PI-Controlled Variable Time-Step Power System Simulation Using an Adaptive Order Differential Transformation

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Motivation

- The order and step size of simulation methods are determined case by case and fixed **based on experiences**.
- The DT method can adjust its step size more easily than numerical methods such as RK methods.
- The optimal pair of step size and the order of the DT **has not been studied well**.
- A more robust method should be considered in *N*-1 dynamic simulations.

Contribution

- **Variable Step Strategy**: Introduces the Variable-Step DT (VSDT) method for power system simulations, ensuring high-speed performance with fixed order SAS.
- **Optimal Variable Order Strategy**: Proposes the Variable-Step-Optimal-Order DT (VSOO-DT) method, which provides an optimal pair of step size and order during simulation, balancing stability and speed.

Proposed Method

$$\mathbf{x}(t) \approx \sum_{k=0}^{K} \mathbf{X}[k](t-t_n)^k,$$

$$\mathcal{E}(K,h) := \sum_{l=K+1}^{\infty} \left(\max_{1\le i\le m_1} \left| \frac{[\mathbf{X}]_i(l)h^l}{|[\mathbf{x}]_i| + \eta_i} \right| \right) \approx \sum_{l=K+1}^{\infty} r^l = \frac{r^{K+1}}{1-r}.$$

$$\max \quad \frac{h_{n+1}}{C(K_{n+1})}$$

$$\text{s.t.} \quad h_{n+1} = h_n \left(\gamma^K \frac{Tol}{e_n} \right)^{K_I} \left(\frac{e_{n-1}}{e_n} \right)^{K_P}$$

