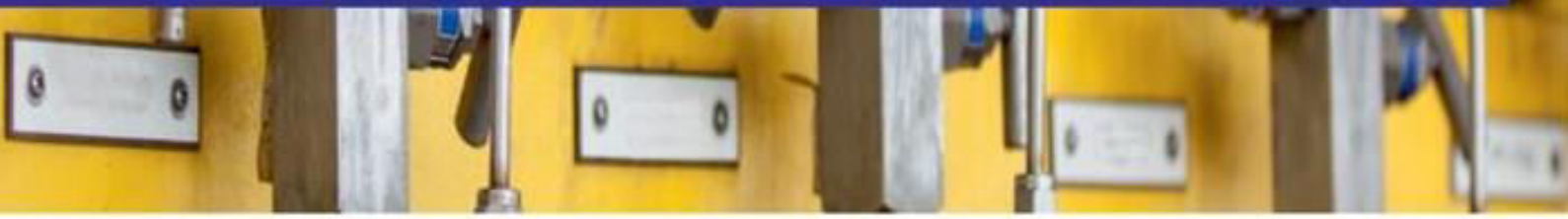


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High-Order Polynomial-Based Analytical Determination of Physically Feasible Roots and Excitation Capacitance Considering Pitch Angle in Wind Turbine-Driven Self-Excited Induction Generators under Variable Loads

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ABSTRACT: The performance of wind-driven self-excited induction generators (SEIGs) depends strongly on the excitation capacitance required to establish and maintain self-excitation under variable load conditions. In stand-alone applications, changes in turbine pitch angle affect the aerodynamic power captured by the rotor and its operating speed, thereby influencing the electrical conditions for self-excitation. This paper presents an analytical approach for determining physically feasible operating roots and estimating the required excitation capacitance under different pitch angles and loading conditions. This approach relies on formulating a high-order polynomial to identify physically acceptable solutions, followed by capacitance estimation based on a steady-state generator model. A MATLAB/Simulink model was used to investigate the combined effect of blade pitch angle and load variation on system performance. The analysis highlights the importance of considering turbine operating conditions, along with electrical load characteristics, when determining the required excitation capacitance. The results also provide useful indicators for capacitance selection in wind-driven SEIG systems operating under varying conditions

KEYWORDS*:* High-Order Polynomial, pitch angle, SEIG, Excitation Capacitance, Various loads

I. INTRODUCTION

Wind turbines are currently considered one of the most important sources of renewable energy. Their performance depends on various factors, the most important of which are how to control the angle of inclination of the blades and the reactive power requirements for excitation. Self-excited induction generators (SEIGs) play a vital role in enhancing energy generation efficiency due to their simplicity, robustness, and ability to operate under variable-speed conditions. One of the major challenges facing the use of these generators is the poor regulation of voltage and frequency under varying speed and load conditions. Dynamic simulations have shown that increasing the excitation capacitance can compensate for voltage drops caused by load variations, but frequency regulation itself requires increasing the rotor speed [1-3]. Besides generator type selection, the design of the wind turbine blades is crucial in controlling the amount of kinetic energy captured from the wind. Dynamic control of the pitch angle allows for a balance between maximizing power output and protecting the system from overloads [4].

Operating induction generators in off-grid renewable energy systems presents several challenges, most notably their inability to self-start and their constant need for an external source of reactive power, such as excitation capacitors. Poor control of rotor speed or excitation capacitance can lead to unstable operation and even failure to achieve self-excitation [5]. A study by Kesari et al. established upper and lower limits for excitation capacitance to avoid both under- and over-excitation problems and compared different methods for calculating the required reactive power [6]. These findings are particularly relevant for off-grid applications and in rural areas.

Numerous studies have focused on analyzing the stability and performance of self-excited induction generators in wind turbine systems, with particular attention to selecting the optimal excitation capacitance that ensures 7–8]. Determining the minimum capacitance required for self-excitation is of practical importance, as it involves solving two nonlinear equations. Although numerous numerical methods exist for solving these equations, many rely on iterative or experimental approaches [9-10]. Some studies have addressed the determination of the optimal excitation capacitance

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in a self-excited induction generator (SEIG) wind turbine powering an induction motor connected to a centrifugal pump, while others have emphasized the practical need for accurate estimation of this value [11-12].

Determining the minimum required self-excitability capacitance is crucial for ensuring efficient and stable performance in standalone SEIG systems. Several studies have proposed simplified methods for calculating this "critical capacitance" using an equivalent circuit model, solving equations that relate the total impedance to the relative frequency [13-16]. Researchers have also investigated the effect of iron loss in the turbine core on the required minimum capacitance, demonstrating that neglecting this loss leads to inaccurate estimates [17-18]. Using PID control strategies, dynamic models of wind turbines have been developed to regulate the pitch angle and improve system performance [19–20]. Previous work has extensively explored how excitation capacitance influences the steady-state characteristics of SEIGs. The capacitor must fall within a certain range; otherwise, self-excitation cannot occur. Furthermore, if the load impedance drops below a critical value, self-excitation becomes impossible regardless of the capacitance [21–25].

Regarding the analytical methods used to study SEIGs, two main modeling approaches exist: the steady-state model and the dynamic model. The steady-state model includes the loop-impedance and nodal-admittance methods. The loop impedance method involves adjusting the total impedance of the generator, including the excitation capacitor, to determine the operating voltage and frequency through an iterative procedure [26-30]. The nodal permittivity method, on the other hand, relies on zeroing the real and imaginary parts of the total permittivity at rest to formulate the governing equations [31-36]. Regarding the dynamic modeling of self-excited induction generators, it typically employs the equivalent circuit of the D-Q axes, which allows for more accurate observation of the system's transient behavior [37-40].

