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Intelligent Fuzzy Logic-Based Load Frequency Control for Multi-Area Power System

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ABSTRACT: Maintaining frequency stability in interconnected power systems is a critical challenge due to continuous load variations and power exchange among multiple control areas. This paper presents an intelligent Fuzzy Logic Controller (FLC) for Load Frequency Control (LFC) in a four-area interconnected thermal power system to minimize frequency deviations and improve dynamic system performance. The proposed controller employs a fuzzy inference mechanism with two input variables, five membership functions, and twenty-five fuzzy rules to regulate the governor control action under varying load disturbances. The complete multi-area system was modeled and simulated in MATLAB/Simulink, and its dynamic performance was evaluated in terms of frequency deviation, maximum overshoot, settling time, and tie-line power exchange. Simulation results demonstrate that the proposed FLC effectively suppresses transient oscillations and restores system frequency to its nominal value within a short duration. The controller achieved a steady-state frequency deviation of 0.006 p.u., while the maximum overshoot was limited to 0.75%, 0.65%, 0.40%, and 0.80% for Areas 1–4, respectively. The corresponding settling times were 2.0 s, 7.5 s, 5.0 s, and 10.2 s, indicating stable and reliable operation across all interconnected areas. Furthermore, the tie-line power exchange settled within approximately 10–12 s, confirming effective coordination among the control areas. The obtained results demonstrate that the proposed fuzzy logic-based LFC significantly enhances frequency regulation, reduces transient oscillations, and provides a robust and computationally efficient solution for modern interconnected power systems

KEYWORDS: Load Frequency Control (LFC).Fuzzy Logic Controller (FLC), Power systems.

I. INTRODUCTION

A power system is an extensive network composed of generation, transmission, and distribution. The active power and the reactive power/the active part of the load and the reactive part of the load are continuously changing with trends in rising and falling. We know that the load is continuously changing; we don’t have control over the load. It depends on consumers, but we need to deal with this change in load.[1] In the power system interconnected grids, areas are linked through tie lines, enabling power exchange. In order to control the active power, the steam input to the generator must be regulated so as to match the demand. We can say that we can have the balance between generation and power demand (Pg = Pd); if we don’t regulate the steam input alternator Suppose the load is decreasing; in that case, the speed of the alternator may go up because of changes in the speed of the alternator. The frequency may change, which is not desirable.[2]

We know that-

$$N = \frac{120\,F}{P}$$

So, Frequency ∝ Speed

1.1 Active Power and Reactive Power

In order to control the frequency deviation problem steam input of the alternator must be regulated, it is regarding the active power. In order to control the reactive power, we have to control the excitation of the alternator where mechanical input we are getting from that steam and next we have to create the magnetic field in the alternator for that we are using those excitation and in order to maintain the reactive power demand suppose if we don’t regulate this excitation we may face the problem with the voltage of the system [3] We know that frequency is a direct correlation with active power and voltage is primarily governed by reactive power. There are changes on the load side, so simultaneously changes on the input side with that only we have to maintain the voltage in frequency deviation.[4] Most of the appliances, or most of the load that we are having in the electrical system, are all designed for a certain

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range of frequency and for a certain range of voltage. If the system is smallest, we have one generator to supply a single load. Suppose here we are increasing or decreasing a load accordingly; we can maintain/change the input to the generator, and we can have control of these two parameters, but practically, a "power system" is a large, interconnected power system.[3]

1.2 Large Interconnected Power System (Multi Area)

In a large interconnected power system, manually operated regulators will not work here or are not feasible. There is continuous fluctuation in load, and in the large interconnected system, there are so many generators connected, so as for the changes in load, if we are going to make the changes in the steam input and excitation control manually, then it will not be feasible, so that is why for all generators in the power system, we have one equipment called automatic generation and voltage control equipment.[5]

II. LITERATURE REVIEW

This research contributes to the improvement of load frequency deviation in two areas by using the GA-PID technique and the Ziegler-Nichols (Z.N.) method. Here, in the Z.N. method, the settling time is 22.37 sec., but in GA-PID, it is only 1.2311 sec. in area-1 and 22.37 and 1.6977, respectively, in area-2, so it is concluded that GA-PID has better performance[6]. Recent studies investigating FLC for 3-area LFC emphasize fast damping of transient errors. The fuzzy controller achieves a frequency deviation of 0.006 per unit; max overshoots are reported as 0.725%, 0.9%, & 1.0%, respectively, while corresponding settling times are 0.9 0.9sec, sec, and 12 sec[7].