$$e_n = \frac{\mathcal{E}(K, h_n)}{h_n}$$

$$(h_{n+1}, K_{n+1}) \in \arg \max_{(h,K)\in\mathcal{I}} \frac{h}{C(K)},$$

$$\mathcal{I} = \{(h_{de}, K_{de}), (h_{es}, K_n), (h_{in}, K_{in})\}$$

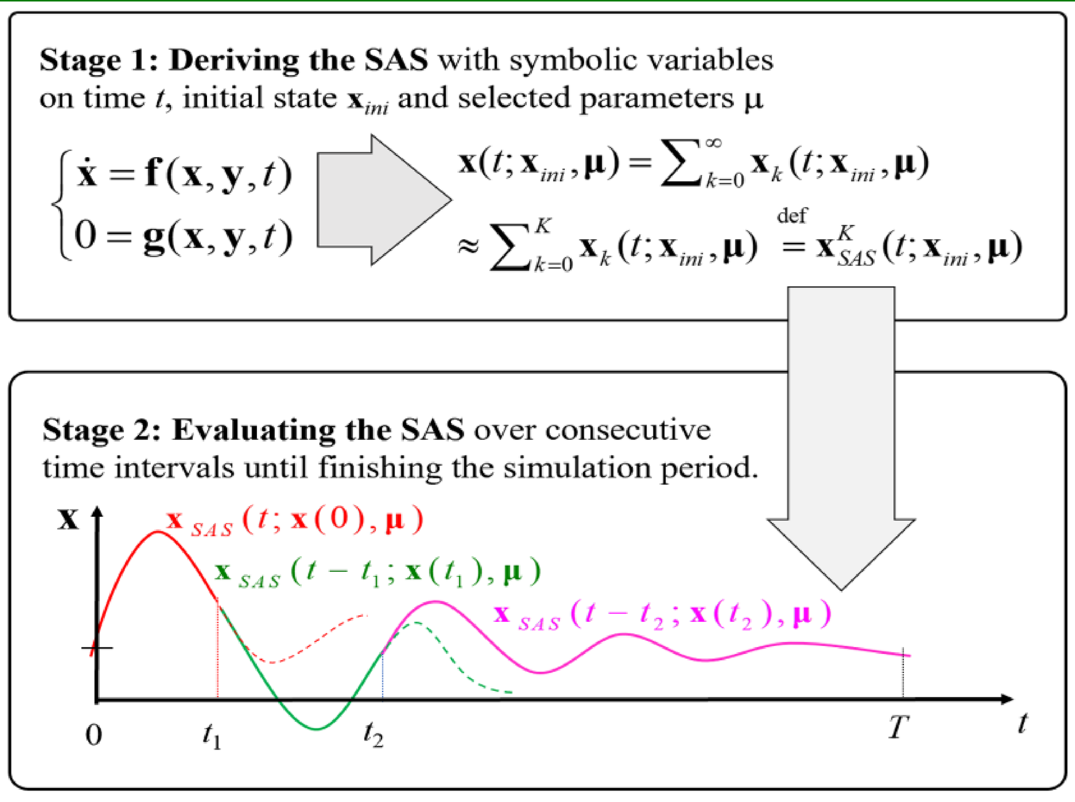
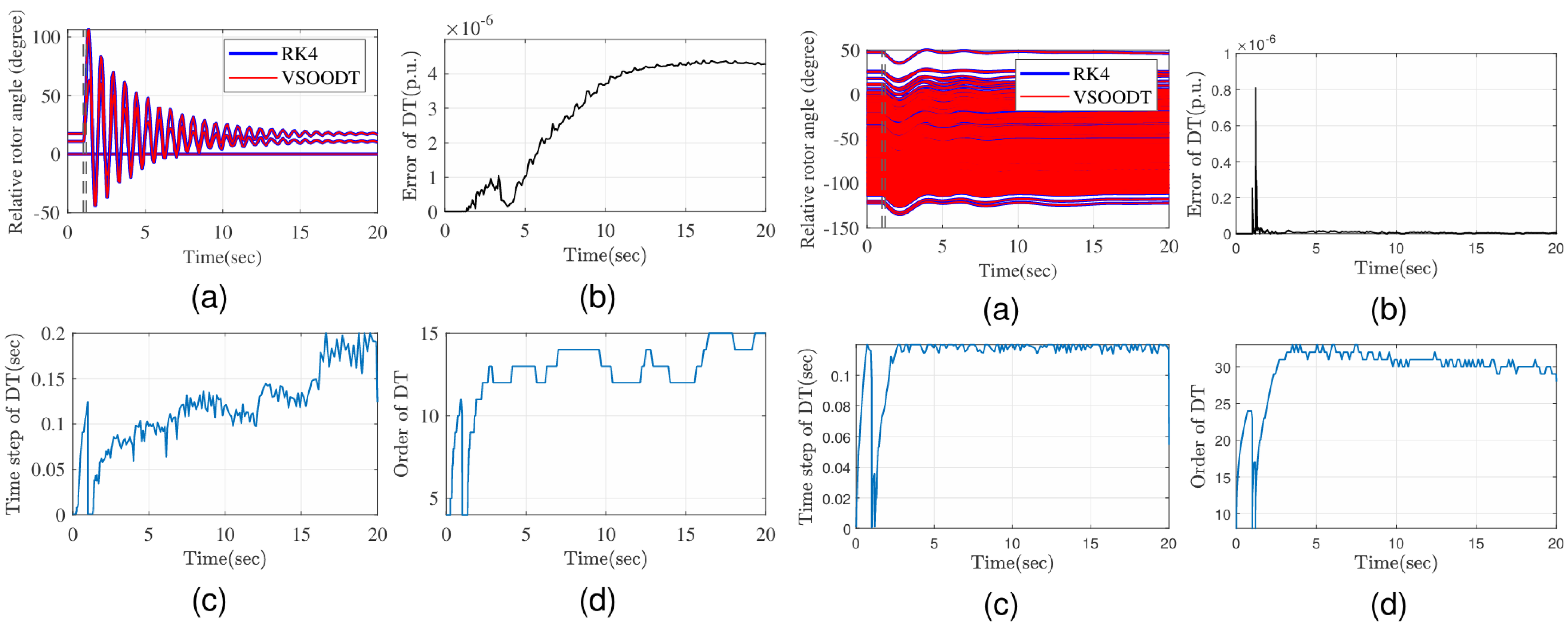