Problem statement

Published literature indicates a clear research gap; the effect of blade pitch angle on the precise determination of excitation capacitance in self-excited induction generators (SEIGs) has not yet been adequately studied. Therefore, the current research aims to explore the relationship between changes in blade pitch angle and the selection of optimal excitation capacitance in SEIG systems powered by low-speed, low-cost wind turbines. Unlike previous studies that often rely on DC motor simulations as power sources, this work uses a dynamic model of the wind turbine that mimics the actual behavior of the generation system. This approach allows for a more realistic simulation of generator performance under varying wind speeds and pitch angles, and facilitates the analysis of transient wind disturbances and their impact on generator stability, providing practical insights that more accurately simulate real-world operating scenarios

II.SYSTEM DESCRIPTION AND ANALYTICAL TECHNIQUE TO SOLVE EQUIVALENT CIRCUIT

Figure 1 illustrates a system consisting of a self-excited induction generator connected to a wind turbine, three-phase R-L load and three phase Capacitors are used to provide reactive power to the generator. For steady-state analysis, the loop impedance and node admittance methods were used to evaluate the variable parameters.

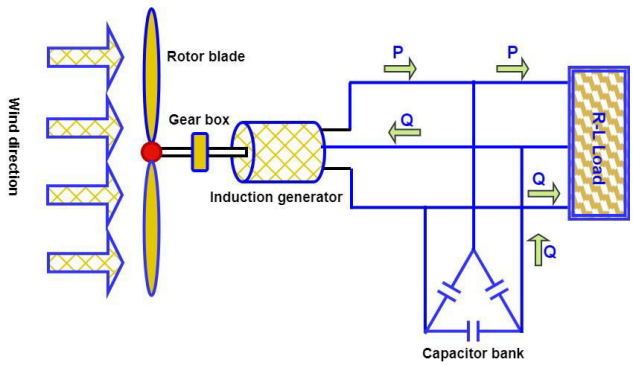


Figure 1. Schematic diagram of SEIG

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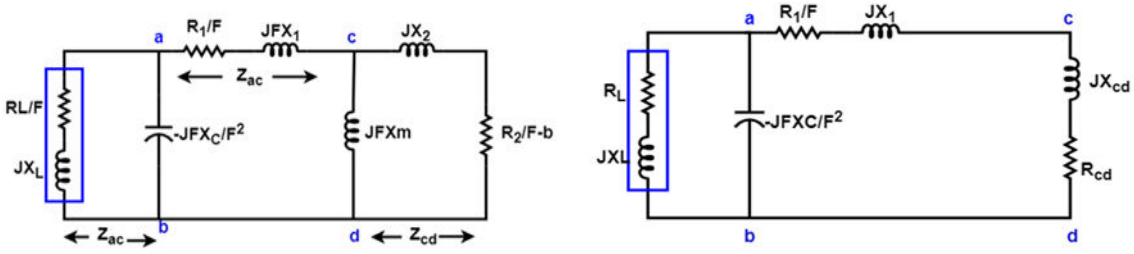
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III. CAPACITANCE REQUIREMENTS FOR SEIG

The steady-state analysis of a self-excited induction generator (SEIG) is based on a per-phase equivalent circuit model, as shown in Figure 2 of the study. In this model, the reactance and voltage values are converted to the base frequency to facilitate analysis. For the machine to self-generate voltage, the capacitance of the excitation capacitor must be above a certain minimum threshold. Stable output voltage also requires the machine to operate within a high magnetic saturation region, meaning that the magnetizing reactance (Xm) is not constant, but varies depending on the load and operating conditions. Successful self-excitation requires that the actual value of Xm generated by the load and capacitor capacitance be less than the maximum unsaturated value (Xms). Fulfilling the condition Xm = Xms determines the minimum required excitation capacitance. If this value is not met, self-excitation will not occur. The literature suggests two basic approaches for analyzing the steady-state behavior of a SEIG [13].

- The loop impedance method.
- The nodal admission method



(a) (b)

Figure 2. equivalent circuit of SEIG (a) Per-phase (b) Simplified equivalent circuit

Simplified equivalent circuit:

$$Z_{ab} + X_{cd} + X_{ac} = 0 \qquad (1)$$

By setting the real and imaginary parts of Equation (1) to zero, the following system of simultaneous non-linear equations is obtained:

$$\mathrm{REAL}(X_c, F) = C_1F^3 + C_2F^2 + (C_3X_c + C_4)F + C_5X_c = 0 \quad (2\text{-a})$$
$$\mathrm{IMEG}(X_c, F) = (Q_1X_c + Q_2)F^2 + (Q_3X_c + Q_4)F + Q_5X_c = 0 \quad (2\text{-b})$$

The coefficients C1 to C5 and Q1 to Q5 of the two characteristic equations are computed using MATLAB and are provided [47]. These nonlinear equations are then solved numerically using the Newton-Raphson method, also implemented in MATLAB. By Apply nodal admittance method in Fig. 2

$$\frac{F*R_L}{R_L^2 + F^2*X_L^2} + \frac{R_{AD}}{R_{AD}^2 + X_{AD}^2} + j*\left(\frac{F^2}{X_C} - \frac{F^2*X_L}{R_L^2 + F^2*X_L^2} - \frac{X_{AD}}{R_{AD}^2 + X_{AD}^2}\right) = 0 \quad (3)$$

By setting the real and imaginary parts of equation (11) to zero separately, we obtain:

$$\frac{FR_L}{R_L^2 + F^2X_L^2} + \frac{R_{ad}}{R_{ad}^2 + X_{ad}^2} = 0 \qquad (4)$$

$$\frac{F^2}{X_c} - \frac{F^2X_L}{R_L^2 + F^2X_L^2} - \frac{X_{ad}}{R_{ad}^2 + X_{ad}^2} = 0 \qquad (5)$$

It is observed that equation (3) is independent of Xc, with the per-unit frequency F being the only variable. Once the value of F is determined, equation (4) allows for the calculation of Xc. Through algebraic transformation, equation (3) is reformulated into a sixth-order polynomial form with respect to frequency (F), allowing numerical root-solving.

