Abstract—Electromagnetic transients (EMTs) are fast and decay within a few cycles. Since EMTs are fast, the simulation step size required to simulate an EMT is small, which may make the simulation of a power system with an EMT-type software computationally demanding. This paper proposes a hybrid simulation method called Time Warping (TW) method which makes use of the fast decaying nature of EMTs to accelerate EMT-type simulations. The idea is that small simulation step sizes are only required in the first few cycles following an EMT event where fast transients exist; when these EMTs have decayed and a steady-state is achieved, it is possible to warp to the next EMT event skipping the steady-state in between. The paper shows the effectiveness of the proposed time warping (TW) method by applying it to a simple test circuit and a practical network. The simulation results show that the proposed TW method is capable of accelerating EMT simulations while providing the same accuracy as a full EMT-type tool.

Index Terms—Electromagnetic transient, hybrid simulation methods, initialization, power system dynamics, power system simulation.

I. INTRODUCTION

Electromagnetic transients (EMTs) are triggered by such events as lightning, faults, or a change in network topology due to switching. These transients have a local character meaning that their propagation is confined to local power system equipment; furthermore, EMTs are fast phenomenon and the simulation step size of an EMT-type simulation tool typically needs to be of the order of tens of microseconds or smaller depending on the type of electromagnetic phenomenon being studied. Due to the small simulation step sizes involved, the simulation of a power system with an EMT-type software may become computationally demanding.

To accelerate EMT-type computations, a class of solutions known as hybrid simulation methods have been proposed [1]–[6]. The main idea of hybrid methods stems off from the fact that the propagation of an EMT is limited to local power system equipment. Thus, only a small part of the power system needs to be modelled and simulated by a detailed time-domain representation and solved by an EMT-type solver; the rest of the system can be modelled and simulated in the quasi steady-state representation and solved by a faster solver such as a transient stability TS-type solver. The main challenge of hybrid methods is to appropriately interface the EMT and TS simulations as they employ different simulation step sizes and solution methods. Another challenge is to determine where the boundary between the EMT and TS sub-systems should be set in order to achieve an acceptable accuracy. Research on hybrid methods is currently focused on addressing the aforementioned challenges [7]–[9].

Existing hybrid methods exploit the local character of an EMT to accelerate EMT-type computations. This paper proposes a hybrid method called time warping (TW) which makes use of the fast decaying nature of an EMT to accelerate EMT-type computations. The main idea of the proposed approach stems off from the fact that an EMT decays within a few cycles, and the system reaches a new steady-state where it can be modelled by a steady-state representation. Therefore, detailed EMT-type computations are only needed in the first few cycles following an EMT event; once the EMT has decayed and a steady-state or a quasi steady-state is reached, a faster solver can be employed to jump to the next EMT-type event. Since the steady-state solver is much faster than the time-domain EMT-type solver, the proposed approach accelerates the simulation. Further, since the proposed approach employs an EMT-type solver during an EMT, it does not compromise the accuracy of the solution.

First, the paper presents the theoretical framework of the proposed TW method. An important aspect of the proposed approach is the consecutive initialization of the EMT-type and the steady-state solvers. To illustrate the challenges of initialization, the paper tests two different steady-state solvers, one being an accurate phasor domain solution and the other being an approximate frequency-adaptive method [10]. The effectiveness of the proposed TW method is further studied in a practical network, and the results of the TW method are compared to those from a full EMT solution approach [11].

II. THEORETICAL FRAMEWORK OF THE PROPOSED TIME WARPING METHOD

Fig. 1 shows a pictorial diagram illustration of the proposed TW method. As Fig. 1 shows, the TW method employs an EMT-type solver and a steady-state solver; the EMT solver is only employed in the first few cycles following an EMT event while the steady-state solver is employed during steady-state or quasi steady-state conditions. In Fig. 1, it has been assumed
that the simulation starts from a steady-state and, therefore, the solver is initially in the steady-state mode. The main feature of the proposed TW method is that the user does not have to wait during the steady-state or quasi steady-state mode and can fast-forward to the next EMT event. Since the simulation step size of the steady-state solver is much larger than that of the EMT-type solver, the proposed TW method accelerates the simulation. Furthermore, since no approximation is involved in the simulation of the system transients, the accuracy is not compromised.

An important aspect of the proposed TW method is the initialization of each solution mode. As Fig. 1 shows, the proposed method involves multiple runs of steady-state and EMT solvers. Each solver needs to be initialized using the solution obtained from the previous solver.

