_1) - \tan(cos^{-1}\,\varphi_2)] \quad (3)$$

Meanwhile, to calculate the value of each filter component in the form of a capacitor (C), inductor (L), and resistor (R) needed based on the QC value obtained, equations (4), (5), and (6) will be applied.

$$C = \frac{Q_C}{2\pi f V^2} \quad (4)$$

$$L = \frac{V^2}{2\pi f Q_C n^2} \quad (5)$$

$$R = \frac{2\pi f L}{Q} \quad (6)$$

Explanation:
f = Fundamental frequency (Hz)
V = Voltage system (V)
n = Harmonic orde
Q = Improvement quality factor (20-100)

After obtaining the required filter specifications, then the circuit is modified by adding passive filter circuit needed. The simulation is carried out again until the voltage THD value that meets the standards is obtained.

## 3 Results and Discussions

The simulation is carried out on a circuit that has been made previously in SIMULINK. There are 3 loads to be simulated, namely 400 KW, 450 KW, and 600 KW DC motors. The FFT Analysis feature is utilized to analyze the AC voltage waves generated by a three-phase power source that represents a transformer.

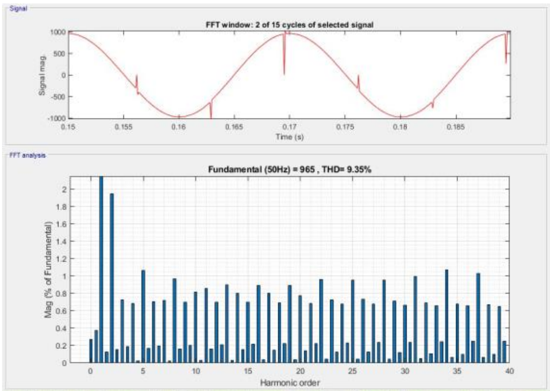


**Fig. 5.** FFT analysis results on DC motor 400KW load

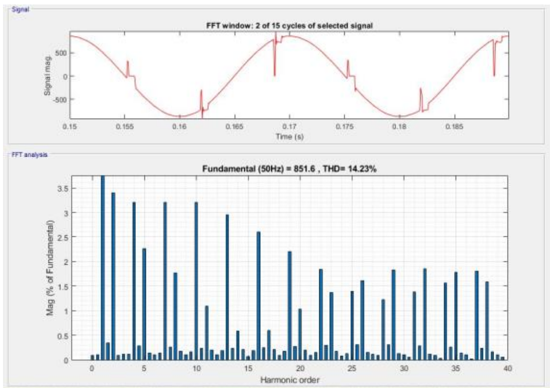


**Fig. 6.** FFT analysis results on DC motor 450KW load

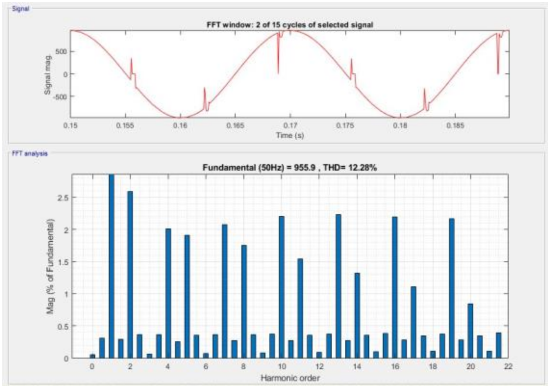


**Fig. 7.** FFT analysis results on DC motor 600KW load

Based on the simulations carried out, at a 400 KW DC motor load it is known to produce a voltage THD value of 9.35% with a power of 119.87 KW and the most dominant harmonic order is in the 2nd order. At a 450 KW DC motor load, a voltage THD value of 14.23% is produced with a power of 254.72 KW and the most dominant harmonic order is in the 2nd, 4th, 5th, 7th and 11th order. And at a 600 KW DC motor load, a voltage THD value of 12.28% is produced with a power of 209.77 KW and the most dominant harmonic order is in the 2nd, 4th, 5th, 7th, and 11th order. The power factor in the three simulations is known of 0.774. The summary of the simulation results can be seen in Table 3.