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$$P_6F^6 + P_5F^5 + P_4F^4 + P_3F^3 + P_2F^{26} + P_1F + P_0 = 0 \quad (6)$$

The derivation of the coefficients P0 to P6 is detailed in References [42]. Equation (5) can be solved numerically to determine both real and complex roots. However, only the real roots are of physical significance in this context. Among them, the largest positive real root corresponds to the per-unit frequency Fmix, which is associated with the minimum required excitation capacitance Cmin. Once the maximum frequency Fmax is identified, Equation (6) can be employed to compute the minimum capacitance value as follows:

$$\text{Cex} = 1/(2 * \text{pi} * \text{fb} * \text{Zb} * \text{Fmax\^{}2}) * \left[F_{max}^2 * \frac{X_L}{R_L^2 + F_{max}^2 * X_L^2} + \frac{B}{A^2 + B^2} \right] (7)$$

Whear:

$$D = R_r^2 + (F - V)^2(X_r + X_m)^2$$

$$A = \frac{R_s}{F} + \frac{(F - V)R_rX_m^2}{D}$$

$$B = X_s + \frac{[R_r^2X_m + (F - V)^2X_rX_m(X_r + X_m)]}{D}$$

IV. APPLICATION PROPOSED METHOD

The induction machine was a three-phase, 400/440V, 8.5A, 50Hz, 4.5/6 kW/hp, 4-pole, 1440 rpm, The machine parameters were: RS = 0.068993 p.u , Rr = 0.012492 p.u. , Xs = Xr = 0.074575 p.u., Xm = 2.157066 p.u. Applying this data to equation (5) and solving for frequency, we obtain Six roots. Of these roots, only two are real and positive, and they are as follows:

$$0.7325\,F^6 - 2.8639F^5 + 5.0979F^4 - 6.1949F^3 + 5.6801F^2 - 3.1838F + 0.7325 = 0$$

By substituting the obtained frequencies into Equation (6), the corresponding minimum capacitance value is calculated as Cmin=50.1874 μF. As before, only the real roots are considered valid, with the largest among them defining the per-unit frequency Fmax associated with this capacitance.

F1,2 = 0.0177 ± j 1.1012 p. u
F3,4 = 1.1379 ±j 0.2734 p. u
F5 = 0.9910 p. u
F6 = 0.6074 p. u

V. CHARACTERISTICS AND PITCH ANGLE CONTROL OF WIND TURBINE

It is important to understand the different operating characteristics of wind turbines, and analyze the overall system performance under different operating conditions. Special features are the relationship between speed and torque, the relationship between power and rotational speed, as well as blade pitch angle and excitation capacity requirements of the self-excited induction generator. The ability to regulate the blade pitch angle is reported to be one of the best ways to reduce turbine power generation above a safe wind speed. The pitch angle is controlled by a system of electric (servo) motors or hydraulic systems. There are different approaches in controlling the pitch angle depending on the type of input signal provided to calculate the optimum angle.One method relies on plotting the relationship between the pitch angle and wind speed, but this approach is limited in accuracy due to the difficulty of obtaining real-time and accurate measurements of the actual wind speed. Therefore, error signals are preferred in modern control systems. For example, a controller can send the power difference between the actual and required values to determine the appropriate angle, or the difference between the generator's rotational speed and its reference value can be used as a control signal to adjust the pitch. This method is more efficient and widespread due to its high accuracy and dynamic response. It's worth noting that wind power is directly proportional to the cube of the wind speed and can be expressed using the well-known equation.

$$p = 0.5\rho AV^3 \quad (8)$$

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Although wind carries a significant amount of energy, a turbine cannot fully exploit this energy. According to the Betz Limit, the theoretical maximum energy extraction from wind does not exceed 59% of the total available energy. This ratio, known as the power factor (Cp), represents the efficiency of converting wind energy into mechanical energy. It is affected by several factors, most notably the angle of inclination of the blades and the ratio of the rotor speed to the wind speed.Accordingly, the mechanical power a turbine can extract from the wind is calculated using the following equation:

$$Pw = \frac{1}{2}\rho AV3Cp(\theta) \quad (9)$$

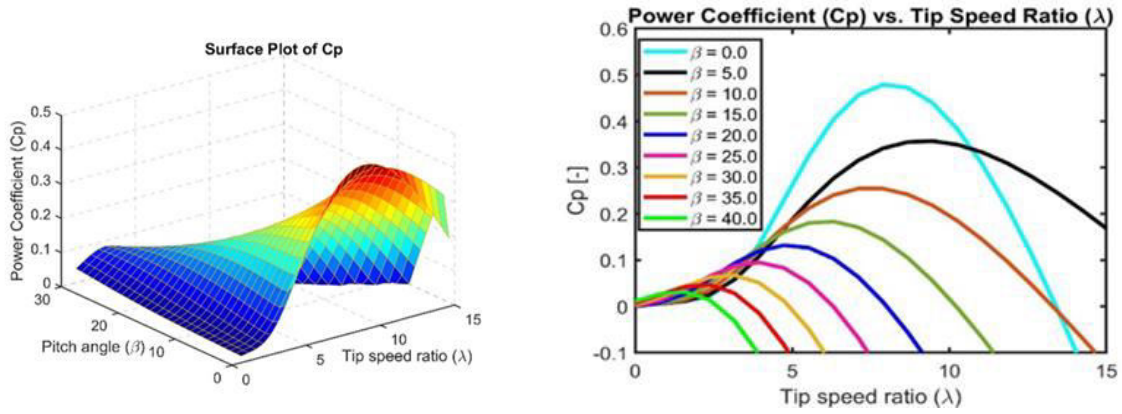
where:
Pw: Mechanical output power of the turbine (W)
ρ: Air density (kg/m3)
A: Turbine swept area (m2).
V: Wind speed (m/s)
Cp(θ): Performance coefficient of the turbine (function that depends on the pitch angle).
The value of Cp is not a constant, but rather varies nonlinearly with changes in a number of operational factors, such as wind speed, turbine rotation speed, and blade characteristics, most notably the pitch angle. In this study, Cp is approximated as a function of λ and β according to Equation (19).