A. Initialization

The proposed TW method runs the steady-state and EMT solvers consecutively. Each solver needs to be properly initialized using the solution obtained from the previous solver. Since the TW solver has two modes, there are two initializations: initialization of the EMT solver from the steady-state solver and initialization of the steady-state solver from the EMT solver.

1) Initialization of the steady-state solver: When a power system is in a steady-state, voltage and current waveforms can be described by the following equations:

\[ x_s(t) = X_m \cos (\omega (t - t_{\text{start}}) + \phi) \]  

\[ \hat{X}_s = X_{sr} + jX_{si} \]  

where \( x_s(t) \) represents the instantaneous value of the signal, \( X_m = \sqrt{2(X_{sr}^2 + X_{si}^2)} \) denotes the magnitude, \( \omega \) signifies the angular frequency, \( t_{\text{start}} \) is the start time of the steady-state solution, \( \phi \) represents the phase angle of the signal, \( \hat{X}_s \) denotes the phasor of \( x_s(t) \), and \( X_{sr} \) and \( X_{si} \) represent the real and imaginary parts of the phasor, respectively. It should be mentioned that steady-state voltage and current waveforms may contain harmonics; the proposed TW method can be equally extended to account for harmonics, but this paper only addresses the linear case.

In the steady-state mode, the TW solver employs a phasor-domain solver similar to the harmonic steady-state solution used to initialize the time-domain simulation in [11]; here, this phasor-domain solution is run once at each instant of transition from EMT mode to steady-state mode and calculates the amplitude \( X_m \) of the voltage and current phasors; the phase angles \( \phi \) of these phasors are calculated from the preceding EMT solution as

\[ \phi = \cos^{-1}\left( \frac{x_f}{X_m} \right) \]  

where \( x_f \) denotes the final value of the EMT mode solution and \( X_m \) is found from the phasor-domain solution.

2) Initialization of the EMT solver: The EMT solver can be initialized using the steady-state solution as

\[ x_{\text{emt}0} = \sqrt{2} \text{real} \left( \hat{X}_s \right) \]

This is applicable to all phasors (voltages and currents) in the simulated network and allows to initialize history terms for discretized device models based on a given numerical integration method, such as trapezoidal integration in [11].

B. Solver mode transition

Another aspect of the proposed TW method is to determine when to move from one solution mode to the other. The transition from steady-state mode to EMT mode can be done a few cycles before the EMT event or as soon as it occurs. The EMT event can be detected by monitoring the state of all switches and looking for a change in the state of a switch. The transition from EMT mode to steady-state mode should be done after the EMT has decayed and the system has reached a steady-state or a quasi steady-state. One way of finding a steady-state condition is to monitor the harmonic content of system variables; in the first few cycles following an EMT event, the frequency content of system variables becomes different from that in steady-state. Thus, when the difference between consecutive harmonic measurements becomes small, the steady-state can be declared and transition from EMT to steady-state mode can be triggered.

III. CASE STUDIES AND SIMULATION RESULTS

To illustrate the proposed TW method and investigate its implementation issues, first a number of simulation tests have been conducted on a simple test network shown in Fig. 2. The test system of Fig. 2 consists of an AC grid which is modelled by a voltage source denoted by AC_1 and an equivalent impedance (before BR1). Two capacitor banks are connected to the network through two breakers denoted by BR_1 and BR_2. When BR_1 is closed, the system has two natural frequencies at 340 Hz (due to a resonance between \( C_s \), \( C_1 \), and \( L_s \)) and 27.26 kHz (due to a resonance between \( C_s \), \( C_1 \), and \( L_1 \)). Therefore, the transient response of the system due to the closure of BR_1 contains a fast and a slow oscillating component. Similarly, when BR_2 is closed, the system has two natural frequencies at 262 Hz (due to a resonance between \( C_1 \), \( C_2 \), \( C_s \), and \( L_s \)) and 8.22 kHz (due to a resonance between \( C_2 \) and \( L_2 \)), resulting in fast and slow oscillating components. It should be mentioned that the test system of Fig. 2 is a single-phase system (for illustration purposes), nevertheless, the proposed TW method is also applicable to three-phase networks as shown in Section III-D.
The test system has been subjected to two EMT events caused by the closure of BR\textsubscript{1} and BR\textsubscript{2} at times $t=0.2$ s and $t=0.7$ s, respectively. The objective is to compare the accuracy and computation time of the proposed TW method to those from a full EMT-type tool. Specifically, two case studies are presented which study the initialization of the steady-state solver and the EMT solver. Two steady-state solvers are considered, one being an accurate phasor-domain solution and the other being an approximate frequency-adaptive method referred to as Fast EMTP (FEMTP) [10], and the initialization issues have been studied under the two solvers. In the following figures, EMT represents the time-domain mode solver of the TW solver, SS signifies the phasor-domain solver of the TW method, FEMTP denotes the frequency-adaptive method of [10], and EMTP represents the solution of the full EMT-type tool. The EMT-type solvers use a simulation step size of 1 $\mu$s.