III. METHODOLOGY

This research employs a fuzzy-logic technique to solve the load frequency problem in a multi-area system. The steps involved are

1. Multi-areas are connected through a tie line.
2. Applying the fuzzy-logic technique with two main objectives: to minimize frequency deviation and settling time.
3. Assigning 25 rules in fuzzy logic and coding of GA-PI in MATLAB.
4. Solving the model using the optimization method and comparing it.

3.1. Fuzzy-Logic controller (FLC)

A fuzzy logic controller is a control system designed to manage the operation of a physical process or plant using the principles of fuzzy logic.[8]

- Fuzzy theory can be implemented in a wide range of applications, including reasoning, clustering of uncertain data, and fuzzy-based programming.
- Among these, fuzzy reasoning is referred to as a **"fuzzy logic controller."**[9]

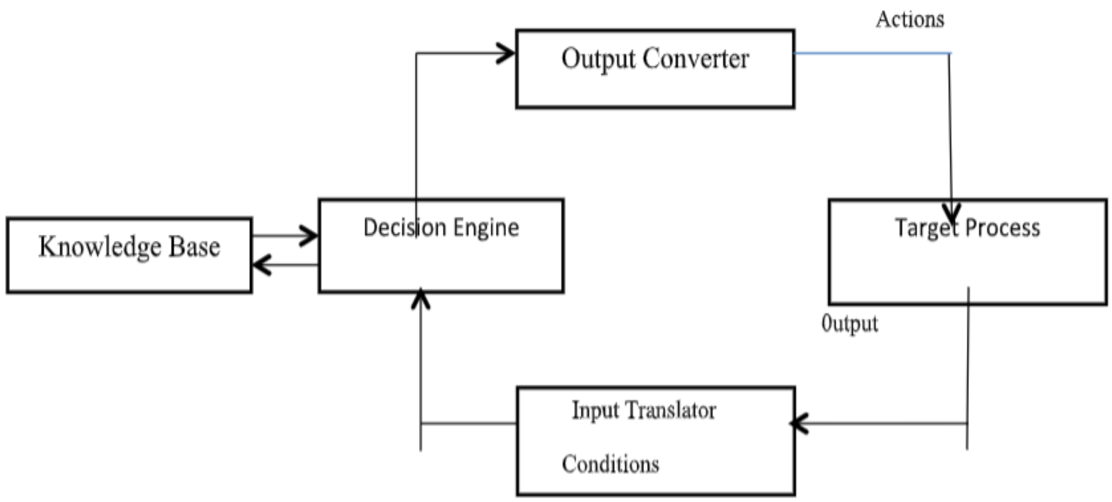

Fig 1: Structural Layout of Fuzzy Logic Controller

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These are the four steps that are involved in case of Fuzzy Theory.

Step 1- Inputs (Knowledge Base):

Here as shown in fig 2. There are two input parameters are taken: Input 1 is shown as e, Input 2 is shown as de, and Output is shown as u.

