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An Intelligent Solid State Transformer with Bidirectional Power-flow for Smart Grid Application

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ABSTRACT: This paper proposes a new bi-directional power flow controller using an intelligent semiconductor transformer for the smart distribution system and smart grid applications. The proposed converter system consists of high-voltage high-frequency ac/dc converter, bidirectional low-voltage dc/dc converter, and hybrid- switching dc/ac inverter. The input to-output isolation is done with a high-frequency transformer. The whole system is compact in size and light weight, capability of compensating voltage sag or swell. For efficient performance of the proposed system a Solar PV is allowed at the DC-link of the proposed converter for more active power. The operational feasibility of proposed system is analyzed using MATLAB/SIMULINK software

KEYWORDS: Bidirectional dc/ac converter, bidirectional intelligent semiconductor transformer, high-voltage ac/dc rectifier, hybrid-switching.

I.INTRODUCTION

Traditional transformer composed of coil and iron core can change only the magnitude of the ac voltage and the quality of supplying power is totally dependent on that of the input power. So, it cannot be applicable for the smart grid, in which the magnitude and frequency of the operation voltage are various and high-quality power is required. Intelligent semiconductor transformer or solid-state transformer was proposed by EPRI to replace the conventional transformer in railway systems and substations, in which light weight is mandatorily required [1]. Recently, EPRI has reported 100 kVA single-phase semiconductor transformer named intelligent universal transformer for distribution automation [2]. Intelligent semiconductor transformer can easily offer small size and light weight because it operates at much higher frequency with reduction of the magnetic component.

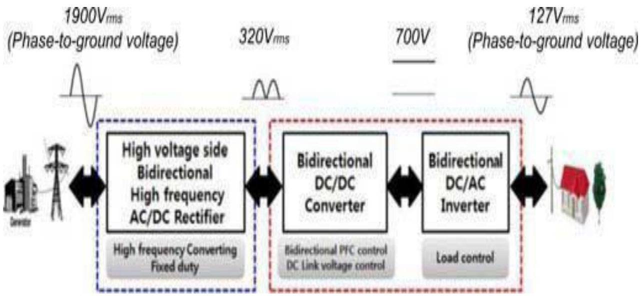

Fig.1 configuration of the proposed system

It can supply not only the dc power, but also high-quality ac power to the customer by compensating the voltage sag, swell, and harmonics. So, it can be utilized for implementing the smart distribution system and the micro grid [3]–[5]. Various kinds of intelligent semiconductor transformers were already proposed. However, since the power flow in these transformers is unidirectional, it is not properly applicable for the dc distribution and micro grid [1], [2], [6]–[10]. One can find some studies on the semiconductor transformer topologies with bidirectional power flow capability. In [11] and [12], bidirectional power flow can be achieved but the power factor is not controlled. The topology can compensate sag/swell voltage; however, it employs heavy and bulky line-frequency transformer for isolation. The

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semiconductor transformer in [14] has not only the bidirectional power flow functions but also voltage sag compensation where high-frequency dc/dc power conversion is employed. The circuit configuration in [14], however, shows too many active

II. PROPOSED SYSTEM

Fig. 2 shows the power circuit of ac/dc rectifier, which converts single-phase ac voltage of 1900 into full-bridge-rectified waveform of 320 V. The ac/dc converter has high-frequency transformers, which offer high-frequency resonance and input–output isolation.

The input side works under high voltage, while the output side works under low voltage. So, the input side is designed with three half-bridge modules connected in series, in which two IGBT units are connected in series in the reverse direction. The output side is designed with three half-bridge modules connected in shunt. Whole system operates in bidirectional high-frequency resonance mode under a fixed frequency with 50% duty ratio to reduce system size and switching loss.

