Comprehensive Technical Compendium: Modeling, Control, and Estimation in Electrical Systems by Melvin Chibudom Amadi-Duru

Abstract: This compendium integrates three critical pillars of modern electrical engineering: the dynamic modeling of electric machines, the design of high-performance closed-loop drives, and the application of statistical estimation theory. By combining Electromechanical Dynamics, Power Electronics, and State-Space Estimation, this work provides a robust framework for developing efficient and reliable Electric Vehicle (EV) powertrains.

2. Dynamic Modeling of Electric Machines

2.1 **Separately Excited DC Machine Analysis**: The dynamic behavior of a DC motor was modeled using coupled first-order differential equations. Electrical Dynamics: $V_{in} = E_a + R_a i_a + L_a \frac{di_a}{dt}$Mechanical Dynamics: $J\frac{d\omega_m}{dt} + B_1\omega_m = T_e - T_L$

Key Findings: Simulation results in MATLAB/Simulink revealed that during the transient startup phase, the motor experiences a significant current overshoot to overcome rotor inertia ($J = 0.0167kg \cdot m^2$). In steady state, the armature current $i_a$scales linearly with the load torque T_L, confirming the model's accuracy.

2.2 **Synchronous Generator (Hydro-Turbine) Modeling**: Modeling a 325 MVA synchronous generator requires the Park's Transformation ($dq0$ frame) to convert time-varying AC stator variables into time-invariant DC quantities.

Rotor reference frame: The transformation simplifies the flux linkage equations ($\lambda = L \cdot i$) and allows for the decoupling of torque and flux.

Stability Analysis: Under a $27.6 \times 10^6 N \cdot m$torque step, the rotor exhibited a characteristic "swing" before settling. The simulated torque angle ($\delta \approx 16°$) closely matched the theoretical prediction (18°), verifying the transient stability of the model.

3. **Advanced Control**: Two-Quadrant DC Drive Design

3.1 Cascaded Control Architecture: To achieve precise speed regulation, a cascaded PI control structure was implemented for a 220V DC motor drive.

Inner Current Loop: Designed for high-speed response to protect power electronics. The controller was tuned for pole cancellation ($T_c = T_2 = 0.0208s$), effectively simplifying the plant dynamics.

Outer Speed Loop: Designed using the Symmetrical Optimum method to ensure stability and minimize overshoot during setpoint changes.

Power Stage: A three-phase bridge converter provides a gain of $31.05V/V$, facilitating Two-Quadrant Operation. This allows the drive to transition from motoring to regenerative braking, a critical feature for energy efficiency in EVs.

4. Estimation Theory: Kalman Filter ApplicationsThe project expanded into "software-based sensors" to estimate states that cannot be directly measured, such as angular velocity $\Omega(t)$or hidden non-linear states.

4.1 **Linear Estimation (DC Motor)** Using a stochastic model with quantization noise, a Time-Varying Kalman Filter was designed. Sensitivity to Noise (Q vs R): Increasing the process noise covariance (Q) made the filter rely more on sensor data, leading to noisy velocity estimates. Lowering Qforced the filter to trust the internal model, producing smoother, more accurate trajectories even under parametric mismatch ($T_{filter} = 25ms$ vs $T_{actual} = 20ms$).

4.2 **Non-Linear Estimation Benchmarking**: A highly non-linear system ($y_n = x_n^2/20$) was used to compare three advanced filters:

Extended Kalman Filter (EKF): Frequently diverged due to the inaccuracies of first-order linearization via Jacobians.

Unscented Kalman Filter (UKF): Significantly outperformed the EKF by using Sigma Points to map the probability distribution across non-linear functions.

Bootstrap Particle Filter (BPF): Optimal Result. By using a sequential Monte Carlo approach with random particles, the BPF achieved the lowest tracking error, proving its superiority for complex, non-Gaussian systems.

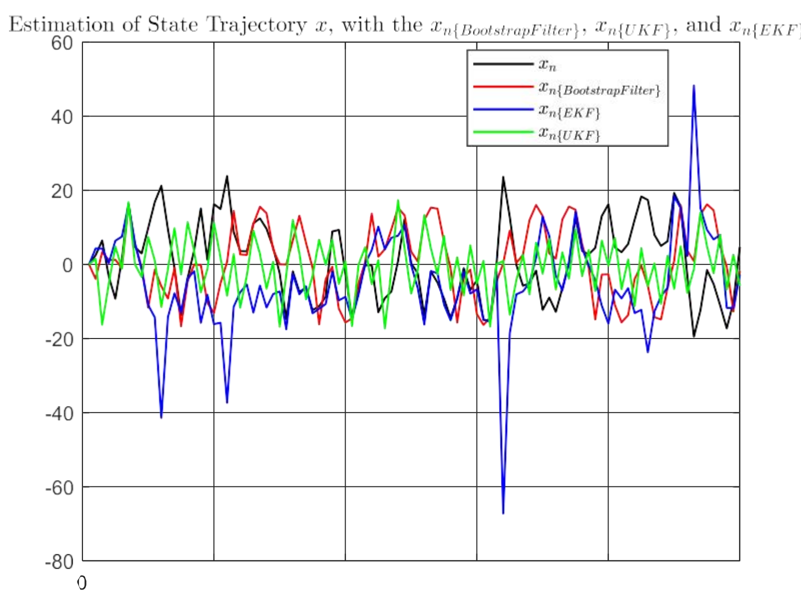

Figure 16: State estimation with Bootstrap Filter, UKF and EKF

5. Unified Results Table

System Component	**Primary Metric**	**Result/Achievement**
DC Motor Dynamics	Steady-state Speed	Proportional to Voltage (V_{in})
Synchronous Gen.	Torque Angle (δ)	$\sim 16^{\circ}$(Generating Mode)
Drive Control	Current Limit	Maintained strictly below 20 A
Linear Estimation	Robustness	Stable with 25% model error
Non-Linear Estimation	Accuracy	**BPF** > UKF > EKF

6. **General Conclusion**: This comprehensive research proves that high-performance electrical systems require a three-tier approach:

High-Fidelity Modeling (dq0 transformation and state-space equations) to understand the physical plant.

Cascaded Control to ensure safety limits and operational flexibility (regenerative braking).

Recursive Estimation (Kalman and Particle Filtering) to overcome sensor noise and provide real-time data for control loops.

The integration of these techniques provides a robust foundation for the future of Electric Vehicle propulsion and smart grid management.

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