**Table 3.** Summary of the simulation result

| Motor Capacity | $THD_V$ | Dominant Order | Power (KW) | Cos φ |
|---|---|---|---|---|
| 400 | 9,35% | 2 | 119,87 | 0,774 |
| 450 | 14,23% | 2,4,5,7,11 | 254,72 | 0,774 |
| 600 | 12,28% | 2,4,5,7,11 | 209,77 | 0,774 |

From the simulation results it is known that the voltage THD value generated at the DC motor load does not meet the standards set in IEEE 514-2014 of 8%. The filter circuit needs to be designed to reduce the harmonics that arise so that it meets the established standards. In this study, a single-tuned passive filter is used to reduce the voltage harmonics emerged.

### 3.1 Harmonic Filter Calculation on 400 KW DC Motor Load

Based on the simulation data obtained on the 400 KW motor, calculations are then carried out to find the reactive power requirement (QC), the value of the capacitor (C), inductor (L), and resistor (R) as components used in passive filters. Specifications of the required filter can be obtained by applying equations (3) to (6).

$$Q_C = 119{,}87\ [tan(cos^{-1}0{,}774) - \tan(cos^{-1}\ 0{,}9]$$

$$Q_C = 40{,}4\ KVAR$$

$$C = \frac{40.400}{2(3{,}14)(50)(720^2)}$$

$$C = 248\ \mu F$$

$$L = \frac{720^2}{2(3{,}14)(50)(40.400)(2^2)}$$

$$L = 10{,}216\ mH$$

$$R = \frac{2(3{,}14)(50)(0{,}010216)}{55}$$

$$R = 0{,}583\ \Omega$$

From the calculation results, the required reactive power value is 40.4 KVAR. So that a capacitor of 248 µF is required, an inductor of 10.216 mH, and a resistor of 0.583 Ω. Specifically for calculating resistor values, the quality factor value (Q) of 55 is used.

### 3.2 Harmonic Filter Calculation on 450 KW DC Motor Load

The same as before, to find the required filter specifications, equations (3) to (6) are applied based on the obtained simulation data.

$$Q_C = 254{,}72\ (0{,}818 - 0{,}484) = 85{,}08\ KVAR \rightarrow 85KVAR$$

$$C = \frac{85.000}{2(3{,}14)(50)(358)^2}$$

$$C = 704{,}22\ \mu F$$

The calculation of the inductor requirement is calculated based on the order of the harmonics to be filtered. The most dominant harmonic orders in the simulation results are the 2nd, 4th, 5th, 7th, and 11th orders. By applying equation (5), the inductor values for each order are obtained as shown in Table 4.

**Table 4.** Inductor Required for Passive Filter on 450 KW DC Motor Load

| Harmonic Order | Inductor |
|---|---|
| $L_2$ | 3,6 mH |
| $L_4$ | 0,9 mH |
| $L_5$ | 0,58 mH |
| $L_7$ | 0,29 mH |
| $L_{11}$ | 0,12 mH |

Just like inductors, the need for resistors is calculated based on the order of the harmonics to be reduced, with the value of the quality factor used being determined at 35. Based on equation (6) the resistor values are obtained for each order of harmonics as shown in Table 5.

**Table 5.** Resistor required for passive filter on 450KW DC motor load

| Harmonic Order | Resistor |
|---|---|
| $R_2$ | 32mΩ |
| $R_4$ | 8mΩ |
| $R_5$ | 5,2mΩ |
| $R_7$ | 2,6mΩ |
| $R_{11}$ | 1mΩ |

### 3.3 Harmonic Filter Calculation on 600 KW DC Motor Load

The same as before, to find the required filter specifications, equations (3) to (6) are applied based on the obtained simulation data.

$$Q_C = 209{,}77(0{,}818 - 0{,}484) = 70KVAR$$

$$C = \frac{70.000}{2(3{,}14)(50)(720)^2}$$

$$C = 430\ \mu F$$

The calculation of the need for inductors and resistors is calculated based on the order of the harmonics to be filtered. The most dominant harmonic orders in the simulation results are the 2nd, 4th, 5th, 7th, and 11th orders. By applying equations (5) and (6) the inductor and resistor values for each order are obtained as shown in Table 6 and Table 7.