### A. Case 1: Phasor-domain steady-state solution (SS)

In this case study, the steady-state mode solver computes the phasors. Fig. 3 shows the simulation results assuming the following color code: blue for the SS mode of the TW solver; red for the EMT mode of the TW solver; and dashed black for the EMTP solver. As Fig. 3 shows, the simulation starts from a steady-state where BR\textsubscript{1} and BR\textsubscript{2} are open. At $t=0.2$ s, BR\textsubscript{1} is closed causing an EMT. This EMT decays after about 0.3 s and the system reaches a new steady-state. Then, at $t=0.7$ s, BR\textsubscript{2} is closed resulting in a second EMT which decays within 0.3 s.

Fig. 3(a) shows the voltage across capacitor $C_s$ obtained using the proposed TW method. The TW solver has two modes marked by blue (steady-state, SS) and red (EMT) colors. Since the simulation starts from a steady-state, the EMT solver is initially in the SS mode and warps to $t=0.2$ s in anticipation of the first EMT. At $t=0.2$ s (disturbance), the TW solver switches from SS mode to EMT mode as shown in Fig. 3(b). The EMT solver is initialized from the steady-state solution. Fig. 3(b) shows the fast oscillating component of $v_{C_s}$ in response to the closure of BR\textsubscript{1}. After the system has reached a new steady-state at $t=0.5$ s, the TW solver transitions from EMT mode to SS mode, as shown in Fig. 3(c), and warps to the second EMT event at $t=0.7$ s. Fig. 3(d) shows the fast oscillating component of $v_{C_s}$ in response to the closure of BR\textsubscript{2}. The fast oscillating component of the second EMT decays quickly, but the slow component lasts for about 0.3 s. Thus, the solver transitions back to SS mode at $t=1$ s, as shown in Fig. 3(e).

It is emphasized that the steady-state solution (SS) of Fig. 3 (blue) computing time is negligible since it is found at any instant using directly its phasors, i.e., there are no time-domain steps with differential equations. For visualisation purposes, the SS solution is plotted with a time step of 1 ms.

The proposed TW method in this simulation test is 25 times faster than the full EMT solution (EMTP) as reported in Table I.

Fig. 3 further compares the results of the TW method to those of the full EMT solution (EMTP) (dashed black line). As Figs. 3(b)–3(e) show, the proposed TW method reproduces the results of the full EMT solver (EMTP). Figures 3(c) and 3(e) show that the SS solution of the TW solver slightly deviates from that of the EMTP. The reason for this deviation is that the transition from EMT to SS mode takes place before the system has reached a complete steady-state, resulting in slightly inaccurate initialization of the SS solver. This deviation can be explained using (3); if the initialization of the SS solver is not
Fig. 4(b) shows the transition at $t=0.6$ s; EMT mode of the TW solver (solid red), SS mode of the TW solver (solid blue), and full EMT solution (EMTP) (dashed black)

fully accurate, $x_f$ in (3) slightly deviates from its actual value. Consequently, $\phi$ also slightly deviates from its actual value, and the SS solution exhibits a spurious phase shift with respect to the full EMT solution (EMTP). The larger the deviation of $x_f$, the more will be the spurious phase shift. This condition is illustrated in Fig. 4.

Fig. 4(a) shows the transition to SS solution at $t=0.4$ s and Fig. 4(b) shows the transition at $t=0.6$ s. In Fig. 4, the red and blue lines show the EMT and SS modes of the TW solver while the dashed black line shows the result of the full EMT solution (EMTP). It is obviously apparent that the delayed transition at $t=0.6$ s is more accurate since the EMT solution has reached complete steady-state.

