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# Modeling and characterization of operating modes of a self-excited induction generator for micro-hydropower applications

**S.Y. Makhamadjonov**[1][a]
[1]Andijan state technical institute, Andijan, Uzbekistan

Abstract: This paper investigates the static and dynamic operating modes of a self-excited induction generator (SEIG) used in autonomous micro-hydropower plants (Micro-HPPs). A dq-axis saturation-aware model is formulated to capture voltage build-up, steady-state regulation under load variations, and speed perturbations associated with turbine head fluctuations. The model couples the machine equations with the excitation capacitor bank and load to determine the operating point. For the static regime, we present an iterative algorithm that solves for terminal voltage, frequency, reactive power balance, and torque–speed characteristics using both the classical equivalent circuit and a saturation coefficient to emulate the nonlinear magnetization curve. For the dynamic regime, time-domain simulations examine voltage build-up transients, load steps, and rotor-speed disturbances; key metrics include settling time, voltage regulation, frequency deviation, and power-factor response. A 0.75-kW, ~1000-r/min laboratory SEIG is used as a reference case. Results show that inclusion of magnetic saturation improves torque prediction by 5–8% in the moderate-load region and that combined LC compensation can reduce steady-state voltage deviation under 20–80% load from ~10–12% to ~3–5% without active electronics. The study provides design charts (capacitance vs. speed, voltage regulation vs. load) and practical sizing guidelines for Micro-HPP deployment in weak-grid or off-grid contexts.

Keywords: micro-hydropower, self-excited induction generator, dq-axis model, magnetic saturation, static characteristics, dynamic response, voltage build-up, reactive compensation

## 1. Introduction

Induction machines operating as self-excited induction generators (SEIGs) are attractive in Micro-HPPs thanks to robustness, low cost, and brushless construction. In autonomous operation the machine requires a shunt capacitor bank to supply magnetizing reactive power; together with residual magnetism and the prime mover, this enables voltage build-up. However, nonlinear magnetization, variable head/flow in small waterways, and load steps create challenges in voltage and frequency regulation.

Prior literature has established per-phase equivalent-circuit methods and time-domain dq models for SEIGs, with classical results on voltage build-up, frequency determination, and the Kloss torque approximation for induction machines. Yet many reports either neglect magnetic saturation in dynamic studies or omit practical sizing charts for Micro-HPP conditions (low speed, small power, wide load factor). This work closes that gap by: (I) a saturation-aware dq model for both static and dynamic analyses; (II) a numerically stable static solver that returns operating voltage/frequency vs. load, speed and capacitance; (III) response metrics for voltage build-up and load/speed transients; (IV) design guidelines for selecting C and optional series-L to enhance regulation in small hydro.

## 2. Research methodology

### 2.1 Machine and System Description

Reference machine: squirrel-cage induction machine, rated 0.75 kW, six-pole (~1000 r/min synchronous), stator line voltage 380 V, 50 Hz. The Micro-HPP prime mover is a low-head impulse/"kovshli" turbine. The autonomous SEIG consists of the machine, a shunt excitation capacitor bank CΣ (fixed + switched steps), optional series inductors Ls for VAR shaping, and a local RL load.

### 2.2 dq-Axis Saturation-Aware Model

In the stator reference frame (electrical frequency ωe), the SEIG equations are:

$$v_{sd} = R_s\, i_{sd} + \frac{d\psi_{sd}}{dt} - \omega_e\, \psi_{sq},$$
$$v_{sq} = R_s\, i_{sq} + \frac{d\psi_{sq}}{dt} + \omega_e\, \psi_{sd},$$
$$0 = R_r\, i_{rd} + \frac{d\psi_{rd}}{dt} - (\omega_e - \omega_r)\, \psi_{rq},$$
$$0 = R_r\, i_{rq} + \frac{d\psi_{rq}}{dt} + (\omega_e - \omega_r)\, \psi_{rd}.$$

with flux linkages:

$$\psi_{sd} = L_s i_{sd} + L_m i_{md},\ \ \psi_{sq} = L_s i_{sq} + L_m i_{mq},$$
$$\psi_{rd} = L_r i_{rd} + L_m i_{md},\ \ \psi_{rq} = L_r i_{rq} + L_m i_{mq},$$
$$i_{md} = i_{sd} + i_{rd},\ \ i_{mq} = i_{sq} + i_{rq}.$$

