

Bridging Classical and Regenerative Mechanisms: A Unified Cyclic Voltammetric Model for Sequential Enzymatic Systems

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Abstract

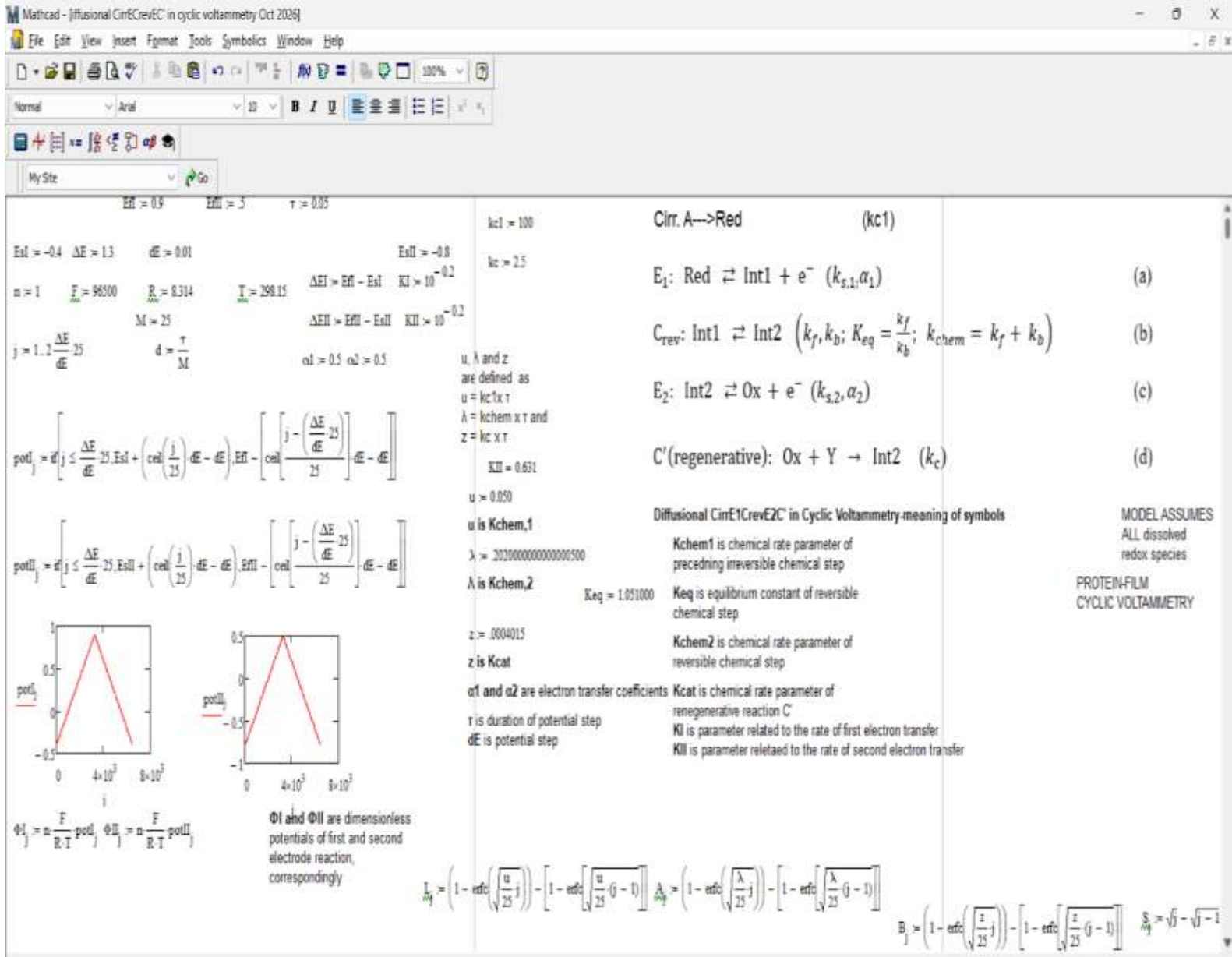
Sequential enzymatic redox mechanisms involving multiple regeneration pathways can generate complex voltammetric responses whose interpretation is difficult within conventional mechanism-specific models. In this work, a comprehensive theoretical framework is developed for the cyclic voltammetry of a diffusion-controlled sequential double-regenerative enzymatic mechanism. The model couples consecutive heterogeneous electron-transfer steps with two regenerative chemical reactions and provides, to the best of our knowledge, the first unified cyclic-voltammetric description capable of encompassing the principal limiting mechanisms commonly encountered in regenerative electrochemical and enzymatic systems.