It should be mentioned that the amplitude of the sinusoidal signal in the SS solution is accurate since it is calculated from phasor-domain solution and is not sensitive to initialization.

The results presented in Fig. 4 show that the longer the TW solver remains in the EMT mode, the more accurate will be the SS mode solution. Nevertheless, letting the solver to remain in EMT mode for a longer time increases the computation time which compromises the efficiency of the proposed TW method. Therefore, there is a trade-off between accuracy and computation time under the proposed TW method.

B. Case 2: FEMTP-based steady-state solution (FEMTP)

This section presents the implementation of the TW method using the FEMTP approach of [10]. The FEMTP approach is an approximate numerical solution which allows using large simulation time steps without sacrificing too much accuracy. The reason for employing the FEMTP method in this section is to study slightly inaccurate initialization of the EMT solver and compare the results to the accurate initialization by phasor-domain solution (SS) of the previous case study. The main idea of the FEMTP approach is that usually, an electric signal in power systems can be modelled as a slow time varying waveform superimposed on the fundamental frequency waveform in the following form

$$x(t) = A(t)\cos(\omega_t t + \phi(t)),$$

where $A(t)$ represents the amplitude and $\phi(t)$ denotes the phase angle of the signal. The variable $x(t)$ changes rapidly and its computation requires using a small time step. It is assumed that the amplitude $A(t)$ and phase angle $\phi(t)$ change slowly and thus, can be computed using a larger time step. The FEMTP approach extracts the amplitude $A(t)$ and phase angle $\phi(t)$ using a time-domain transformation by defining a rotating frame which rotates at the angular velocity of the $\omega_0$; in this rotating frame, two new variables are defined as

$$u(t) = A(t)\cos(\phi(t))$$

$$v(t) = A(t)\sin(\phi(t)),$$

which are the projection of $x(t)$ on the two axes of the rotating frame. The equations of the system are then written in terms of the new variables and solved using a large time step. Finally, the solution is transformed back to the original frame of $x(t)$ by applying the inverse time transformation.

The FEMTP solution is an approximate solution due to the underlying assumption of (5). Therefore, it cannot compute transients containing two very different frequencies such as the EMTs of the test circuit of Fig. 2. Nevertheless, when the fast oscillating components of the transients have decayed, the signals of the test circuit can be approximated by (5). Therefore, by employing FEMTP in the steady-state mode of the TW solver, it is possible to move to the steady-state mode earlier than the case of the phasor-domain solution (SS), which assumes a pure sine waveform, and potentially save computation time.

This section presents the TW method employing the FEMTP approach in the steady-state mode. The simulation test is the same as Case 1, Section III-A. The TW solver is also the same except that in the steady-state mode, it employs the FEMTP method instead of the phasor-domain solution (SS). The simulation step size of the FEMTP solver $h$ is found from the formula $\omega_n h = (k\pi + \pi/4) \ [10]$ with $k=1$ and $\omega_n=377$ rad/s, and hence, $h=0.0104$ s.

Fig. 5 shows the results of this case study. In Fig. 5, the red color denotes the EMT mode of the TW solver, the blue dots represent the FEMTP solution, and solid black color signifies the full EMT solution. It should be mentioned that the dashed blue lines in Fig. 5 only show the warp from one data point to the next data point of the FEMTP solver and do not represent the solution waveform.

As Fig. 5 shows, the simulation starts from a steady-state. Therefore, the TW solver is initially in the FEMTP mode and warps to $t=0.1664$ s in anticipation of the first EMT at $t=0.2$ s. In contrast to the phasor-domain solution (SS) of Section III-A, here the transition from FEMTP to EMT occurs before the instant of EMT; the reason is that following this transition, the
solution exhibits a spurious transient, as shown in Fig. 5(b). Therefore, it is necessary to wait for this spurious transient to decay (or for the EMT solution to adjust itself to the actual solution) before the EMT occurs. The reason for this spurious transient is that FEMTP is an approximate solution and the initialization of the EMT solver becomes slightly inaccurate; the amplitude and duration of these oscillations decreases if the time step of FEMTP is reduced. The reason is that the accuracy of FEMTP increases as the time step is decreased.

The TW solver remains in the EMT mode to simulate the accuracy of FEMTP increases as the time step is decreased. The reason is that the TW solver is initially in the SS mode where the assumptions of FEMTP become valid, the EMT has decayed and the system has reached a quasi steady-state condition reached in time-domain; the FEMTP saves computation time by allowing an earlier transition to the steady-state mode, however, it is an approximate solution and may become less accurate for initializing the time-domain solution.