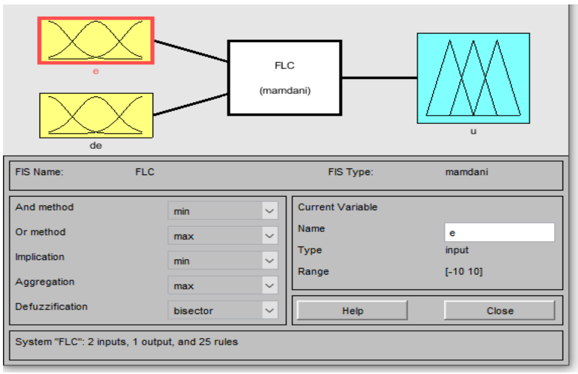

Fig 2 : Fuzzy Logic Controller with Two Inputs and One Output[7]

Step 2- Fuzzy Sets:

These measurements are transformed into fuzzy sets to represent the uncertainties. In mathematics, fuzzy sets are sets whose elements have a degree of membership. There are 5 membership functions in Input 1, i.e., e; 5 membership functions in Input 2, i.e., de; and 5 membership functions in Output, i.e., u [7], as shown in the fig.3,4,5 below.

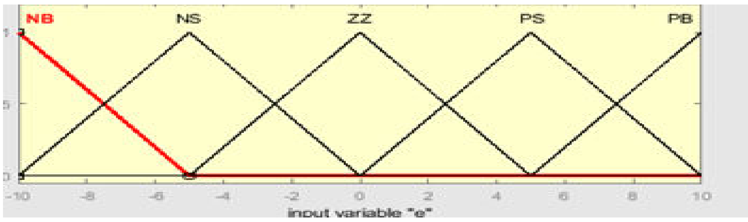

Fig 3:Membership Functions of Input-1 (e)[7]

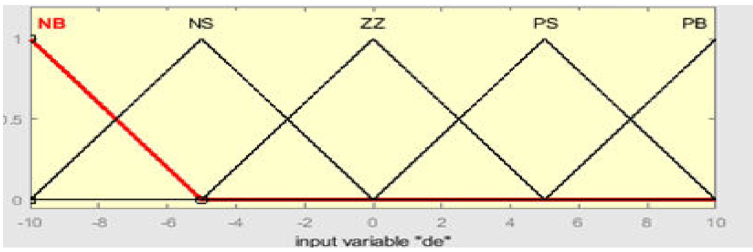

Fig 4:Membership Functions of Input-2 (de)[7]

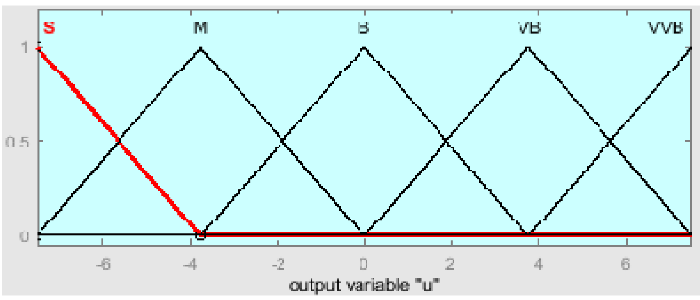

Fig 5:Membership Functions of Output (u)[7]

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Step 3- Fuzzy Inference Engine:
The fuzzy inference mechanism interprets the fuzzified inputs by employing the control rules stored in the fuzzy rule base. After evaluation, the outcome appears as a fuzzy set (or multiple fuzzy sets) spread over the range of possible actions. Inference mechanisms serve as software modules of an intelligent system that applies logical reasoning to the knowledge base to deduce new conclusions..[10] There are 25 sets of rule as[11] shown in figure 6 below-

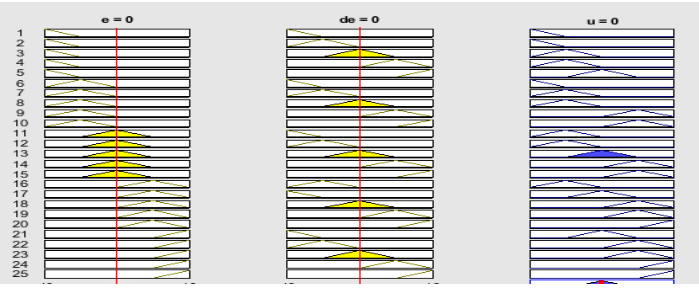

Fig 6 : Fuzzy Rules[11]