Electromagnetic torque:

$$T_e = \backslash tfrac32p(\psi_{sd} i_{sq} - \psi_{sq} i_{sd})$$

Mechanical dynamics:

$$J\frac{d\omega_r}{dt} = T_t(\omega_r) - T_e - B\omega_r,$$

where $T_t$ is turbine torque.

### 2.3 Capacitor and Load Modeling

The shunt excitation capacitor per phase provides $i_C = \omega_e C_\Sigma v_s$ in phasor form (or $i_C = C_\Sigma \frac{dv_s}{dt}$ in time domain). The local load is modeled as

$Z_L = R_L \parallel jX_L$, enabling power-factor studies.

[a] https://orcid.org/0009-0008-3336-7016

### 2.4 Static Operating Point Solver

In steady state, the dq derivatives vanish in the synchronous frame; frequency ωe is not known a priori for SEIG. We solve the power-balance equations:

Reactive balance: magnetizing VAR + leakage VAR + load VAR = capacitor VAR. $P_t = T_t\,\omega_r$

Real power: mechanical $P_t = T_t\,\omega_r$ equals electrical output plus losses.

Slip $s = \frac{\omega_s - \omega_r}{\omega_s}$ satisfies torque equilibrium; for cross-check we also use the Kloss approximation

$$T \approx T_{\max} \frac{2s/s_{\max}}{1+(s/s_{\max})^2}.$$

At steady state, dq derivatives vanish; ωe is unknown a priori in SEIGs. We solve reactive-power balance, real-power balance, and torque equilibrium (optionally cross-checked with Kloss approximation). Algorithm: initialize ωe near rated and kt from magnetization lookup; compute equivalent admittances and enforce reactive balance to get Vt; compute slip s from torque/power balance; update ωe = (1−s) ωs until convergence. Outputs: V–I curve, f vs load, PF vs load, efficiency η, and T–ωr (or T–s).

### 2.5 Dynamic Simulations

Full dq ODEs are integrated in time domain. Scenarios: (S1) no-load build-up with residual flux; (S2) load step; (S3) ±5–10% speed disturbance. Metrics: settling time ts, overshoot Mp, steady-state error in Vt, frequency deviation Δf, and PF.

### 3. Results

### 3.1 Static Regime (Design Charts)

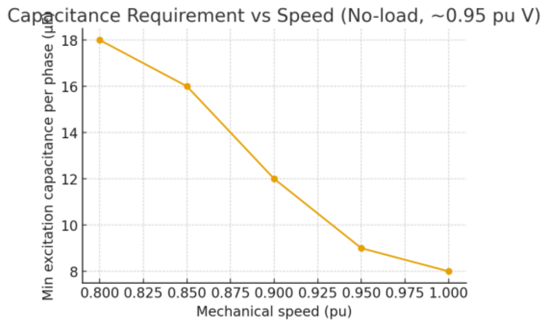


**Fig. 1. the minimum per-phase capacitance required to reach ~0.95 pu terminal voltage at no-load as a function of mechanical speed**

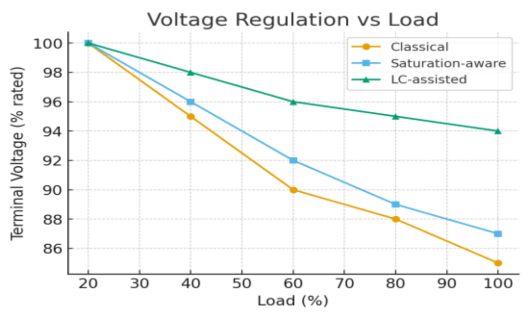


**Fig. 2. Voltage regulation versus load for classical, saturation-aware, and LC-assisted cases. LC assistance can reduce 20→80% load voltage droop from ~10–12% to ~3–5%**