Theoretical voltammograms are systematically analyzed as functions of the kinetics of electron transfer, rates of the regenerative reactions, thermodynamic relationships between consecutive redox steps, substrate availability, scan rate, and relative positions of the formal potentials. Depending on the kinetic and thermodynamic regime, the model predicts transitions between conventional reversible and quasi-reversible responses, EC- and EC'-type behavior, sequential regenerative pathways, merged or separated redox waves, catalytic current enhancement, peak suppression, and complex multipeak patterns. Importantly, these apparently distinct electrochemical signatures emerge naturally as limiting cases of the same general reaction scheme rather than requiring separate theoretical treatments.

Particular attention is given to identifying diagnostic relationships between voltammetric morphology and the competition among electron transfer, diffusion, and chemical regeneration. The simulations reveal characteristic electrochemical fingerprints through which individual kinetic regimes can be distinguished and demonstrate how coupling between two regenerative cycles can profoundly alter peak currents, peak potentials, wave multiplicity, and scan-rate dependence.

The proposed model therefore establishes a common theoretical platform connecting a wide spectrum of classical and regenerative voltammetric mechanisms. Beyond its relevance to enzymatic electrochemistry, the framework should be applicable to electrocatalytic, bioelectrochemical, mediator-assisted, and other multistep redox systems in which sequential electron transfer is coupled to chemical regeneration. It provides a basis for mechanistic discrimination and for extracting kinetic information from experimentally observed cyclic voltammograms of complex catalytic systems.

The Mathcad Simulation Protocol in Cyclic Voltammetry



$$\Phi I_1 = \frac{K I_1 e^{\alpha_1 \Phi I_1}}{1 - K I_1 e^{\alpha_1 \Phi I_1} \left[\frac{-L_1}{u^{0.5}} + \frac{-2 S_1}{(25-\pi)^{0.5}} \left(\left(1 + \frac{e^{-\Phi I_1}}{1 + K_{eq}} \right) - \frac{1 e^{-\Phi I_1} A_1}{\lambda^{0.5} (K_{eq} + 1)} \right) \right]}$$

$$\Phi II_1 = \frac{K II \frac{2}{(25-\pi)^{0.5}} e^{\alpha_2 \Phi II_1}}{1 + \frac{1 B_1}{z^{0.5}} K II e^{\alpha_2 \Phi II_1} + \frac{1 B_1}{z^{0.5}} K II e^{-\Phi II_1 (1-\alpha_2)}}$$

$$\Phi II_1 = 2.981 \times 10^{-14}$$

$$\Phi I_1 = 7.833 \times 10^{-7}$$

$$\Phi I_j = \frac{K I e^{\alpha_1 \Phi I_j} \left[1 - \frac{1}{u^{0.5}} \sum_{i=1}^{j-1} (\Phi I_i L_{j-i+1}) \right] - \frac{2}{(25-\pi)^{0.5}} \left(1 + \frac{e^{-\Phi I_j}}{1 + K_{eq}} \right) \sum_{i=1}^{j-1} (\Phi I_i S_{j-i+1}) - \frac{1 e^{-\Phi I_j}}{(1 + K_{eq}) \lambda^{0.5}} \sum_{i=1}^{j-1} (\Phi I_i A_{j-i+1})}{1 - K I e^{\alpha_1 \Phi I_j} \left[\frac{-L_1}{u^{0.5}} + \frac{-2 S_1}{(25-\pi)^{0.5}} \left(\left(1 + \frac{e^{-\Phi I_j}}{1 + K_{eq}} \right) - \frac{1 e^{-\Phi I_j} A_1}{\lambda^{0.5} (K_{eq} + 1)} \right) \right]}$$

$$\Phi II_j = \frac{\frac{K II e^{-\Phi II_j (1-\alpha_2)}}{(1 + K_{eq}) \lambda^{0.5}} \sum_{i=1}^j (\Phi I_i A_{j-i+1}) - K II e^{\alpha_2 \Phi II_j} \left[-1 + \frac{1 + e^{-\Phi II_j}}{z^{0.5}} \sum_{i=1}^{j-1} (\Phi II_i B_{j-i+1}) \right]}{1 + \frac{K II e^{-\Phi II_j (1-\alpha_2)} A_1}{(1 + K_{eq}) \lambda^{0.5}} + \frac{K II e^{\alpha_2 \Phi II_j} B_1}{z^{0.5}} (1 + e^{-\Phi II_j}) + K II e^{\alpha_2 \Phi II_j} B_1}$$

