Three-Phase Radial EMTP and Stealthy Attack Detector for Distribution Systems

James Ranjith Kumar R.
National University of Singapore
jamesranjithkumar@nus.edu.sg

Biplab Sikdar
National University of Singapore
bsikdar@nus.edu.sg

Deepa Kundur
University of Toronto
dkundur@ece.utoronto.ca

***Abstract*—This paper presents an algorithm for obtaining the transient solution for three-phase radial networks. The proposed Radial EMTP (electromagnetic transient program) is based on a backward-forward sweep technique which exploits the radial nature of distribution network. Using this Radial EMTP, a technique is developed to detect stealthy attacks targeted against distribution systems. This method requires lesser computational resources as compared to conventional EMTP programs. This paper also develops a transient model for three-phase synchronous generators which is compatible with the proposed three-phase radial EMTP. The proposed technique has been tested on 5-bus three-phase system which is powered by two synchronous generators. The proposed Radial EMTP has been benchmarked with Opal-RT's HYPERSIM and it is shown that the proposed technique can identify stealthy attacks.**

***Index Terms*—Distribution system, EMTP, Stealthy Attack, Synchronous Generator, Transients**

I. Introduction

EMTP is one of the popular tools which is used to obtain the transient solution in the area of power systems and power electronics [1]. Although various versions of EMTPs have been developed in the past four decades, all such versions employ variants of nodal analysis for obtaining the transient solution in their respective EMTP version [2]. This classical approach of using nodal analysis is followed in available EMTP versions because of the general consideration that the network topology are usually meshed in nature. Even the most recent approach proposed in EMTP-RV [3] follows a Modified Augmented Nodal Analysis to obtain the solution. It is well known that by using nodal analysis, EMTP requires to solve simultaneous linear equations for every time step. Applying such a classical approach based EMTP for radial distribution networks is like using a sledgehammer to crack a nut since it may not be able to provide any computational advantage. This paper aims to exploit the topological nature of distribution networks by developing a backward-forward sweep technique to obtain a transient solution. With this technique, a single line section is solved for a given instance of time which significantly reduces the computation effort. Hence, the proposed radial EMTP requires lower computational resources as compared to the conventional EMTP technique. As synchronous generators are the commonly used power generators, it has been modeled for the radial EMTP technique developed in this paper.

Though considerable research has been conducted on cyber threats in conventional power systems, only a few amount of literature is available for stealthy attacks against distribution systems. A general overview of cybersecurity aspects on distribution systems is discussed in [4]. The attack strategy which is given in [5] manipulates the status of overcurrent relay and circuit breaker in a distribution feeder. Stealthy attacks that can bypass conventional bad data detection schemes in distribution systems is developed in [6] which uses an approximate estimate of state to generate the attack vector. Such stealthy attacks against three phase linear distribution system state estimators are studied in [7]. Although such studies on distribution system cybersecurity are available, no technique have been proposed to detect such stealthy attacks.

TABLE I: Description of EMTP Models for Basic Elements.

Resistor	$i_{mn}^k = \frac{1}{R}\left(V_m^k - V_n^k\right)$
Inductor	$i_{mn}^k = \frac{\Delta t}{2L}\left(V_m^k - V_n^k\right) + H_L^{k-1}$ $H_L^{k-1} = i_{mn}^{k-1} + \frac{\Delta t}{2L}\left(V_m^{k-1} - V_n^{k-1}\right)$
Capacitor	$V_m^k - V_n^k = \frac{\Delta t}{2C} i_{mn}^k + H_C^{k-1}$ $H_C^{k-1} = V_m^{k-1} - V_n^{k-1} + \frac{\Delta t}{2C} i_{mn}^{k-1}$

This paper develops a technique to detect such stealthy attacks in distribution systems where the Radial EMTP is used to calculate the transients and they are compared against the obtained measurements. If there are any significant deviations between the calculated and the measured values, then it can be concluded that there is a stealthy attack in the measurements. As this detection scheme is based on the proposed Radial EMTP, it takes lesser computational resources as compared to conventional EMTP which needs to solve a linear system at every time step. In the following section, the mathematical models for the proposed three-phase radial EMTP technique has been developed such that it can be incorporated in the backward-forward sweep algorithm to obtain the transient solution.

II. Proposed EMTP for Radial Networks

EMTP employs the trapezoidal rule to simplify the integro-differential equations into algebraic form which is solved over discrete time with an interval of Δt. At a given time step k, the EMTP models of resistance R, inductance L and capacitance C are tabulated in Table I where V and I represent the values

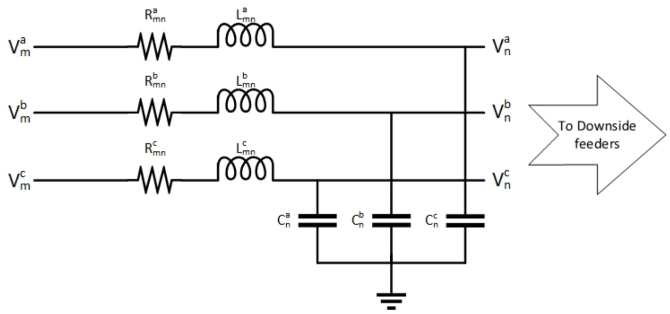


Fig. 1: Line section.

