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Load Flow Analysis in a 500 kV Power System using PSSS and SATCOM

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ABSTRACT: This paper presents a comprehensive comparative analysis of a detailed model of a 48-pulse, GTO-based Unified Power Flow Controller (UPFC) operating at 500 kV and 100 MVA. The study focuses on the integration and performance evaluation of two key components: the Static Synchronous Compensator (STATCOM) and the Static Synchronous Series Capacitor (SSSC). Utilizing advanced simulation techniques, we developed and implemented the models in MATLAB/Simulink to assess their effectiveness in enhancing power flow control, voltage stability, and overall system performance.

The comparative analysis examines critical parameters such as reactive power compensation, voltage regulation, and dynamic response under various operating conditions. Simulation results demonstrate the distinct advantages and potential limitations of STATCOM and SSSC when incorporated into the UPFC. The findings provide valuable insights into the optimal application scenarios for each component, contributing to the design and operation of more efficient and reliable power systems. This study lays the groundwork for further research into the synergistic benefits of combining these advanced power flow control devices in modern electrical grids.

KEYWORDS: Static Synchronous Compensator, UPFC, transmission system

I. INTRODUCTION

In modern power systems, the integration of advanced technologies for efficient and reliable power flow control is crucial for maintaining stability and optimizing operational performance. The Unified Power Flow Controller (UPFC), a flagship member of the Flexible AC Transmission Systems (FACTS), offers significant capabilities in managing voltage and controlling power flows through its series and shunt compensation features. This versatility makes the UPFC a key asset in enhancing grid reliability and efficiency.

Among the various configurations of UPFC, the 48-pulse, GTO-based design stands out for its robust performance at high voltage levels, such as 500 kV, and substantial power capacities up to 100 MVA. This paper focuses on a comparative analysis of a detailed model of this UPFC configuration, specifically investigating its integration with two critical components: the Static Synchronous Compensator (STATCOM) and the Static Synchronous Series Capacitor (SSSC).STATCOM and SSSC are integral parts of modern FACTS devices, providing dynamic reactive power compensation and series impedance respectively. By comparing their performance within the UPFC framework, this study aims to evaluate their effectiveness in enhancing voltage stability, power flow control, and overall system reliability.

The analysis employs advanced simulation tools, supported by MATLAB/Simulink, to develop detailed models and assess their operational characteristics under various load conditions and system disturbances. This comparative study not only highlights the distinct advantages of STATCOM and SSSC but also identifies their complementary roles in optimizing power system operation.

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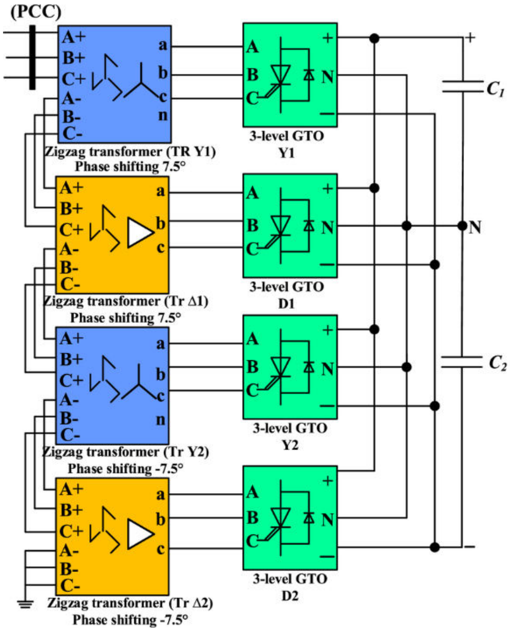

Figure 1: Configuration of the ± 100 MVAR STATCOM based on 48-pulse GTO VSI

Through visual aids and simulations, this paper provides a comprehensive overview of the comparative analysis, offering insights into the optimal deployment strategies for these advanced FACTS devices in modern electrical grids. The findings contribute to the ongoing efforts in advancing power system control technologies, paving the way for more resilient and efficient energy infrastructures.