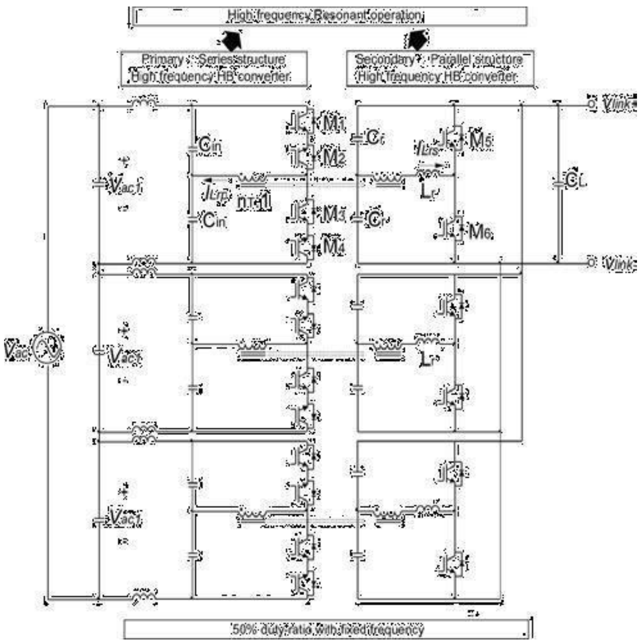

Fig. 2. Bidirectional high-frequency ac/dc converter

Because the resonant stage is basically an LLC converter, the input-to-output gain of each resonantconverter, that is defined by $v_{link}/|vac1|$, is determined only by its transformer turns-ratio nT if the resonant frequency fr is equal to the switching frequency fsr [24], where vac1 is the input voltage of each resonant stage and it is equal to vac/3. Since the input and output filter capacitors of Cin and CL are much larger than Cr and parasitic capacitances of switches are much smaller than Cr, the resonant frequency fr

, which is equal to fsr , is calculated as $1/[2\pi(2LrCr)^{0.5}]$ with resonant inductor Lr and two resonant capacitors of Cr .

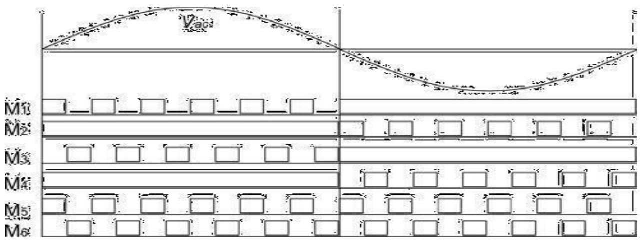

Fig. 3. Driving signals of high-voltage resonant stage.

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Fig. 3 shows the switching pulses for each switch in single-module of the bidirectional high-frequency ac/dc converter according to the polarity of the ac input voltage. The gating pulses for each switch are generated with same pattern regardless of the direction of power flow. Before explanation, it is assumed that the magnetizing inductance Lm is infinity.

Mode 1: The direction of power flow is forward and the polarity of input voltage is positive as shown in Fig. 4(a). In the first stage, the primary current flows through the transistor in M1 and the diode in M2 when M1 turns ON. At this instance, the secondary current flows through diode in M5. In the next stage, the primary current flows through the transistor in M3 and the diode in M4 when M3 turns ON. At this instance, the secondary current flows through the diode in M6 .