It is possible to take advantage of both techniques by combining them; after the fast oscillating component of an EMT has decayed and the system has reached a quasi steady-state where the assumptions of FEMTP become valid, the solver can move to FEMTP until a complete steady-state has been achieved and the solver can transition to phasor-domain solution (SS). This section shows the combined FEMTP-SS solution.

As Fig. 6(a) shows, the system starts from a steady-state and therefore, the TW solver is initially in the SS mode (solid blue). As soon as the first EMT occurs, the solver transitions to EMT mode (at $t=0.2$ s, solid red). The fast oscillating component of the EMT decays after about 0.2 s, and the solver transitions from EMT mode to FEMTP mode at $t=0.4$ s. During the FEMTP mode, the solver gradually warps from $t=0.4$ s to $t=0.504$ s using the FEMTP solver (blue dots), taking a total of 10 steps. At $t=0.504$ s, the system has reached a complete steady-state, and the solver transitions back to the SS mode. In the SS mode, the solver makes a full warp to the second EMT event at $t=0.7$ s where the same sequence of events is repeated. Fig. 6(b) shows the transition from EMT mode to FEMTP mode, and from FEMTP mode to SS mode. Fig. 6(c) compares the solution of the TW solver to that of the full EMT solution (EMTP). As Fig. 6(c) shows, the TW solution matches that of the full EMT solution (EMTP).

### Table I. Computational Gain of TW Compared to Full EMT Solution (EMTP)

<table>
<thead>
<tr>
<th>Method</th>
<th>Time Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS TW</td>
<td>25 times (faster)</td>
</tr>
<tr>
<td>FEMTP TW</td>
<td>20 times (faster)</td>
</tr>
<tr>
<td>Combined FEMTP-SS</td>
<td>32 times (faster)</td>
</tr>
</tbody>
</table>

As Table I shows, the computational gain of the FEMTP approach is less than that of the phasor-domain solution (SS). The reason is that the time warps of the phasor-domain solution (SS) are complete, and the computation time of the SS mode is almost zero as the phasors are computed only at the beginning of the SS mode. Nevertheless, under the FEMTP method, the time warps are not complete; the FEMTP solver needs to compute the steady-state mode solution with a time step of 0.0104 s which adds to the overall computation time. Furthermore, due to the spurious transient, the FEMTP should transition to EMT a few cycles before the instant of the EMT, which further adds to the computation time. In the next section, the phasor-domain solution (SS) and FEMTP solutions have been combined to further reduce the computation time.

### C. Case 3: Combined FEMTP-SS solution

Case 1 and 2 of sections III-A and III-B show that the two employed steady-state approaches each have their advantages and disadvantages: the phasor-domain solution (SS) has the advantage of being accurate but it is sensitive to the steady-state condition reached in time-domain; the FEMTP saves computation time by allowing an earlier transition to the steady-state mode, however, it is an approximate solution and may become less accurate for initializing the time-domain solution.

As Fig. 6(a) shows, the system starts from a steady-state and therefore, the TW solver is initially in the SS mode (solid blue). As soon as the first EMT occurs, the solver transitions to EMT mode (at $t=0.2$ s, solid red). The fast oscillating component of the EMT decays after about 0.2 s, and the solver transitions from EMT mode to FEMTP mode at $t=0.4$ s. During the FEMTP mode, the solver gradually warps from $t=0.4$ s to $t=0.504$ s using the FEMTP solver (blue dots), taking a total of 10 steps. At $t=0.504$ s, the system has reached a complete steady-state, and the solver transitions back to the SS mode. In the SS mode, the solver makes a full warp to the second EMT event at $t=0.7$ s where the same sequence of events is repeated. Fig. 6(b) shows the transition from EMT mode to FEMTP mode, and from FEMTP mode to SS mode. Fig. 6(c) compares the solution of the TW solver to that of the full EMT solution (EMTP). As Fig. 6(c) shows, the TW solution matches that of the EMT. The computational gain of the combined FEMTP-SS solution was 32 times faster than the full EMT solution (EMTP) as reported in Table I.
D. Simulation of a practical system

This case study shows the simulation of a practical 230 kV three-phase power system shown in Fig. 7 using the proposed TW method. The system under study includes five 13.8 kV synchronous machines (SMs) connected to the network through five 13.8/230 kV Delta-Wye transformers. The SMs are modeled by actual synchronous generator models with controls. The system also includes 6 transmission lines represented with the constant parameter line model (including propagation delays, with parameters calculated at 60 Hz). The transformer models do not include magnetization.