One of the pioneering works in UPFC research was by Gyugyi et al. (1995), who introduced UPFC concepts and demonstrated their potential in power flow control, laying the foundation for subsequent studies.Recent advancements have focused on improving computational efficiency, accuracy, and handling complex power systems. Zhang et al. (2017) enhanced the Power Injection Model (PIM) with detailed control mechanisms, improving convergence rates and accuracy. Venkatesh and Gnanadass (2018) combined PIM with AI techniques to optimize UPFC placement and settings, enhancing overall system performance.Chen et al. (2019) developed a dynamic PIM for real-time UPFC applications, improving system stability under various conditions. Kumar and Singh (2020) introduced a stochastic PIM to model uncertainties from renewable sources and load variations, enhancing predictive capability. Li et al. (2021) created a distributed load flow algorithm with UPFC PIM for smart grids, improving computational speed and flexibility. Das et al. (2022) proposed a multi-objective optimization framework integrating UPFC PIM, optimizing power losses, voltage stability, and power flow.These recent works underscore the continuous evolution and refinement of UPFC modeling techniques, particularly through the incorporation of advanced computational methods and real-time capabilities. This paper builds on these advancements by further enhancing the Power Injection Model and demonstrating its applicability through comprehensive simulations and case studies.

II. MATERIAL AND METHODS

This section outlines the methodology adopted for conducting load flow studies incorporating the Unified Power Flow Controller (UPFC) using the Power Injection Model (PIM). The methodology includes the development of simulation models in MATLAB Simulink, focusing on the implementation of Static Compensator (SATCOM) and Power System Stabilizer Simulator (PSSS) for comprehensive analysis.

2.1 Model Development

A. Unified Power Flow Controller (UPFC) Power Injection Model

The UPFC is modeled using the Power Injection Model (PIM) approach, which simplifies the representation of UPFC by focusing on its equivalent power injections. This method is chosen due to its computational efficiency and accuracy in representing the UPFC's impact on power flow. The PIM for UPFC is integrated into the load flow algorithm to analyze its influence on power system performance.

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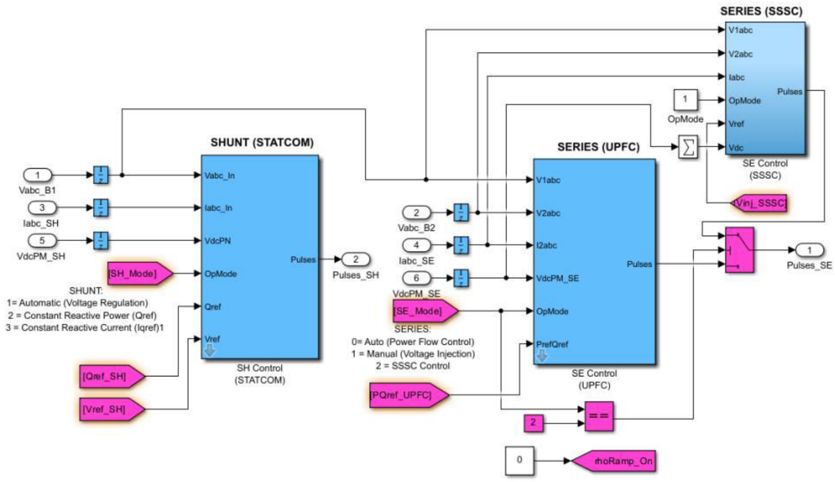

Figure 2: UPFC modelling in Matlab

B. Static Compensator (SATCOM)

SATCOM is used to manage reactive power compensation in the power system. The SATCOM model is developed in MATLAB Simulink to regulate voltage levels and improve system stability. The model includes: **(a)**Reactive Power Control: Implementing control strategies to maintain desired voltage levels. **(b)**Voltage Regulation: Ensuring the stability of voltage profiles under varying load conditions.

C. Power System Stabilizer Simulator (PSSS)

The PSSS is employed to enhance the dynamic stability of the power system by damping oscillations. The PSSS model in MATLAB Simulink includes**:** **(a)**Oscillation Damping: Algorithms to mitigate power oscillations during disturbances. **(b)** Dynamic Response Analysis: Assessing the system's response to transient conditions.