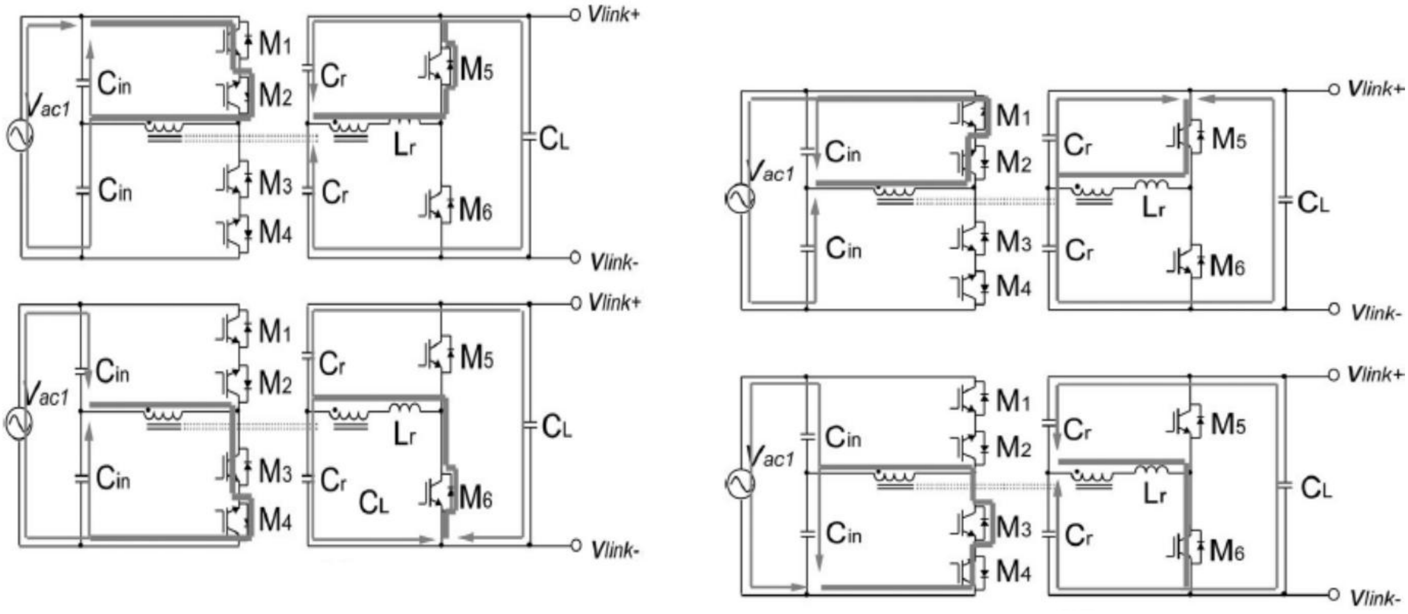

Fig. 4. Current path for each operation mode in the ac/dc rectifier. (a) Mode 1: forward power flow_ positive input voltage. (b) Mode 2: forward power flow_negative input voltage. (c) Mode 3: Reverse power flow_ positive input voltage. (d) Mode 4: Reverse power flow_ negative input voltage.

Mode 2: The direction of power flow is forward and the polarity of input voltage is negative as shown in Fig. 4(b). In the first stage, the primary current flows through the transistor in M2 and the diode in M1 when M2 turns ON. At this instance, the secondary current flows through diode in M6 . In the next stage, the primary current flows through the transistor in M4 and the diode in M3 when M4 turns ON. At this instance, the secondary current flows through the diode in M5 .

Mode 3: The direction of power flow is backward and the polarity of input voltage is positive as shown in Fig. 4(c). In the first stage, the secondary current flows through transistor inM5 when M5 turns ON. At this instance, the primary current flows through the diode in M1 and the transistor in M2 . In the next stage, the secondary current flows through the transistor in M6 when M6 turns ON. At this instance, the primary current flows through the diode in M3 and the transistor in M4 .

Mode 4: The direction of power flow is backward and the polarity of input voltage is negative as shown in Fig. 4(d). In the first stage, the secondary current flows through transistor inM6 when M6 turns ON. At this instance, the primary current flows through the transistor in M1 and the diode in M2. In the next stage, the secondary current flows through the transistor in M5 when M5 turns ON. At this instance, the primary current flows through the transistor in M3 and the diode in M4.

The low-voltage part consists of the dc/dc converter and the dc/ac inverter connected in cascade as shown in Fig.5. The dc/dc converter changes the full-bridge rectified waveform of 320 V into the constant dc voltage of 700 V and the dc/ac inverter changes the constant dc voltage of 700 V into the single-phase ac voltage of 127 V. The dc/dc converter and

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dc/ac inverter use a hybrid switch with IGBT and MOSFET connected in parallel. The dc/dc converter and dc/ac inverter are composed of two half-bridges connected in cascade. The dc/dc converter operates to control the power factor and the dc-link voltage, while the dc/ac inverter operates to control the output voltage. As the switching frequency in IGBT increases, the switching loss increases due to tail-current, which critically reduces the system efficiency.

In order to improve this switching loss, a MOSFET is connected in parallel to implement a hybrid switch. The MOSFET turns ON a few microseconds ahead when the IGBT switch turns OFF. After the MOSFET turns ON, the IGBT turns OFF immediately and the MOSFET turns OFF at the instant that the IGBT is originally to turn OFF. Hybrid switching offers reduction of recovery loss due to tail-current. If a diode is connected in series with MOSFET, MOSFET destruction due to counter electromotive force can be protected. If resistance is connected in parallel with diode, ringing phenomenon can be reduced.

III. SIMULATION RESULTS

The MATLAB simulation has carried out to confirm the circuit operation and control performance of the proposed semiconductor transformer. Fig. 6 to 10 shows simulation results to check the operation of the proposed transformer under power flow reversal. The first graph shows the input voltage and current waveform

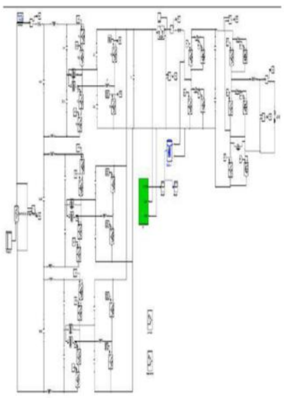

Fig.6 Matlab/Simulink design of proposed system

The second graph shows the 50-kHz resonant current for ZVS when the power flow is reversed from forward to backward at 0.18 ms

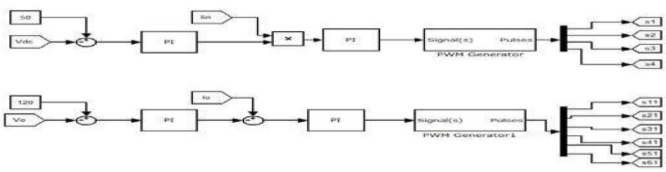

Fig.7 Control strategy used

The third graph shows the output voltage waveform with the full-bridge rectified voltage and current. The fourth graph shows the dc-link voltage, which maintains constant voltage of 700 V with negligible ripples. The fifth graph shows the output voltage and current, which are almost sinusoidal with negligible harmonics. The inner system of string of Solar modules used to produce required amount of Volatge and current. The amount of voltage is about 700V dc at the BUS but current is decided based on the load.