Fig.1. SAS-based simulation in two stages

Case Studies



- **The 9-bus system**: a three-phase bus grounding @bus5 at 1s and is cleared after 0.2s
- **The Polish 2383-bus system**: a three-phase bus grounding @bus9 at 1s and the branch 6-9 is tripped after 0.2s
- **N-1 dynamic screening**:
- All three-phase grounding faults in the Polish 2383-bus system are considered, and each fault lasts 0.2 seconds.

Fig.2. Simulation results for 9-bus system and the Polish2383-bussystem. (a) Relative rotor angles. (b) maximum errors. (c) Step size during the simulation. (d) Optimal order of DT during the simulation.

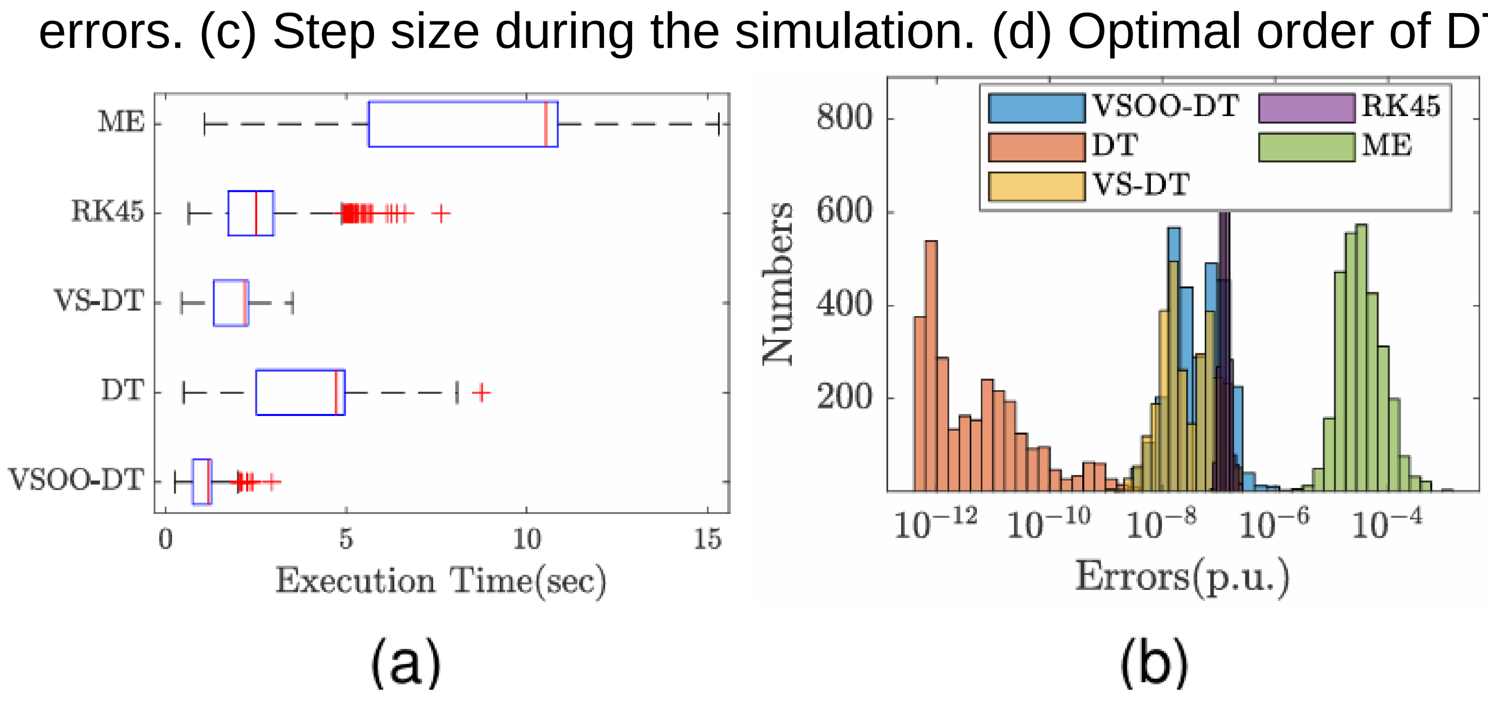


Fig.3. Distribution of N-1 dynamic screenings. (a) Execution times distributions. (b)Mean-Max error distributions.

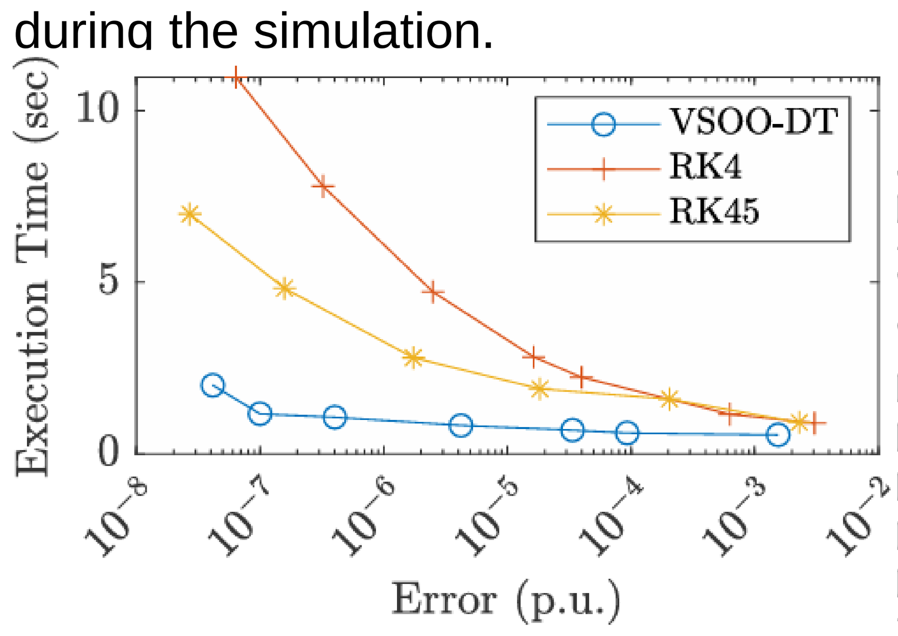


Fig.4. Comparison of execution times for different errors by using different methods

TABLE I
COMPUTATIONAL PERFORMANCE BY DIFFERENT METHODS FOR 2383-BUS SYSTEMS

Method	CPU time (s)	Mean-Max Error(p.u.)
VSOO-DT$(Tol = 10^{-5}, K_0 = 4)$	1.8943	8.79×10^{-8}
VS-DT$(Tol = 10^{-5}, K = 8)$	3.3317	3.11×10^{-8}
DT$(h = 0.008\text{ s}, K = 4)$	3.7092	1.63×10^{-5}
RK4$(h = 0.005\text{ s})$	4.3180	2.49×10^{-6}
RK4$(h = 0.01\text{ s})$	2.2454	3.80×10^{-5}
ME $(h = 0.001\text{ s})$	11.7445	2.15×10^{-4}
ME $(h = 0.005\text{ s})$	2.4866	0.0054
TR $(tol = 10^{-4})$	146.8446	0.017
TR $(tol = 10^{-2})$	44.8635	0.033

Conclusions and Future Work

In summary, this paper introduces the VS-DT and VSOO-DT methods, addressing the limitations of fixed step size and order in power system simulations. These methods dynamically adjust step size and optimize SAS order, ensuring stability and speed.