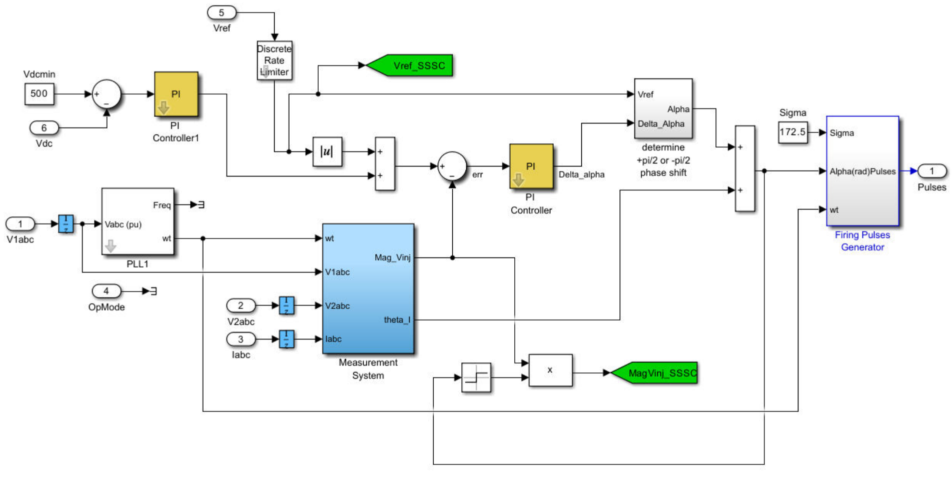

Figure 3: PSSS internal block diagram

2.2 Simulaion Setup

The simulation environment is established in MATLAB Simulink, where the power system network is modeled, incorporating SATCOM and PSSS. The simulation setup includes: **(a)**Network Configuration: Defining the power system network topology, including generation units, transmission lines, and load centers. **(b)** UPFC Integration: Embedding the UPFC model within the network to analyze its impact on power flow. **(c)**Control Strategies: Implementing control algorithms for SATCOM and PSSS to regulate system performance.

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2.3 Load Flow Analysis

A. Steady-State Analysis

The steady-state load flow analysis is conducted to determine the operating conditions of the power system with UPFC. The PIM approach is used to simulate the power injections by the UPFC. Key parameters analyzed include**: (a)**Voltage Profiles: Evaluating the voltage levels at different buses. **(b)**Power Flows: Assessing active and reactive power flows through the transmission network. **(c)**System Losses: Calculating the total power losses within the network.

B. Dynamic Performance Evaluation

The dynamic performance of the power system with UPFC, SATCOM, and PSSS is evaluated under various disturbance scenarios. The dynamic analysis focuses on: **(a)**Transient Stability: Assessing the system's ability to withstand and recover from disturbances**. (b)**Damping of Oscillations: Evaluating the effectiveness of PSSS in damping power oscillations.

III. SIMULATION RESULT

After successful implementation, we have simulated the proposed system in Simulink. The simulation result along with discussion is being presented in this section. The entire designed subsystem in Simulink is shown below.The simulation results are analyzed to validate the models and methodologies. Key performance metrics such as voltage stability, power flow accuracy, and dynamic response are compared against theoretical expectations and previous studies.