$$p = 1.2 \frac{\Delta E}{dE} - 1$$

p is serial number of potential steps

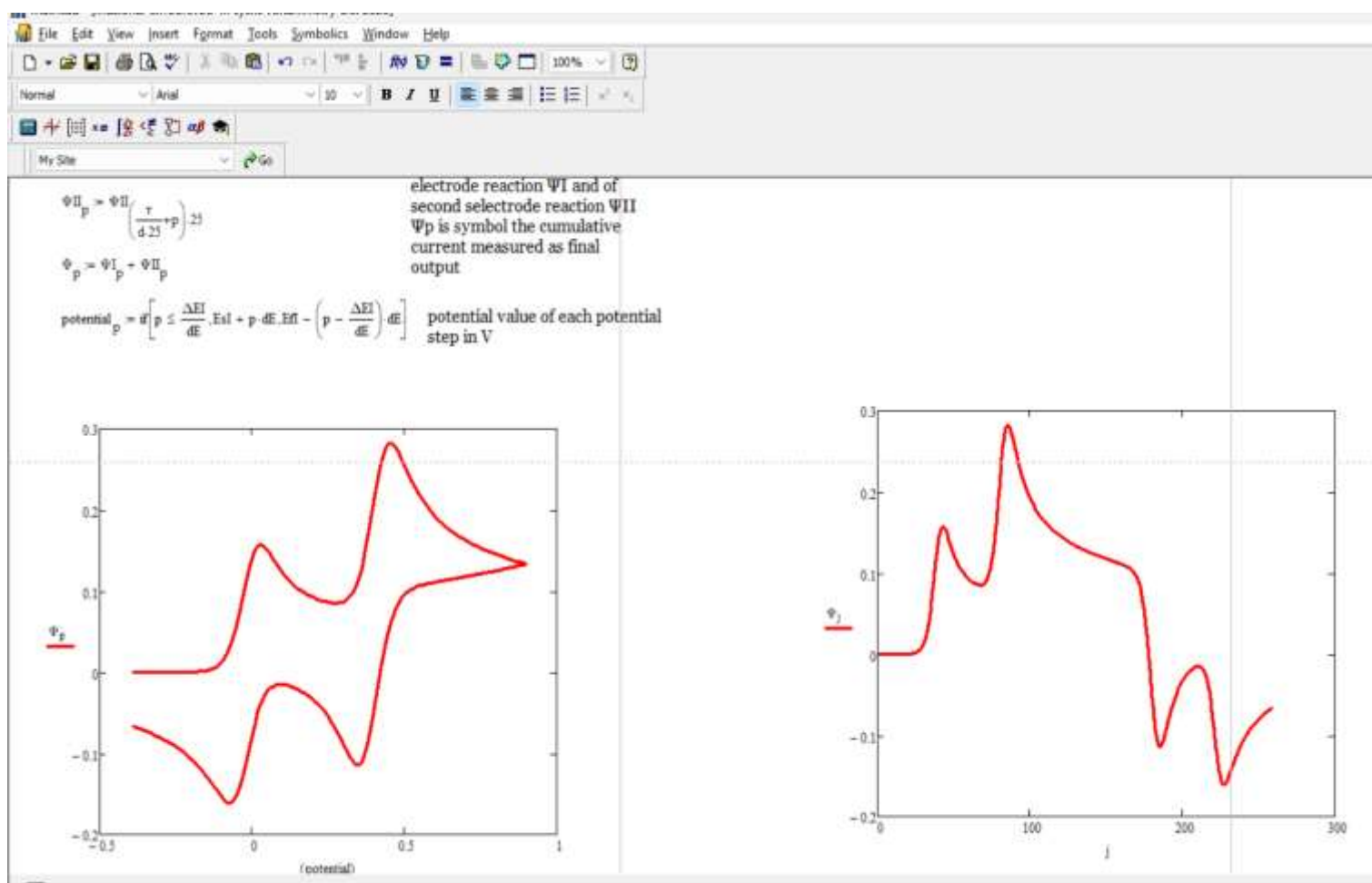
$$\Phi I_p = \Phi I \left(\frac{1}{d \frac{\Delta E}{dE}} p \right)^{25}$$

dimensionless current at the end of each potential step of first electrode reaction ΦI and of second electrode reaction ΦII
 Φp is symbol the cumulative current measured as final output

$$\Phi II_p = \Phi II \left(\frac{1}{d \frac{\Delta E}{dE}} p \right)^{25}$$

$$\Phi_p = \Phi I_p + \Phi II_p$$

$$\text{potential}_p = d \left[p \leq \frac{\Delta E}{dE} \text{End} + p dE \text{End} - \left(p - \frac{\Delta E}{dE} \right) dE \right] \quad \text{potential value of each potential step in V}$$



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