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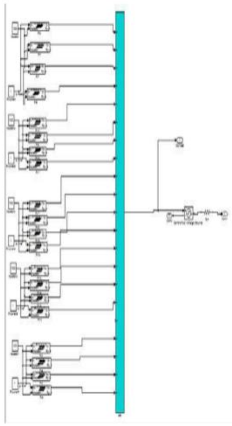

Fig.8 Solar PV stack system

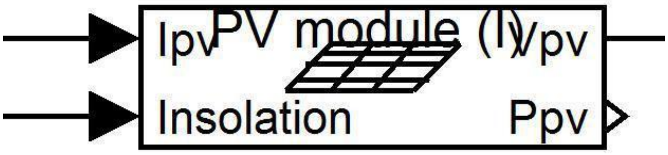

Fig.9 Solar PV module

The individual module of solar plate is as shown in fig.9 with insolation of 1000cal. The equivalent circuit of the solar PV cell is shown in fig.10

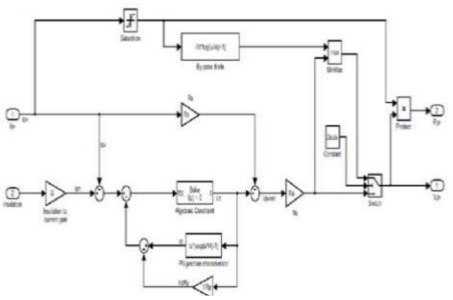

Fig.10 equivalent circuit of PV module

Through the simulation results, it is confirmed that the proposed semiconductor transformer operates properly as analyzed with the theoretical approach. Fig. 11 shows simulation results to check the operation of the proposed semiconductor transformer under input voltage sag in forward power flow and reverse power flow. Fig. 11(a) shows the input voltage and current, rectified voltage and current, dc-link voltage, and output voltage and current when sag occurs in the forward power flow.

The input current and rectified current slightly increase during sag to maintain same input power. The dc-link voltage is maintained with 700 V through the voltage control of the dc/dc converter. Fig. 11(b) shows the input voltage and current, rectified voltage and current, dc-link voltage, and output voltage and current when sag occurs in the reverse power flow. The input current and rectified current slightly increase during sag to maintain same power. The dc-link voltage is maintained with 700 V through the voltage control of dc/dc converter

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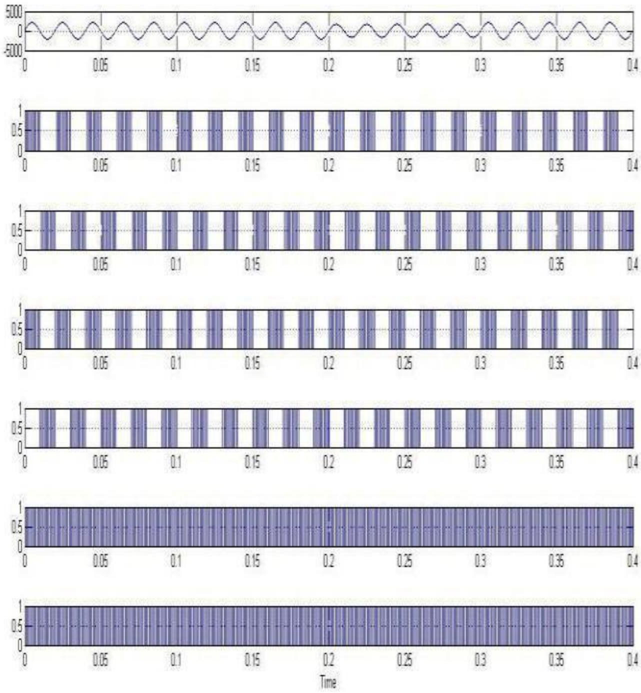

Fig.11 gate pulses of proposed converter

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V. CONCLUSION

This paper proposes a new bidirectional intelligent semiconductor transformer for the smart distribution system and micro grid applications. The proposed BIST consists of high-voltage part and low-voltage part. The high -voltage part is composed of several half-bridge ac/dc converters connected in series through high-frequency transformers to cope with high input voltage, while the low-voltage part is composed of bidirectional half-bridge dc/dc converter and dc/ac PWM inverter. In the proposed BIST, the input voltage on the high-voltage side is 1900 V and the output voltage on the low-voltage side is 127 V, in which the primary and secondary dc-link voltages are 320 V and 700 V, respectively. A three-phase 3.3 kV/220 V transformer can be built using three units of 1.9 kV/127 V single-phase module. The operational feasibility of the proposed transformer was verified by computer simulation with MATLAB/SIMULINK software. The proposed transformer could be applicable for implementing the smart grid.