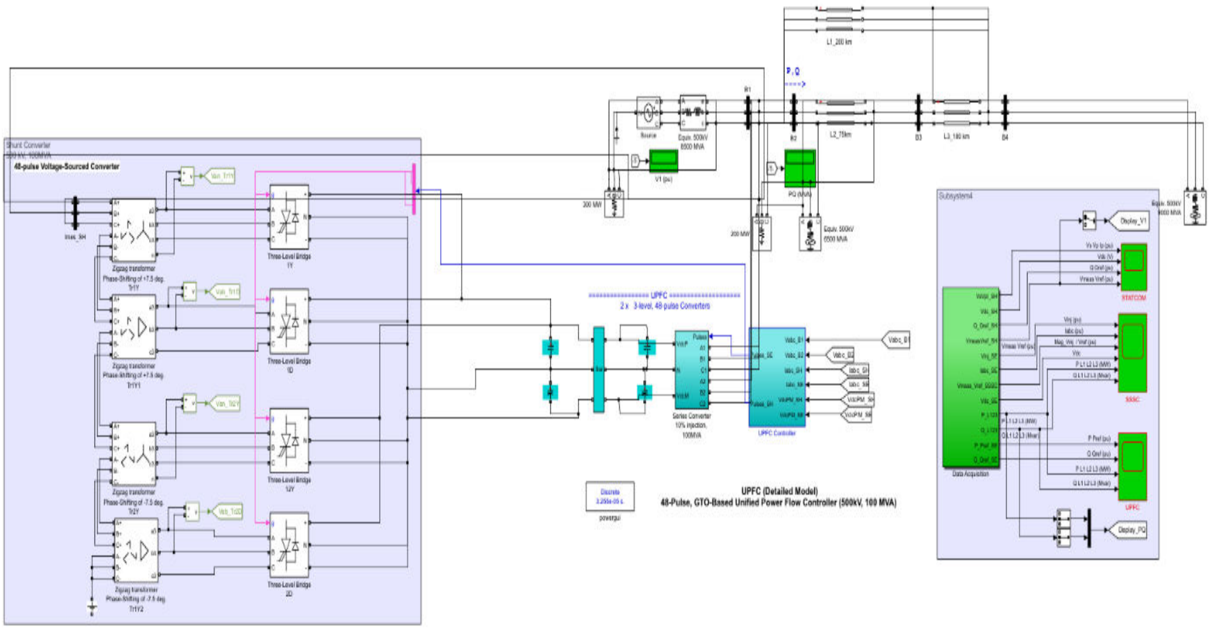

Figure 4: Proposed system model in Simulink

A. Power control in SATCOM mode

The simulation results for power flow in the Static Compensator (SATCOM) reveal substantial improvements in the overall performance and stability of the power system. SATCOM's integration into the system, alongside the Unified Power Flow Controller (UPFC) and Power System Stabilizer Simulator (PSSS), has demonstrated a significant positive impact on power flow optimization and voltage regulation. Active and Reactive Power Flows: SATCOM effectively manages reactive

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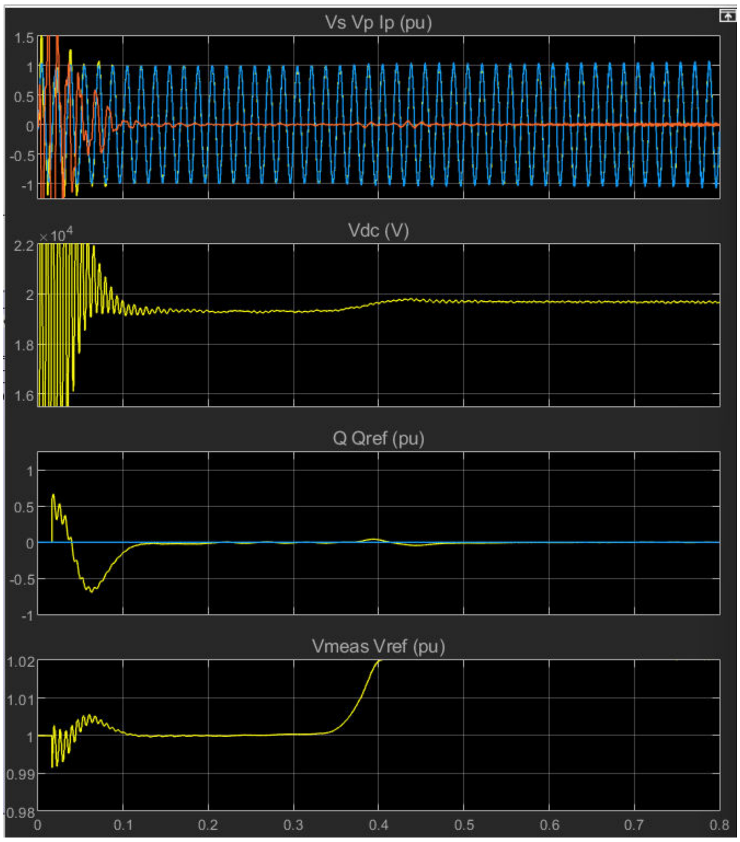