$$C_P = (\beta, \lambda) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{-C_5/\lambda_i} + C_6\lambda_i \quad (10)$$

The coefficients C1 to C6 are: C1 = 0.5176, C2 = 116, C3 = 0.4, C4 = 5, C5 = 21 and C6 = 0.0068.
β: blade pitch angle in degrees, and λ is the tip speed ratio (the ratio between the speeds of the turbine blade tip and the wind) can be calculated as:

$$\lambda = \frac{R\,\omega_{tr}}{V_w} \quad (11)$$

where: ω_{tr} the turbine rotor speed, and R is the radius of the wind turbine blade.
Therefore, any change in rotor speed or wind speed modifies the tip speed ratio, affecting the power factor. Figure 2 illustrates the relationship between the mechanical power of a 5 MW wind turbine rotor and the rotor speed at different wind speeds.



(a) (b)

Figure 3. power coefficient vs tip speed ratio (a) Typical power coefficient curve (b) for different pitch angle

VI. EFFECT OF PITCH ANGLE ON CAPACITANCE REQUIREMENT

The dynamic relationship between the pitch angle and excitation capacitance has a direct impact on generator performance. Increasing the pitch angle reduces the power received from the wind, resulting in lower output voltage and current and thus reducing the need for excitation. Decreasing the pitch angle allows for a greater amount of power to be received, requiring greater excitation control to maintain voltage and current stability and prevent fluctuations. In autonomous systems, the pitch angle adjustment and excitation adjustment are continuously coordinated to ensure optimal power generation and avoid any sudden voltage or current spikes that could affect system stability.In induction generators, the process of generating voltage and current depends on excitation, which is defined as the induction

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current required to create the magnetic field within the generator. Excitation requirements change according to the change in pitch angle and the resulting rotational speed, as follows:

At small pitch angles, the induction generator is receiving the highest possible power, resulting in high output voltage and current. This requires increased excitation to adjust and maintain voltage stability.

At medium pitch angles, the blades are adjusted so that the input power is gradually reduced, stabilizing voltage and current and reducing the need for excessive excitation.

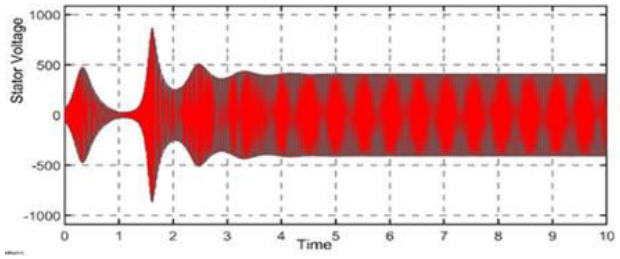
At large pitch angles, the power received from the wind is significantly reduced, which lowers the generator's rotational speed. This reduces excitation requirements, and in some cases, the need for excitation may cease altogether if the generator shuts down to protect the system from unstable loads.

VII. SIMULATION RESULTS AND DISCUSSION

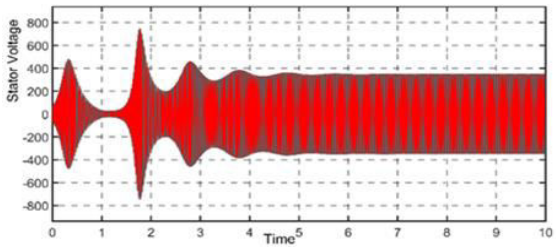
7.1 Simulation of the Effect of Pitch Angle

Observed from Figures 6 (a, b, c, and d) the effect of pitch angle on the voltage build up, when the excitation capacitance is set at 85μF. From the figures we can see that the lower the pitch angle the higher the voltage and the lower the oscillation, which accelerates the voltage's steady-state recovery.

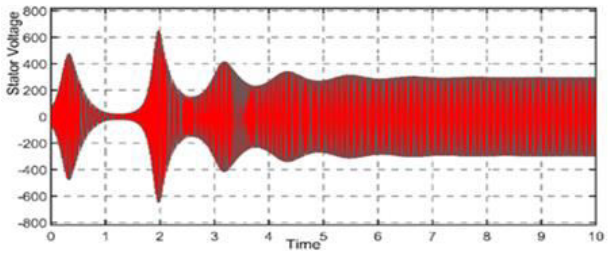
At a 15-degree pitch angle, the voltage reaches 206 V and takes more than 10 seconds to stabilize. When the pitch angle is reduced to 10 degrees, the voltage rises to 302 V and the stabilization time decreases to 7.5 seconds. Continuing to reduce the pitch angle to 5 degrees, the voltage increases to 347 V and stabilizes in 5.5 seconds. Finally, at a 0-degree pitch angle, the voltage reaches 380 V and stabilizes in a shorter time, approximately 4 seconds. These results indicate that decreasing the pitch angle increases the voltage and reduces the stabilization time, indicating the impact of the pitch angle on system response and stability.