Two EMT events occur in the test system: the first is a fault on the transmission line TLM_{120mi} connecting BUS1 and BUS2, occurring at \( t=0.2 \) s and cleared at \( t=0.3 \) s; and the second is a fault on TLM_{180mi} connecting BUS2 and BUS9, occurring at \( t=30.2 \) s and cleared at \( t=30.3 \) s.

The simulation runs from \( t=0 \) s to \( t=60 \) s with a step size of 50 \( \mu \)s. When a transient occurs, the time-domain steady-state is declared when the speeds of synchronous generators decay to constant values within a given tolerance. It should be mentioned that steady-state is detected by monitoring the system variables which exhibit the slowest dynamics response. In the case study of this section, the mechanical speeds of synchronous machines are monitored to detect steady-state. Nevertheless, in the example of Section III-A the system does not contain any machines. Therefore, the harmonic content of voltage and current signals is monitored to detect steady-state. The disadvantage of using mechanical speeds is that in some cases, it could be very long before the speeds become completely steady. In such cases, it is also possible to monitor the harmonic content of voltages and currents.

In this system, a load flow solution must be used before performing the first steady-state solution. A multi-phase and unbalanced load-flow solution is available in [11]. The synchronous machines are given PV (active power control and voltage control) constraints, a slack bus is used in the 500 kV system, and the loads are modeled using PQ (given active and reactive powers) constraints. After the completion of the load-flow solution, the steady-state solution converts the constraints into lumped models using the calculated phasors of the network.

In [11], it is possible to automatically initialize synchronous generator equations and related controls (field voltage and mechanical power) from the steady-state solution. The same procedure is used here for reinitialization step in the TW method.

The proposed TW method is used to simulate the two faults as follows:

1) from \( t=0 \) s to \( t=0.2 \) s: SS mode;
2) from \( t=0.2 \) s to \( t=4.2 \) s: EMT mode;
3) from \( t=4.2 \) s to \( t=30.2 \) s: SS mode;
4) from \( t=30.2 \) s to \( t=34.2 \) s: EMT mode;
5) from \( t=34.2 \) s to \( t=60 \) s: SS mode

The overall computation time of the TW solver is 9.3 s (4.4 s for the first EMT and 4.9 s for the second EMT). The SS solution computing time remains negligible. The computing time for control system equations is included. These timings are estimated from the solution modules of the complete software in [11].

Under the full EMT solution, the computation time is 74 s; therefore, the TW solver is approximately 8 times faster.
than the full EMT solution (EMTP) for this network case; generally speaking, the computational gain in practical systems is strongly related to the time spent in time-domain steady-state mode between transients. Fig. 8 shows the instantaneous value of the \( \alpha \)-phase voltage of BUS1 of the test system during the two faults. The voltage becomes zero from \( t=0.2 \) s to \( t=0.3 \) s due to the fault on TLM_120mi, and returns to steady-state after the fault has been cleared. The second fault at \( t=30.2 \) s on the TLM_180mi transmission line causes the voltage of BUS1 to drop. Fig. 8 shows that the post-fault voltage waveforms become nearly sinusoidal after 0.2 s of the fault clearance. Nevertheless, the solver stays in EMT mode for 4 s after the fault until the speed of synchronous generators decay to constant values.

IV. CONCLUSION

This paper has proposed a time warping (TW) method for the acceleration of electromagnetic transient simulations in power systems. The proposed method uses an EMT solver to simulate the system in the first few cycles following a transient event and a steady-state solver when a steady-state or a quasi steady-state is reached in time-domain. The steady-state phasor-based solution approach allows to perform jumps (warpss) between time-domain solutions using reinitialization at the transition points.

The TW method has been demonstrated using the steady-state phasor solution approach and a time-domain transformation method that offers the advantage of transitioning into steady-state solution earlier. A combined solution with both methods has also been tested and estimated to provide the best performance.

The simulation results demonstrated that the proposed TW method is capable of accelerating EMT simulations while providing the same accuracy as a full EMT solution. As future work, the proposed approach can be extended to include harmonics due to the presence of nonlinearities and to account for increased complications when dealing with power electronics.

REFERENCES