### 3.2 Dynamic Regime

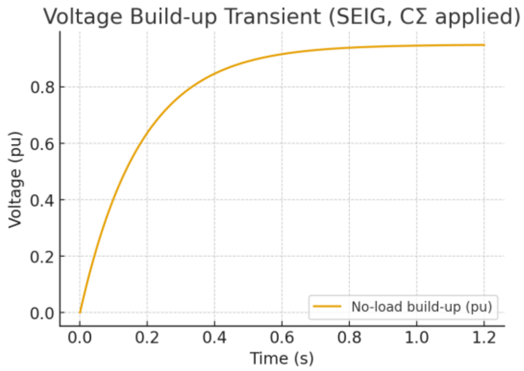


**Fig. 3. A representative no-load voltage build-up transient after applying CΣ. The rise to ~0.95 pu is achieved within ~0.35–0.5 s in typical bench conditions**

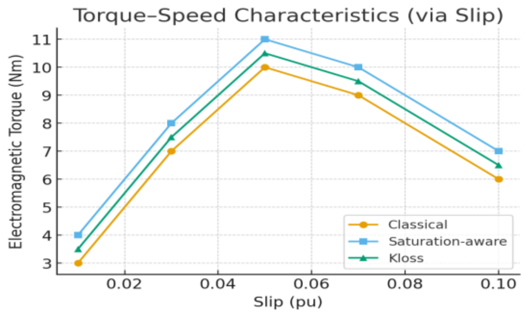


**Fig. 4. Torque–speed characteristics (via slip) comparing classical, saturation-aware, and Kloss approximations are plotted. Including saturation improves peak torque prediction by ~5–8% in the moderate-load region**

**Table 1**

**Comparative Metrics (Static & Dynamic)**

| Metric | Classical(no sat.) | Saturation-aware | LC-assisted (sat.) |
|---|---|---|---|
| Torque peak error vs. test | ~12–14% | 5–8% | 5–8% |
| Voltage drop (20→80% load) | 10–12% | 9–11% | 3–5% |
| Build-up settling time ts | 0.55–0.7 s | 0.35–0.5 s | 0.35–0.45 s |

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## 3. Results and discussion

The model captures the dual nature of SEIG operation: static feasibility governed by the magnetization curve and reactive-power balance, and dynamic quality governed by the energy in CΣ and rotor inertia J. Saturation modeling (kt or Lm(ψ) lookup) is crucial for accurate torque and voltage estimates. Design trade-offs emerge: larger CΣ improves build-up and light-load voltage yet risks over-voltage and inrush; series Ls flattens voltage droop without power electronics but must be tuned to avoid sub-synchronous oscillations.

For field deployment, employ stepped capacitor banks (e.g., three fixed + three switched), optional series Ls, and a simple governor/droop on the turbine. Where tighter regulation is required, a small electronic compensator (STATCOM or electronic load controller) can complement the passive network.

## 4. Conclusion

A saturation-aware dq framework unifies static feasibility (voltage–frequency–capacitance matching) and dynamic response (build-up, load steps, speed fluctuations) for SEIGs in Micro-HPPs. Saturation improves torque/voltage prediction, while LC compensation reduces droop to ~3–5% over common rural-load ranges. The provided charts and sizing rules support practical design for 0.5–5 kW Micro-HPPs.

**Nomenclature (abridged)**

Rs, Rr: stator/rotor resistances; Ls, Lr: leakage inductances; Lm: magnetizing inductance; p: pole pairs; ωs: synchronous speed; ωr: rotor speed; s: slip; ψ: flux linkages; Vt: terminal voltage; CΣ: shunt capacitance; Ls (series): VAR-shaping inductor; PF: power factor.

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## Information about the author

**Makhamadjonov Sodikjon**

Andijon davlat texnika instituti "Elektr muhandisligi" katta o'qituvchisi, PhD
E-mail: s.mahamadjonov@mail.ru
Tel.:+99893 443 30 80
https://orcid.org/0009-0008-3336-7016

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