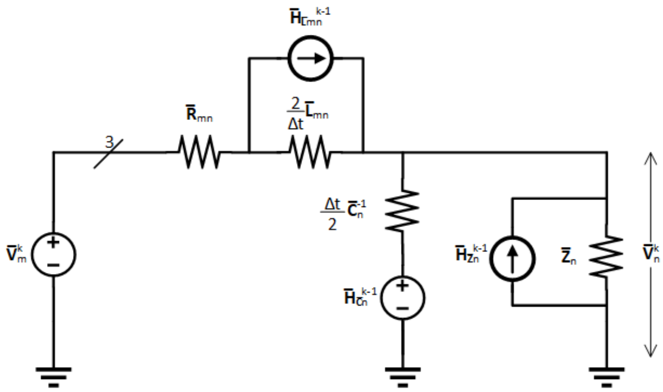


Fig. 2: EMTP model equivalent

of voltage and current at the specified instant and the subscripts m and n indicate the positive and negative terminals of the respective elements. H^{k-1} indicates the history component of the respective element which uses the values taken at $k-1$. To utilize these EMTP models in backward-forward sweep algorithm, consider a three phase line section in a radial network between upside bus m and downside bus n as shown in Fig. 1. Let the three-phase elements given in Fig. 1 be represented in matrix form as $\bar{\mathbf{R}}_{mn}$, $\bar{\mathbf{L}}_{mn}$ and $\bar{\mathbf{C}}_n$. Similarly, the history components of corresponding elements are denoted in vector form as $\bar{\mathbf{H}}^{k-1}$. With these values, the discretized equivalent of this line section is obtained using EMTP models as shown in Fig. 2. Let $\bar{\mathbf{Z}}_n$ and $\bar{\mathbf{H}}^{k-1}_{\bar{\mathbf{Z}}_n}$ be the thevenin's resistance and Norton current of all the downside feeders from bus n. The thevenin's resistance of this line section from bus m is given as

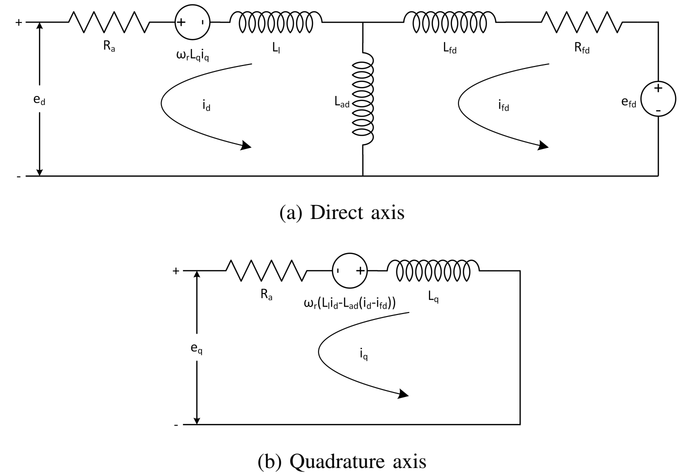
$$\bar{\mathbf{Z}}_{mn} = \bar{\mathbf{R}}_{mn} + \frac{2}{\Delta t}\bar{\mathbf{L}}_{mn} + \bar{\mathbf{Z}}^{sh}_{mn} \tag{1}$$

where

$$\bar{\mathbf{Z}}^{sh}_{mn} = \left(\frac{2}{\Delta t}\bar{\mathbf{C}}_n + \bar{\mathbf{Z}}_n^{-1}\right)^{-1} \tag{2}$$

Similarly the Norton equivalent current value can be computed as

$$\bar{\mathbf{H}}^{k-1}_{\bar{\mathbf{Z}}_{mn}} = \bar{\mathbf{Z}}^{-1}_{mn}\left(\bar{\mathbf{Z}}^{sh}_{mn}\bar{\mathcal{J}}^{k-1}_{mn} - \frac{2}{\Delta t}\bar{\mathbf{L}}_{mn}\bar{\mathbf{H}}^{k-1}_{\bar{\mathbf{L}}_{mn}}\right) \tag{3}$$



(a) Direct axis

(b) Quadrature axis

Fig. 3: Synchronous generator equivalent circuit.

TABLE II: Feeder Data for 5-bus system.