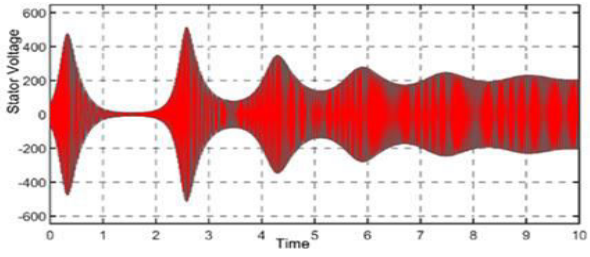
(a) $\beta = 0^0$



(b) $\beta = 5^0$



(c) $\beta = 10^0$



(d) $\beta = 15^0$

Figure 6. Stator Voltage built up process with time at different pitch angle.

7.2 Simulation of Changing Excitation Capacitance at a Pitch Angle of zero

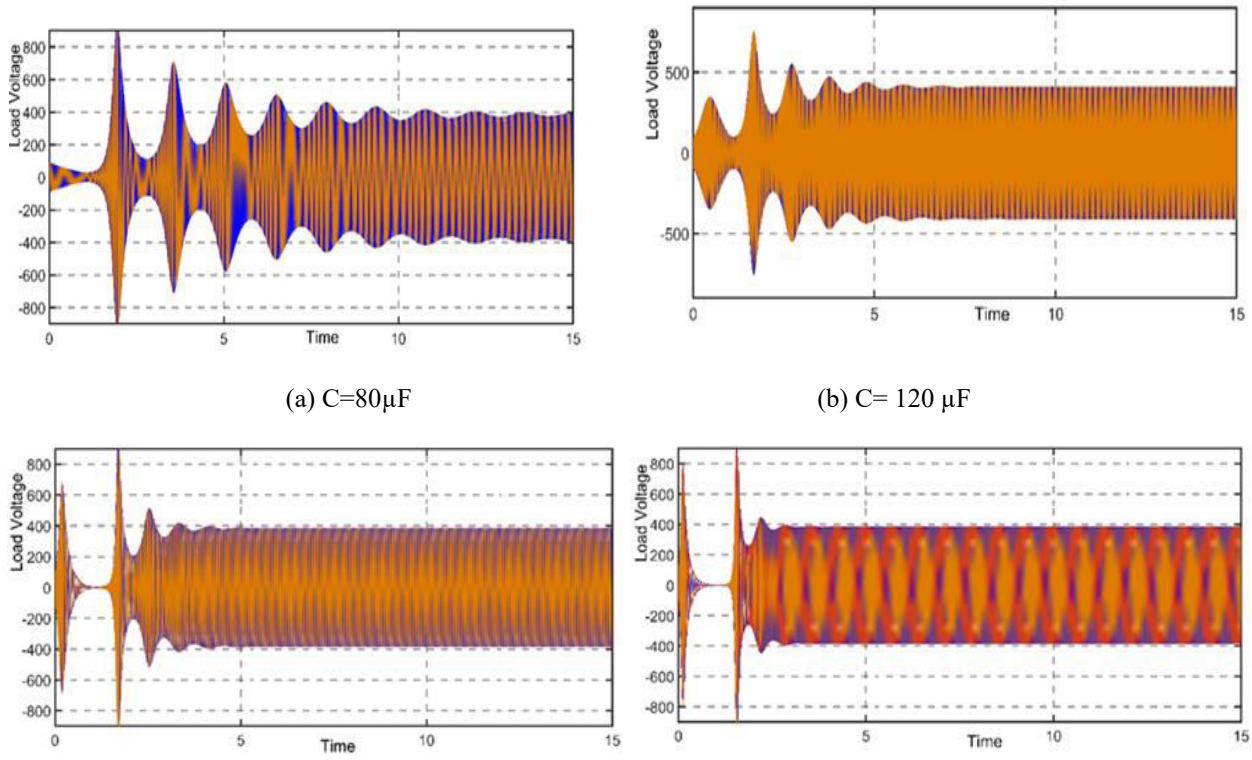
As shown in Figures. 7 (a, b, c and d), increasing the excitation capacitance clearly affects the system's dynamic response. At a low capacitance (80 μF), sharp oscillations appear and a long settling time of approximately 15 seconds is observed. As the capacitance increases to 120 μF and then to 200 μF the oscillation intensity decreases and the settling time is significantly shortened, while the voltage remains at a good level during increased speed, indicating

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improved system stability. This change is made in order to balance between oscillations reduction and maintaining the voltage level. Therefore, the selection of the optimum value of the excitation capacitance is crucial in the design to ensure an optimum balance between settling speed and desired voltage response.



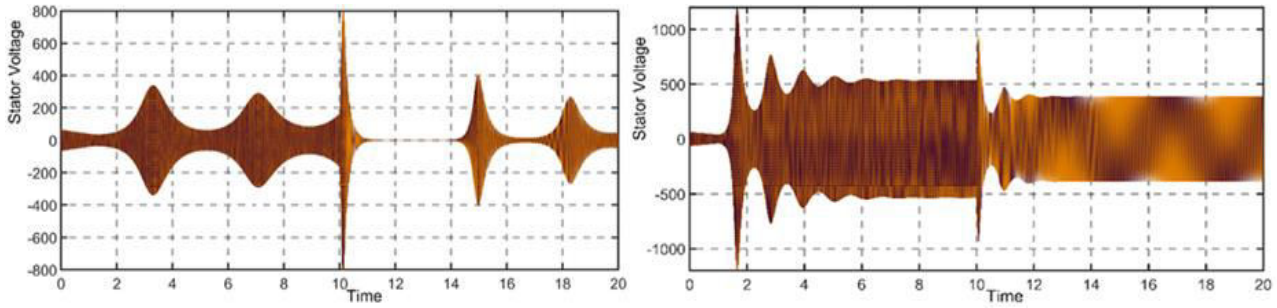
(a) C=80μF (b) C= 120 μF

(c) C=200 μF (d))C=300 μF

Figure 7. Load Voltage built up process with time at different excitation capacitance

