where $U_j$ is the solution by parallel-in-time method. The system equations can be solved by Newton-Raphson method according to

$$U_j^k = \widehat{U}_j^k + \frac{\partial \widehat{U}_j^k}{\partial U} \Delta U_{j-1}^k, \tag{32}$$

where $\Delta U_{j-1}^k = U_{j-1}^k - U_{j-1}^{k-1}$. $U_{j-1}^k$ is the system output at $k$th iteration.

Because both the coarse and the precise operator use the same model and system parameters, $\widehat{U}_j^k$ and $U_j^k$ are approximately is the same with the acceptable error. Based on the backward differentiation formula, the partial differential item in equation (32) can be approximately obtained by

$$\frac{\partial F}{\partial U} = \frac{\widehat{U}_j^k - \widehat{U}_j^{k-1}}{U_{j-1}^k - U_{j-1}^{k-1}}. \tag{33}$$

Thus, when substituting the assumption into system equations (31), the solution by parallel-in-time algorithm can be obtained by

$$U_j^k = \widehat{U}_j^k + U_j^k - U_j^{k-1}. \tag{34}$$

Notice that the parallel-in-time method is differentiated by the iteration number index $k$ not the time-step $j$. As shown in Fig. 4, the solution process starts from $t = 0$ time step, when $k = 1$. The coarse operator provides the initial value of $\widehat{U}_j^k$ for precise operator iteratively. $N_{po}$ precise operators are running in parallel from the perspective of time with time-step of $\Delta t$.

### B. Parallel-in-Time Simulation of EV Power System

The parallel-in-time algorithm is implemented in device-level simulation due to the computation burden is mainly caused by the solution process for MMC. Fig. 5 shows the parallel-in-time design in GPU kernels. The powertrain model generates the IM speed, and the SOC model calculates the required power in the CPU. Then these data and global variables are sent to GPU through PCIe bus.

The first value $U_0^0$ of MMC and IM at $k = 0$ is assumed known at the beginning. The coarse operator is initialized with the system states $U_0$ with the time-step with $\Delta T = 100\,ns$.

Meanwhile, there are multiple precise operators to solve the system ODE at the time-step of $\Delta t$ in a parallel manner. Each precise operator is programmed as a gird which is also known as a kernel, which simulates the output voltage and current of MMC, the output power, and the inner variables of IGBT and diode pairs using the initial values from the coarse operator.

For each kernel, there are eight threads of parallelism, which is the same as the number of arms in the MMC. As shown in Fig. 6, each thread is designed to solve the dynamics of individual arms including phase-shift control and the NBM model of IGBT and diode pair.

Finally, the device-level parallel-in-time simulation results are available based on equation (34) using the solution vectors of coarse operators and precise operators. The deviation between $U^k$ and $U^{k-1}$ is calculated by

$$errU^k = \sum_{j=k}^{Num_1} \frac{\| U_j^k - U_j^{k-1} \|}{\| U_j^k \|}. \tag{35}$$

In this work, $errU^k$ is expected to less than 1%.

The parallel-in-time implementation in device-level simulation for power systems generally requires 4 GB of memory and 100 GB/s bandwidth between CPU and GPU. For a specific MMC (e.g., five-level), at least 100 GPU cores are used for the proposed parallel-in-time method.

TABLE II
PARAMETERS OF TESLA X 75D [34]

| Parameters | Value | Parameters | Value |
|---|---|---|---|
| Engine power | 193 kW | $m_{ev}$ | 2352 kg |
| Engine torque | 329 Nm | $C_{r,ev}$ | 0.02 |
| Battery capacity | 75 kWh | $C_{ae,ev}$ | 0.24 |
| Range EPA | 381 km | $\eta_{gr}$ | 8.2752 |

## V. Simulation Results and Discussion

The device-level simulation was carried out on both CPU and GPU on the 2.2 GHz Intel Xeon E5-2698 v4 CPU and 192 GB RAM. The GPU configuration is the Nvidia Tesla V100 with 5120 CUDA cores, 16 GB of memory whose bandwidth is 900 GB/s [33]. In addition, the system-level simulation results are validated by the datasheet of the Tesla Model X 75D whose parameters as listed in Tab. II.

### A. Device-Level Switching Transients

The switching transients of IGBT/diode pair from five-level MMC with the DC bus voltage of 400 V are provided in Fig. 7. The gate voltage is ± 15 V and the gate resistance is 10 Ω. With the dead-time of 5 $\mu$s and switching frequency of 4 kHz, the turn-on current of IGBT overshoots lightly at around 0.382 ms. During the turn-off period, $V_{CE}$ increased from 0 V to 600 V, which is the same as $V_{CE}$ from the datasheet. Fig. 7(c) shows the diode reverse recovery process.

Figs. 7(d) and 7(e) show the upper and lower switch currents of one submodule. When the IGBT turns on, the switch current is changed according to the submodule currents, while when the IGBT turn-off the switch current increased in the reverse direction which accounts for the diode reverse recovery. In the Fig. 7(f), the junction temperature of the IGBT suddenly surges when the MMC starts to operate, and the curve decreases gradually along with the steady-state of MMC. Simulation is also conducted in the commercial EMT tool to validate the NBM of IGBT and diode pair and the designed MMC GPU kernel.