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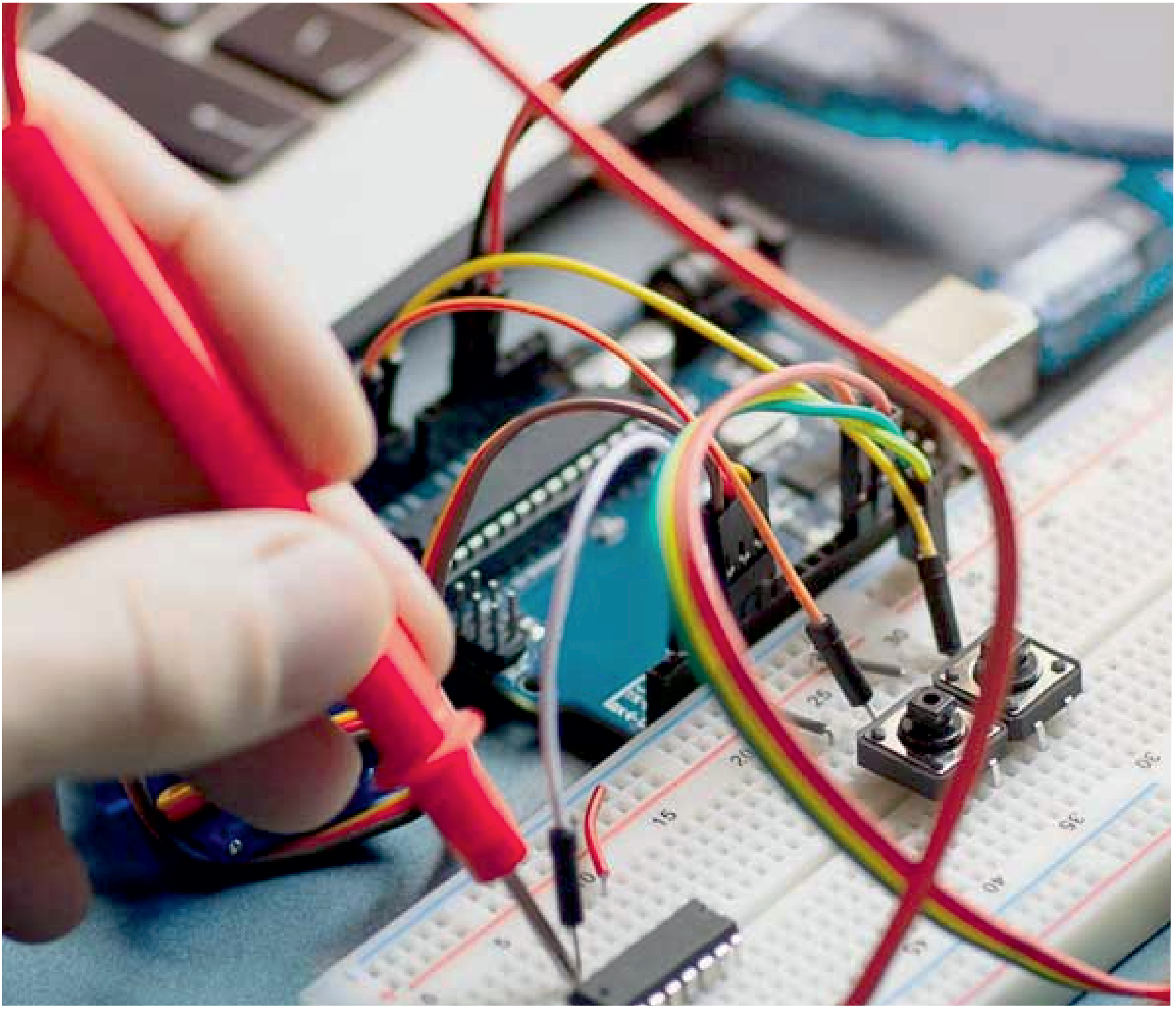

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