7.3 Simulation of Sudden Change in Excitation Capacitance at Different Pitch Angles

Figures 8 (a, b and c) show Suddenly the change in the excitation capacitance from 40μF to 120 μF at different pitch angles (0°, 10°and 18°). These figures demonstrate the combined effect of both the excitation capacitance and the pitch angle on system stability, voltage build-up, and the oscillation of the generator. At pitch angles (such as 0°), the system is relatively more stable, and increasing the excitation capacitance promotes faster voltage build-up, while gradually reducing oscillations. At pitch angles (such as 18°), the abrupt change in the capacitance results in a marked nonlinear response in the generator, characterized by increased oscillations and complete loss of stability. This indicates the sensitivity of the generator's behavior to both the pitch angle and the excitation capacitance changes, as the interaction between these two factors plays a pivotal role in determining the generator dynamic response

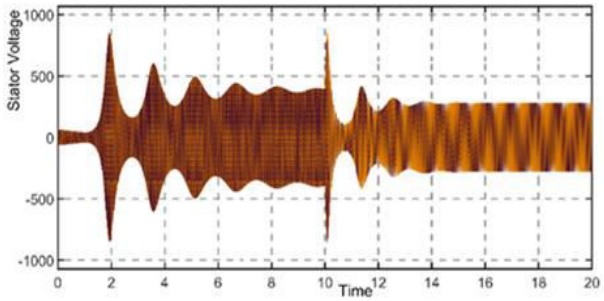


(a) $\beta = 0^0$ (b) $\beta = 10^0$

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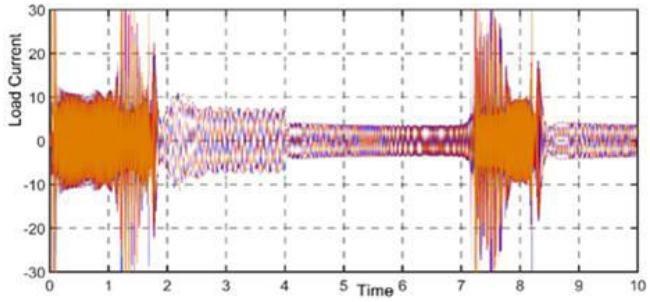


(c) $\beta = 18^0$

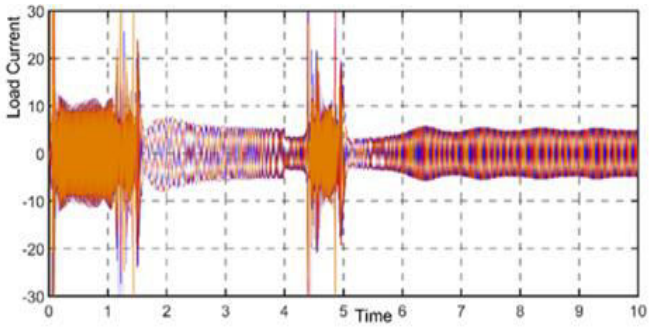
Figure 8. Stator voltage build-up with change in the excitation capacitance at different pitch angle

7.4 Simulation of Sudden Dynamic Load at different Pitch Angles

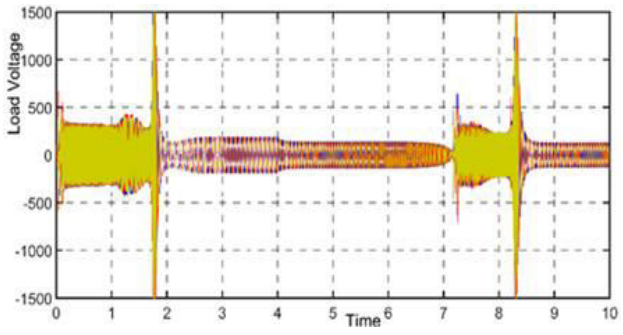
Fig. 9. shows the variation of the load current and load voltage building-up, when the excitation capacitance value is fixed at 160 µF and a sudden dynamic load is introduced under three different wind pitch angles (β = 0°, 10°, and 18°). show that the pitch angle directly affects the current and voltage behavior and stability of the system. At β = 0°, high oscillations and an unstable response are observed due to the high mechanical power resulting from maximum wind energy extraction. As the angle increases to 10°, the oscillations decrease, and the system begins to exhibit calmer and more stable behavior. A stable response is present clearly at β = 18° with the oscillations being reduced significantly and achieving quick steady state. This sequence shows that it can be beneficial to increase the pitch angle to decrease the mechanical power input to increase the dynamic performance, as well as to reduce the effect of sudden load on the stability of the self-excited generator.