**Table 6.** Inductor required for passive filter on 600KW DC motor load

| Harmonic Order | Inductor |
|---|---|
| $L_2$ | 5,9 mH |
| $L_4$ | 1,47 mH |
| $L_5$ | 0,94 mH |
| $L_7$ | 0,48 mH |
| $L_{11}$ | 0,19 mH |

**Tabel 7.** Resistor required for passive filter on 600KW DC motor load

| Harmonic Order | Resistor |
|---|---|
| $R_2$ | 53 mΩ |
| $R_4$ | 13 mΩ |
| $R_5$ | 8,4 mΩ |
| $R_7$ | 4,3 mΩ |
| $R_{11}$ | 1,7 mΩ |

### 3.4 Simulation Result After Filter Installation

After obtaining the required filter component parameters for each motor, the next step is to modify the simulation circuit by adding a single-tuned passive filter circuit at the 3-phase transformer output. Simulation with FFT Analysis was carried out again after the addition of a single-tuned passive filter component in the simulation series.

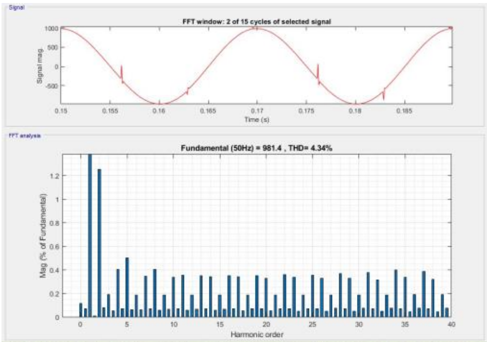


**Fig. 8.** FFT analysis result after filter installation on 400KW DC motor load

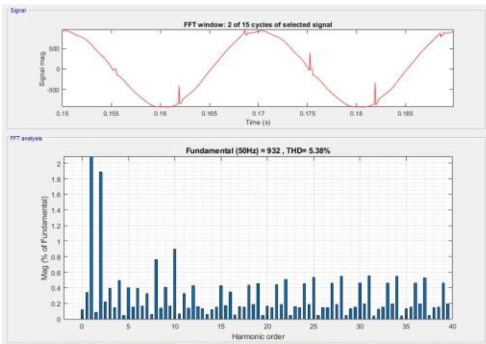

**Fig. 9.** FFT Analysis result after filter installation on 450KW DC motor load

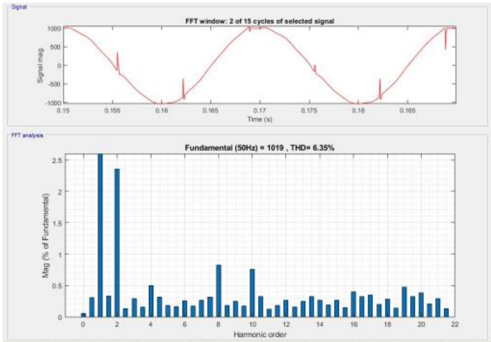


**Fig. 10.** FFT Analysis result after filter installation on 600KW DC motor load

From the simulation results, the THD value of the voltage on the 400 KW DC motor is 4.34%. Meanwhile, the 450 KW and 600 KW DC motors obtained THD voltage values of 5.38% and 6.35%, respectively. The ripples that arise in the voltage sinusoidal waves at each load have been relatively reduced compared to before being filtered. From the simulation results it is known that the use of filters has succeeded in reducing the THD voltage at each load to meet the specified standards. A summary of the results of the simulation using filters can be seen in Table 8.

**Table 8.** Simulation result of circuit after being reduced using filter

| Motor | $THD_V$ After Reduced | Difference |
|---|---|---|
| 400 KW | 4,34 % | -5,01 % |
| 450 KW | 5,38 % | -8,85 % |
| 600 KW | 6,35 % | -5,93 % |

## 4 Conclusion

The use of DC motors in the steel milling process still produces voltage harmonic values that exceed the established standards. Additional filter circuits are needed to mitigate the resulting harmonics. The use of a single-tuned passive filter has succeeded in reducing the THD value of the resulting voltage so that it meets the set standards. Further research is needed using more adequate measuring instruments to produce more accurate and actual data.

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