Top Bus	Bottom Bus	Line Parameters		Load at the bottom bus	
		R (mΩ)	L (mH)	Active Power (kW)	Reactive Power (kVAr)
0	1	96.3	12.45	-	-
1	2	64.2	8.3	3.6	2.7
0	3	44.94	5.81	3.6	2.7
3	4	96.3	12.45	3.6	2.7

where

$$\bar{\mathcal{J}}^{k-1}_{mn} = \frac{2}{\Delta t}\bar{\mathbf{C}}_n\bar{\mathbf{H}}^{k-1}_{\bar{\mathbf{C}}_n} - \bar{\mathbf{H}}^{k-1}_{\bar{\mathbf{Z}}_n} \tag{4}$$

To incorporate the synchronous generator model in the proposed technique, its stator and rotor elements are transformed to direct and quadrature axes where the time varying components are eliminated. The notation used in [8] for the elements of synchronous generator has been adopted in this

TABLE III: Synchronous Machine Data.

$R_a = 0.062$	$L_d = 1.71$	$L'_d = 0.43$	$L''_d = 0.12$	$T'_{d0} = 0.1$
$L_q = 1.22$	$L''_q = 0.37$	$L_l = 0.064$	$H = 0.34$	

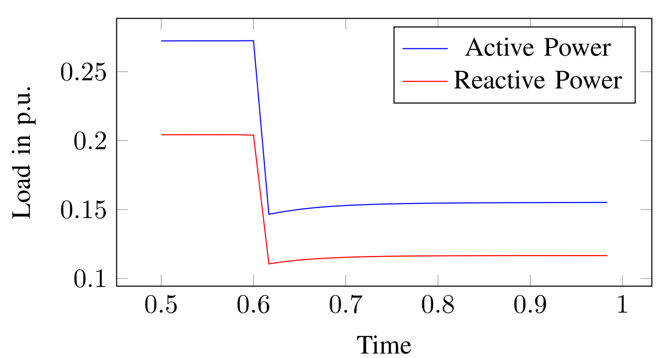
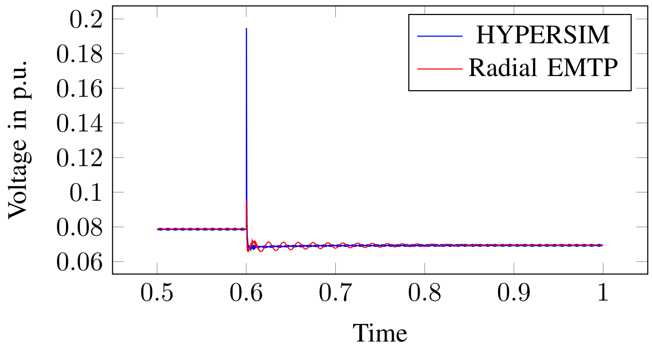
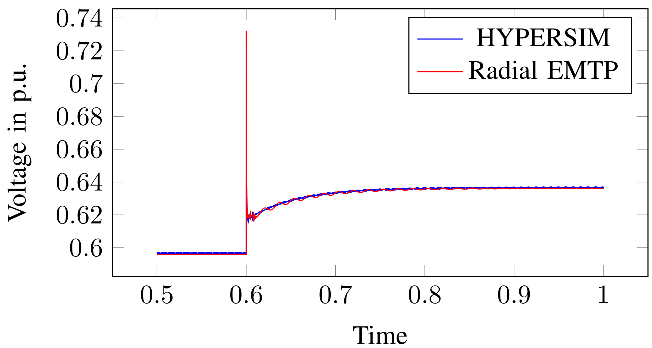


Fig. 4: Load power drawn at Bus 4.