Step 4- Defuzzification:
This fuzzy set outcome is transformed into a single (crisp) value; this final step is known as "defuzzification." The defuzzified values indicate actions to be taken by the fuzzy controller..[11]

4. Model:
Below Fig.7.shows 4 areas are interconnected by tie line for load frequency control-

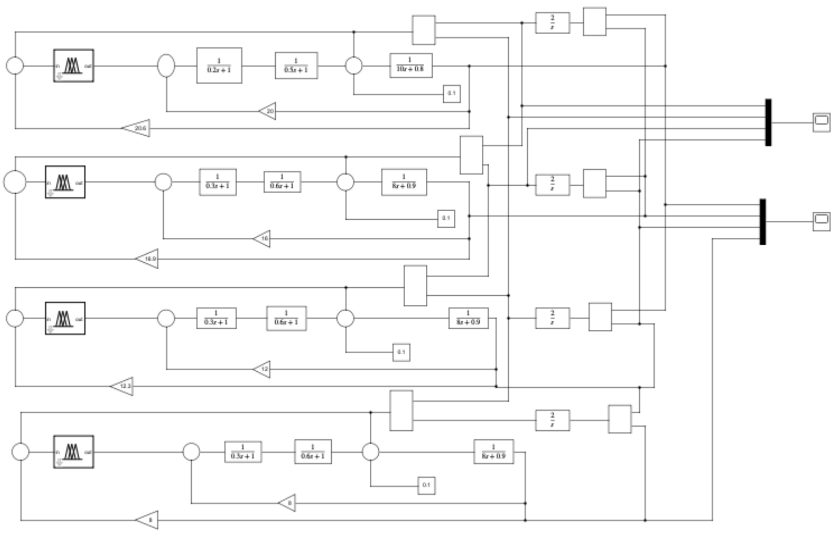

Fig 7: Load Frequency Control for Multi-Area System

According to figure 7, four single areas are interconnected by a tie-line and transformed into a Laplace function, as shown in figure 3.2 above. There are four areas, i.e., A-1, A-2, A-3, and A-4, interconnected by tie lines shown as P12, P23, P31, and P43. Here, the fuzzy logic controller is applied to minimize the frequency deviations. Governors, turbines, and generators are taken as a transfer function form.Two cathode ray oscilloscopes are connected, i.e., Cathode Ray Oscilloscope-1 and Cathode Ray Oscilloscope-2. Scope 1 shows the tie line power exchange between all four areas, and Scope 2 shows the graph of frequency deviation, its settling time, and overshoot value. Fuzzy technique is applied in all four areas, and the output from Scope 1 and Scope 2 is shown in the result.[12]

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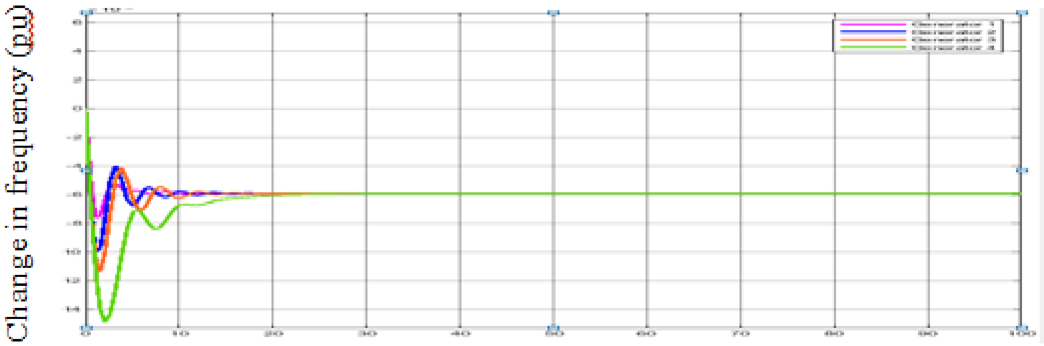
IV. RESULT AND DISCUSSION