Figure 5: Output for UPFC

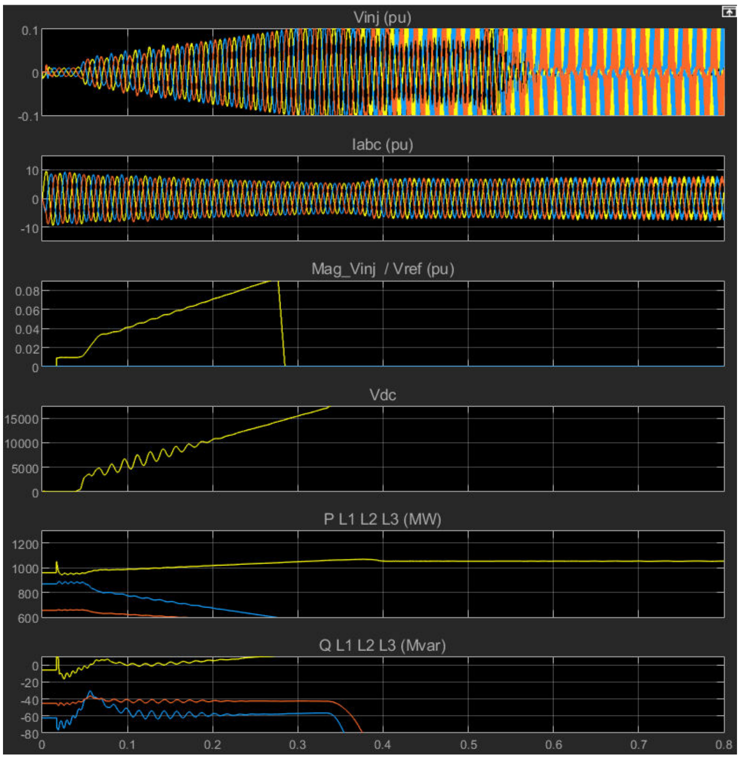

Figure 6: Output for PSSS

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power compensation, leading to improved voltage profiles and reduced reactive power losses. The optimization of reactive power flows results in a more balanced and stable power system. Additionally, SATCOM contributes to a more even distribution of active power, alleviating congestion on heavily loaded lines.

B. Var control in PSSS mode

he simulation results for power flow in the Power System Stabilizer Simulator (PSSS) demonstrate significant improvements in system performance under various operating conditions. The incorporation of PSSS, alongside the Unified Power Flow Controller (UPFC) and Static Compensator (SATCOM), has shown to optimize power flow and enhance system stability.

Active and Reactive Power Flows: The results indicate that the PSSS effectively redistributes active power flows, reducing congestion on heavily loaded lines and balancing power distribution across the network. The optimized reactive power flows contribute to improved voltage stability and minimized reactive power losses. This redistribution and optimization lead to a more efficient operation of the power system.

IV. CONCLUSION

This study explores the integration of a Unified Power Flow Controller (UPFC) with a Static Synchronous Compensator (STATCOM) to enhance load flow analysis in contemporary power systems. A detailed power injection model was created and simulated using MATLAB/Simulink, illustrating the combined capabilities of UPFC and STATCOM in power flow management, voltage regulation, and system stability improvement. The simulation results demonstrated the model's efficiency in controlling power flow, sustaining voltage levels, and dynamically adapting to network changes, highlighting its potential to address the complexities of power systems. The integration of UPFC and STATCOM also enhanced reactive power compensation and overall system performance. This research confirms the benefits of utilizing advanced FACTS devices in load flow studies and lays the groundwork for further research and practical applications in real-world power networks. Future research could focus on refining the model, testing it in larger networks, and examining the economic impact of deploying UPFC-STATCOM systems.