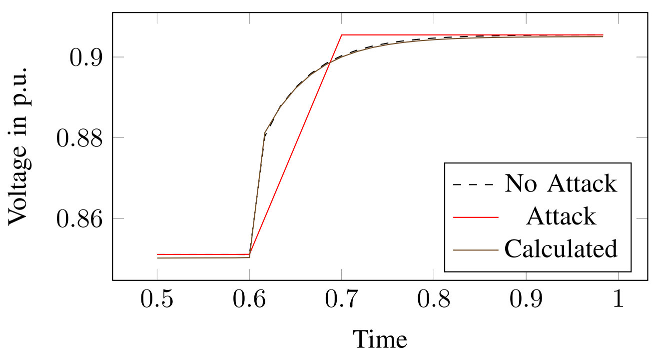


(a) e_d

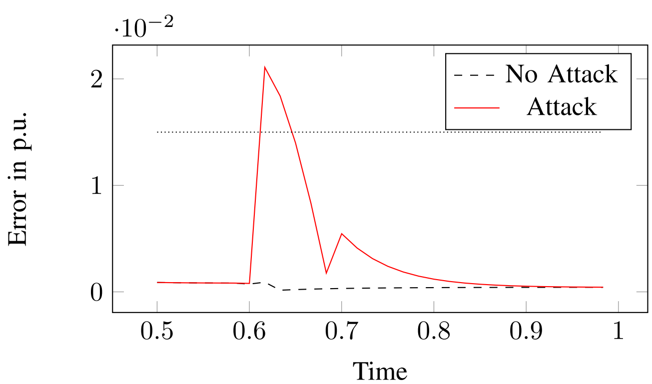


(b) e_q

Fig. 5: Direct and Quadrature axis Voltages at Synchronous Generator 1



(a) Voltage Magnitude at bus 2



(b) Error

Fig. 6: Voltage Magnitude measurement and error at bus 2

paper. Considering that the damper resistances are negligible in small generators, the equivalent circuit of synchronous generator can be given as shown in Fig. 3. Using the EMTP models tabulated in Table I, it is further simplified as

$$\begin{bmatrix} e_d \\ e_q \end{bmatrix} = \begin{bmatrix} V_d^{OC} \\ V_q^{OC} \end{bmatrix} - \begin{bmatrix} \mathcal{Z}_{11} & \mathcal{Z}_{12} \\ \mathcal{Z}_{21} & \mathcal{Z}_{22} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \tag{5}$$

where

$$\mathcal{Z}_{11} = R_a + \frac{2}{\Delta t} L_l + \left(\frac{1}{R_{fd} + \frac{2}{\Delta t} L_{fd}} + \frac{1}{\frac{2}{\Delta t} L_{ad}} \right)^{-1} \tag{6}$$

$$\mathcal{Z}_{22} = R_a + \frac{2}{\Delta t} L_q \tag{7}$$

$$\mathcal{Z}_{12} = -\omega_r L_q \tag{8}$$

$$\mathcal{Z}_{21} = \omega_r \left(L_l + L_{ad} - \frac{L_{ad}^2}{\frac{\Delta t}{2} R_{fd} + L_{fd} + L_{ad}} \right) \tag{9}$$

and the definitions of V_d^{OC} and V_q^{OC} are given in (10) and (11) respectively.

Renumbering the buses in a hierarchical sequence is necessary for the backward-forward sweep technique and such a sequenced numbering is made for all buses. For the given time step, the procedure begins with a backward sweep where the Norton equivalent is calculated using (1) and (3), starting from the bottom-most bus and continuing towards the top-most bus. In this backward sweep, the Norton equivalent of a synchronous generator is calculated using (6) to (11). After its completion, a forward sweep is made from the top-most bus towards the bottom-most bus where the upside bus voltage is used to calculate the downside bus voltage.

III. Results

The proposed technique is validated on a 5-bus three-phase radial system [9] and its performance is compared with HYPERSIM. The system data are given in Tables II and III. A transient is created in this simulation by reducing both active and reactive power drawn by load at bus 4 to half its rated value at 0.6 seconds as shown in Fig. 4. The values of e_d and e_q calculated by the proposed radial EMTP and HYPERSIM is shown in Fig. 5 which indicates that the proposed technique provides the results with similar accuracy as conventional EMTP. The proposed detection scheme is tested in no-attack scenario, where the load at bus 2 is legitimately reduced to half at 0.6 sec and in an attack scenario where such a change in measurement is made due to manipulation by the attacker. Fig. 6(a) and (b) show the voltage and error in these scenarios and demonstrates that using the difference between the calculated and measured values, the presence of stealthy attacks can be identified.

IV. Conclusion

This paper presents a three phase radial EMTP technique which can exploit the topographical nature of distribution systems. The proposed radial EMTP has been extended to detect stealthy attacks against distribution networks. This technique is demonstrated on 5-bus system to show that the

$$V_d^{OC} = \left(\left(R_{fd} + \frac{2}{\Delta t} L_{fd} \right)^{-1} + \left(\frac{2}{\Delta t} L_{ad} \right)^{-1} \right)^{-1} \left(\frac{e_{fd} + \frac{2}{\Delta t} H_{fd} L_{fd}}{R_{fd} + \frac{2}{\Delta t} L_{fd}} + H_{ad} \right) + \frac{2}{\Delta t} H_l L_l \tag{10}$$

$$V_q^{OC} = \frac{2}{\Delta t} H_q L_q + \omega_r L_{ad} \left(\frac{e_{fd} + \frac{2}{\Delta t} \left(H_{fd} L_{fd} - H_{ad} L_{ad} \right)}{R_{fd} + \frac{2}{\Delta t} \left(L_{fd} + L_{ad} \right)} \right) \tag{11}$$

radial EMTP provides similar results as HYPERSIM and the detection technique can distinguish stealthy attacks and legitimate measurements.

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