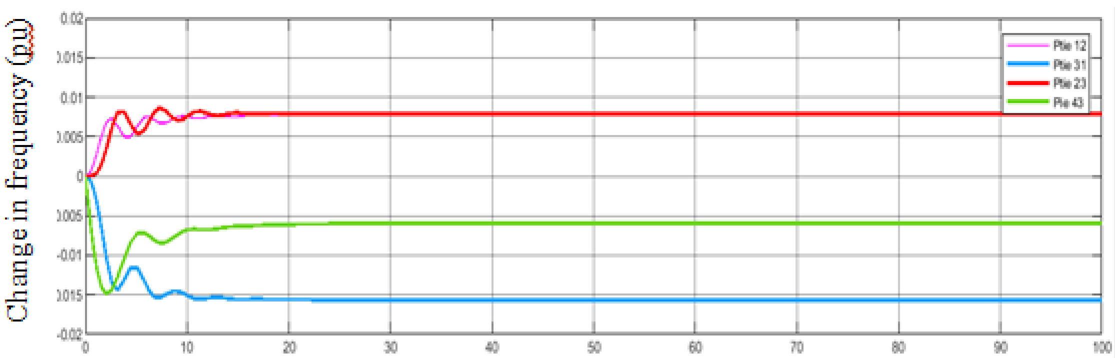
The following Graph presents the result of all four areas in power system-



TIME(Sec.)

Fig 8: Frequency Deviation in Multi-Area

Fig. 8 shows the frequency deviation in all four areas (A-1, A-2, A-3, and A-4) for the fuzzy logic controller; here the pink line represents area-1, the blue line represents area-2, the orange line represents area-3, and the green line represents area-4. At the start, when the four generators operated simultaneously, a transient response was observed. Initially, the load frequency deviation of the four areas was different, but after almost 10 seconds, frequency deviation was controlled and became constant in all areas. Fuzzy logic-based load frequency deviation for all four areas is 6 x 10^{-3} = 0.006 per unit / 0.6%. That means if the frequency is 50 Hz, then 0.6% is the error, which indicates reduced deviation due to the fuzzy logic approach. [13][14]



TIME(Sec.)

Fig 9-:Tie-Line Power Exchange of Multi-Area[14]

Fig.9 Show the multiple curves; all of these curves represent the tie-line power exchange between all four areas, i.e., P12, P31, P23, and P43. All curves initially oscillate and then settle almost around 10-12 seconds.[15]

V. CONCLUSION & FUTURE SCOPE

5.1 Conclusion

This paper presented an intelligent Fuzzy Logic Controller (FLC) for Load Frequency Control (LFC) in a four-area interconnected power system to improve frequency stability under varying load disturbances. The proposed FLC was designed using two input variables, five membership functions, and twenty-five fuzzy rules, and its performance was evaluated through MATLAB/Simulink simulations. The simulation results demonstrate that the proposed controller effectively minimizes frequency deviations and suppresses transient oscillations in all interconnected areas. The system

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achieved a steady-state frequency deviation of 0.006 p.u., while the maximum overshoot was limited to 0.75%, 0.65%, 0.40%, and 0.80% for Areas 1–4, respectively. The corresponding settling times were 2.0 s, 7.5 s, 5.0 s, and 10.2 s, indicating stable and reliable dynamic performance. In addition, the tie-line power exchange stabilized within approximately 10–12 s, confirming effective coordination among all four control areas. These results demonstrate that the proposed fuzzy logic-based controller provides accurate frequency regulation, improved transient response, and enhanced stability, making it a promising solution for modern interconnected multi-area power systems.

5.2 Future scope

1. Fuzzy-Logic can be used for five area power system.
2. Frequency deviation as well as voltage fluctuation can be controlled simultaneously.[16]

Competing Interests

The authors have no competing interests to declare that are relevant to the content of this article.

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No funding was received to assist with the preparation of this manuscript.

Author contribution

The corresponding author conceptualized the research work, designed the methodology, supervised the overall study, performed data analysis, interpreted results, and prepared the original manuscript draft. The corresponding author also handled manuscript submission, revision, and communication with the journal.
Co-Author 1 assisted in result validation, manuscript editing and final review

Data Availability Statement

Data used during this study are available from the corresponding authors on request.