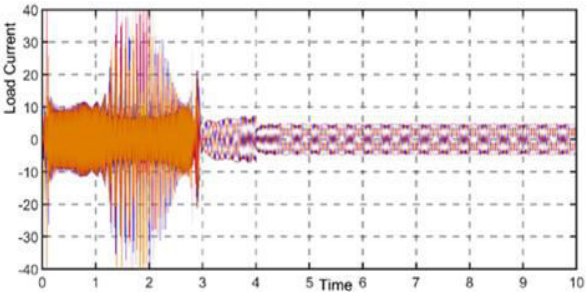
(a) Load current with β = 0°



(b) Load voltage with β = 0°



(c) Load current with β =10°

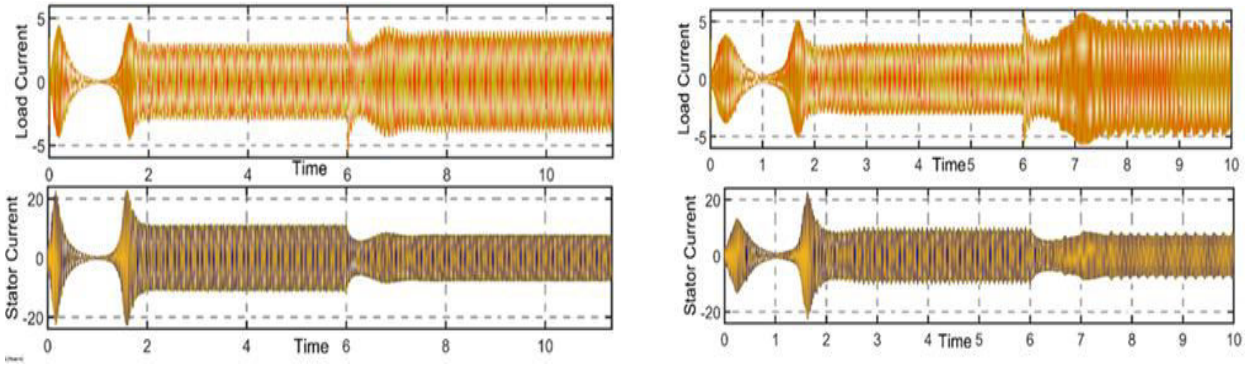


(d) Load voltage with β =1 0°

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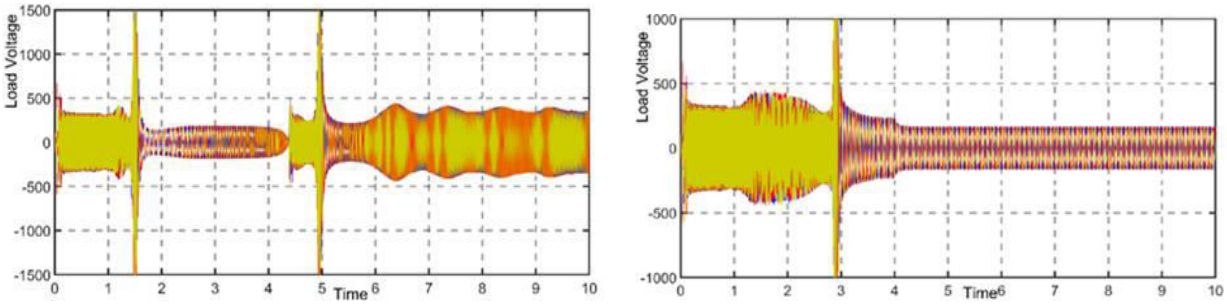


(e) Load current with β = 18° (f) Load voltage with β = 18°

Figure 9. Variation of load voltage and load current with application of dynamic load at different pitch angle

7.5 Simulation of R-L Load at different excitation capacitance

Fig.10. (a and b) illustrate the load current and stator current responses of a self-excited generator when the excitation capacitor was set at two different values: 200 µF and 150 µF, respectively, with the pitch angle fixed at 0°. In both cases, the generator was started under a dynamic initial load with an active power of P = 1500 W and an inactive power of Q = 566 VAR. At the sixth second, an additional R-L load with a power of P = 1400 W and Q = 770 VAR was introduced. Figure (10-a) shows that using an excitation capacitor of 200 µF resulted in a more stable current response after the load was introduced, with fewer oscillations and a shorter settling time. In contrast, Figure (10-b), in which a 150 µF capacitor was used, shows clearer oscillations and a slower response. The results indicate that increasing the excitation capacitor value improves the system's ability to handle sudden changes in R-L loads, by improving voltage support and reducing momentary fluctuations.



(a) C=200µF (b)=150 µF

Figure 10. Variation of stator current and load current with application of R-L load at different excitation capacitation value

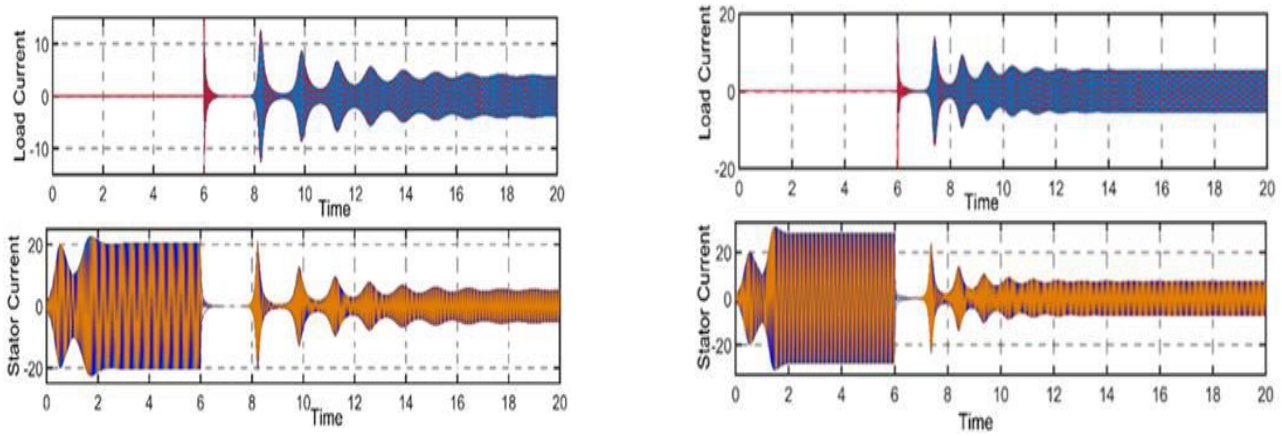
7.6 Simulation of R-L Load at different pitch angle

Fig.11. (a and b) show the load current and stator current responses of a self-excited generator at two different pitch angles (β = 10° and β = 0°), with the excitation capacitor set to 100 µF. Operation began without load, and an R-L load was added after 6 seconds with a power of P = 2400 W and Q = 1450 VAR. The results show that at β = 0°, the fluctuation is lower, and the current stabilizes more quickly compared to the case at β = 10°, indicating that controlling the tilt angle contributes to reducing the mechanical input power and improving the system's response under sudden loads. Compared to higher excitation capacitor values, reducing the pitch angle under a large capacitor yields a similar stability effect, underscoring the importance of balancing the tilt angle and capacitor for optimal performance

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(a) at β = 10° (b)at β = 0°

Figure 11. Variation of load voltage and load current with application of RL load.