Fig. 8 shows the MMC output voltage with the source frequency of 60 Hz, the submodule capacitor of 6 mΩ, and the arm inductance of 1 mH. Fig. 8(a) demonstrates the capacitor voltage in the first submodule of the upper arm. Since the DC voltage is 400 V, the capacitor voltage reference for individual submodules in the five-level MMC is expected to be 100 V. Fig. 8(a) shows the voltage overshoot during the MMC start-up, with the maximum value of 132.1 V, and eventually remains at

TABLE III
EXECUTION TIME AND SPEED-UP OF EV SIMULATION FOR 10 S DURATION

| Time-step (ns) | Execution Time ( $\times 10^2$ s) | | | | Parallel-in-time Speed-up | | Max. Memory (MB) | |
|---|---|---|---|---|---|---|---|---|
| | CPU | GPU | Parallel-in-time (10 kernels) | Parallel-in-time (30 kernels) | 10 kernels | 30 kernels | CPU | GPU |
| 10 | 84.31 | 78.35 | 19.06 | 12.72 | 4.11 | 6.16 | 1081 | 1256 |
| 40 | 31.57 | 24.56 | 8.62 | 6.88 | 2.85 | 3.57 | 786 | 846 |
| 80 | 22.67 | 18.87 | 7.63 | 6.55 | 2.47 | 2.88 | 571 | 691 |

100 V at steady-state. The phenomenon in the zoomed-in figure is also caused by the diode reverse recovery. The single-phase voltage and three-phase voltage of MMC are shown in Figs. 8(b) and 8(c). The accuracy of these results is validated by SaberRD.

### B. System-Level Simulation for EVs

As is well known, different types of EVs have been recently designed with a wide capacity of driving range. As shown in Fig. 7, the speed profiles of Environmental Protection Agency (EPA) urban dynamometer driving schedule and the New York City Cycle (NYCC) [13] are chosen for the system-level testing.

Figs. 9(a) and 9(b) show $v_{eh}$ from EPA and NYCC, respectively, using which the load power and angular velocity can be calculated using the powertrain model. Figs. 9(g) and 9(h) demonstrate the SOC variation along with the EPA and NYCC cycles.

Fig. 10 provides the five-level MMC connected with the IM responses to the vehicle speed variation from 60 s to 70 s under the condition of the EPA driving cycle. The angular velocity increased to 51.2 rd/s, then gradually decreased started at about 64 s. During this period, the current of MMC phase A decreased at around 63 s when the rate of the angular velocity changing decreased. During 65 s to 70 s, $\omega_m$ keeps increasing, while the rate varies with time after 68 s.

Table III summarizes the execution times, the parallel-in-time speed-up, and maximum used memory for device-level simulation of EV in different time steps. The test is conducted on the five-level MMC at the switching frequency of 4 kHz during 10 s. The results show that the GPU processor takes less time than CPU simulation since the submodules of MMC are processed in a parallel manner in several threads. The proposed parallel-in-time simulation can significantly reduce the execution time using 10 kernels and 30 kernels. Table III shows that the proposed parallel-in-time interpolation strategy significantly accelerates the device-level and system-level MMC-based EV simulation.

Furthermore, the parallel-in-time performs better when the precise time-step becomes smaller, because more nonlinear solution procedures can be processed in a parallel manner. In other word, the larger the difference between the operator's time interval, the more significantly the proposed method performs. However, the time step of coarse operator cannot be too large, which will cause the convergence problem of device-level simulation. Moreover, with the increasing kernel number of precise operators, the proposed method requires less execution time.

## VI. CONCLUSION

In this paper, a parallel-in-time device-level simulation method is proposed for the MMC-based power system of EVs. The NBM can reveal thermal information and EMT behavior during the MMC operation, which is essential for the design of energy management strategy and EVs testing. Particularly, an interpolation strategy is designed based on the parallel-in-time algorithm to reduce the simulation execution time with the two operators working at different time-step. The proposed interpolation strategy can significantly speed up the device-level simulation by processing the nonlinear solution procedures in precise operators in a parallel manner, using the coarse operators' initial values. The simulation results show that system-level EMT simulation involving NBM of IGBT and diode pair is feasible when the parallel-in-time algorithm is utilized. The simulation execution time shows that the proposed parallel-in-time simulation method can speed up the device-level simulation of EVs. Future research will extend the approach to achieve a comprehensive multi-domain simulation of EVs.

## APPENDIX

The Siemens BSM300GA160D IGBT behavioral model parameters $i_{sD1} = 0.01$, $L_{D1} = 10^{-11}$ H, $r_{D1}$ =12.8 $\mu\Omega$, $V_{bD1} = 0.1495$, $K_{rr} = 9874.1$, $V_{ch} = 6.3$ V, $a_1 = 0.022$, $b_1 = 0.004$, $a_2 = 92.5129$, $b_2 = 4.0188$, $a_3 =$ -0.1943, $b_3 =$ -0.4827, x = 0.974, y = 1.429, z = 0.369, $r_{tail} = 1$ $\mu\Omega$, $C_{tail} = 10$ F.

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