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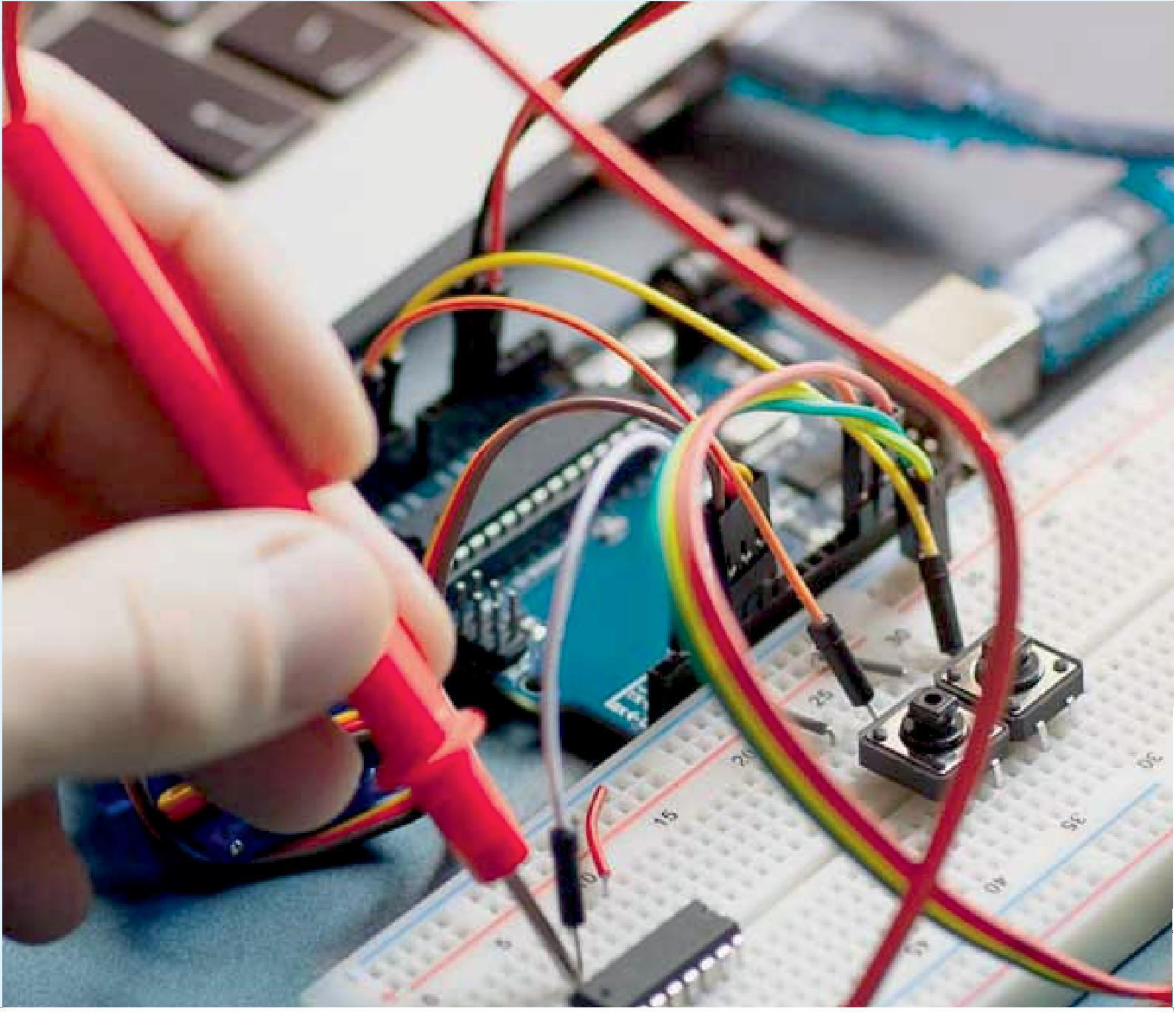

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