This study investigated the effects of excitation capacitance and wind turbine blade pitch angle on the dynamic performance of a wind-driven self-excited induction generator (SEIG) under variable loading conditions. The results highlight the importance of considering both electrical and aerodynamic operating conditions when assessing voltage stability and transient response. The analytical determination of physically feasible operating roots provides a basis for estimating the excitation capacitance required for self-excitation. The results showed that capacitor selection should consider load conditions and turbine operating status, not just power demand and electrical load characteristics. Dynamic simulations demonstrated that increasing the excitation capacitance can improve voltage, aid voltage recovery after load disturbances, and reduce transient fluctuations within the studied operating range. However, excessive capacitance can lead to undesirable steady-state voltage; therefore, it is essential to select a capacitance that balances transient response with steady-state performance.

The blade pitch angle also significantly impacted generator response. Optimal dynamic performance was achieved at a pitch angle of β = 0°, resulting in higher output voltage, lower fluctuations, and faster stabilization time. At β = 10°, voltage recovery after disturbances was lacking, while generator speed increased at β = 18°, and response was slower at other angles. The response to abrupt changes in resistive and inductive load (R–L) was also found to be dependent on the pitch angle. When the effects of excitation capacitance and pitch angle are combined, these two factors should be appropriately controlled to optimize transient performance, with the appropriate capacitance calculated for each operating condition. Overall, the results underscore the importance of using analytical capacitance estimation in conjunction with verifying the turbine pitch angle and load variations as a good starting point for independent wind-driven SEIG systems. Future work could explore coordinated or adaptive control strategies for voltage stabilization over a wider operating range, taking into account variations in wind speed and electrical loads.

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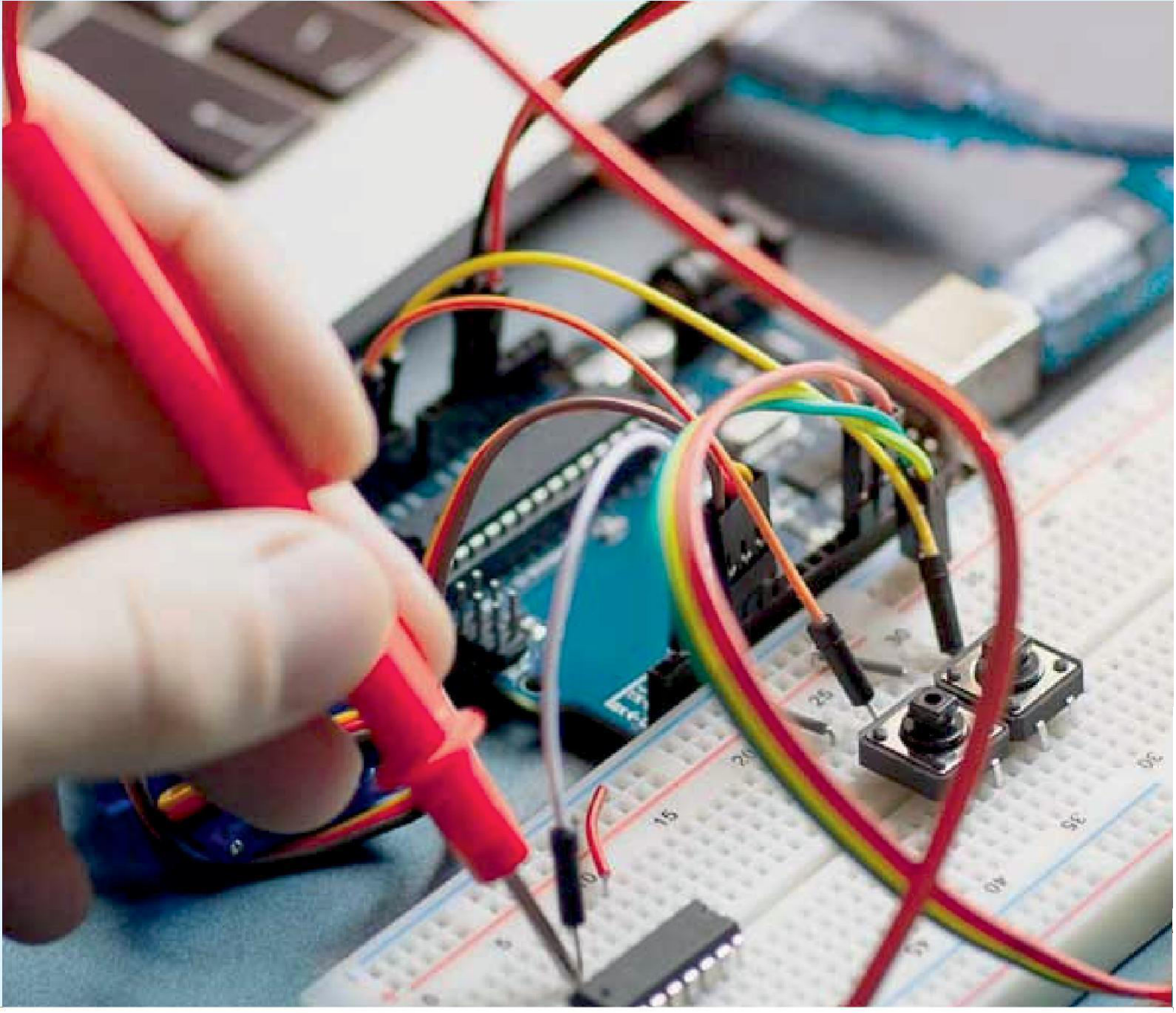
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