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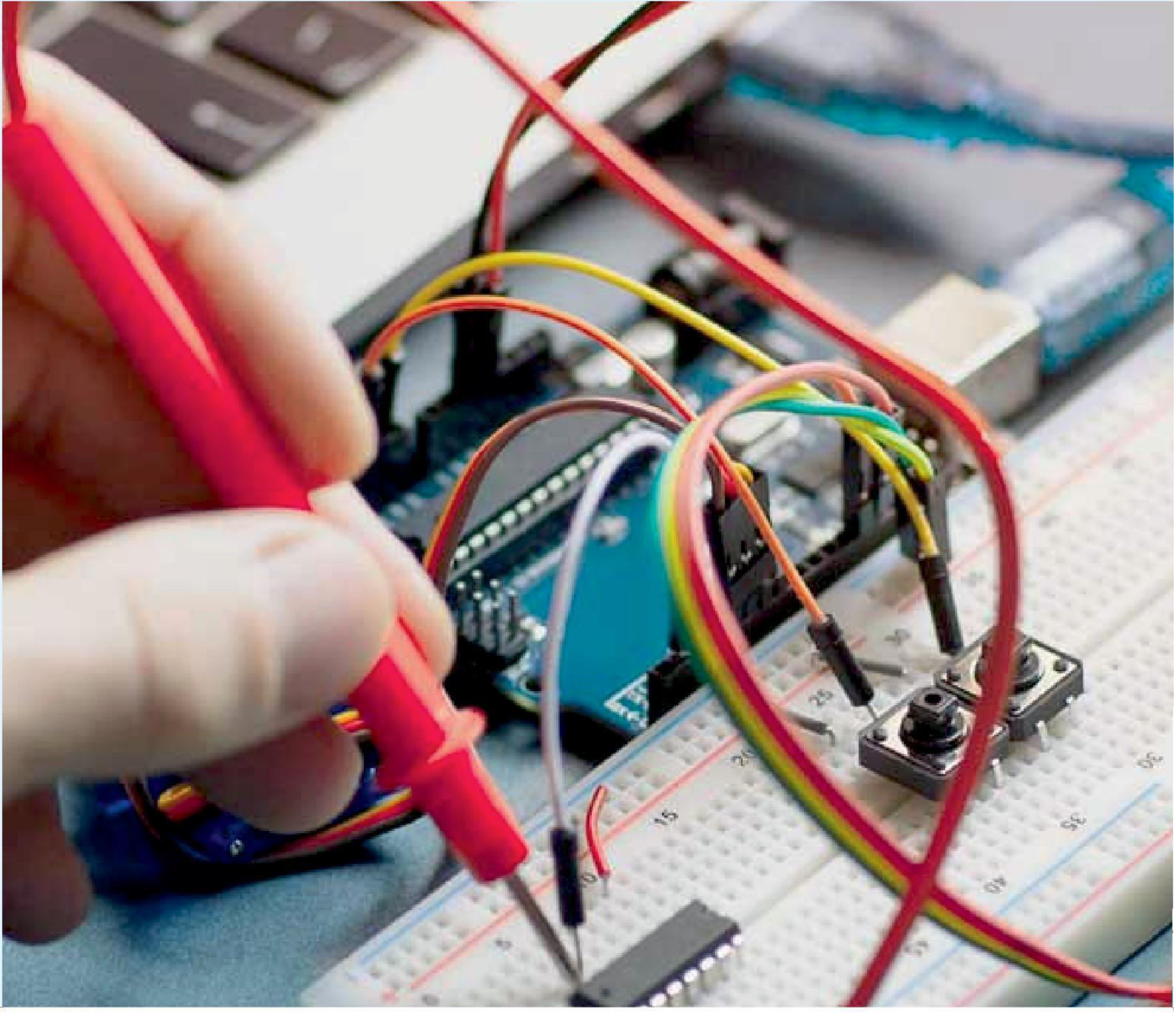

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