On the Applicability of Exponential Recovery Models for the Simulation of Active Distribution Networks

Eleftherios O. Kontis, *Student Member, IEEE,* Theofilos A. Papadopoulos, *Member, IEEE,* Andreas I. Chrysochos, *Member, IEEE,* and Grigoris K. Papagiannis, *Senior Member, IEEE*

***Abstract*—This letter delivers a method to extend the use of the exponential recovery model (ERM) for the dynamic simulation of active distribution networks (ADNs). The conventional ERM uses exponential functions to describe the steady-state and transient characteristics of the grid, failing to replicate reverse power flow phenomena which may occur in modern ADNs during or after voltage disturbances. To solve this issue a new formulation employing polynomial functions instead of the original exponential is proposed.**

***Index Terms*—Active distribution networks, dynamic equivalencing, exponential recovery model, measurement-based approach, polynomial functions.**

I. Introduction

During the last decades, the exponential recovery model (ERM) has been widely used for the dynamic simulation of passive distribution networks [1]–[3]. However, the increased penetration of distributed generation (DG) into the existing networks has altered drastically the dynamic properties of power systems, posing into question the reliability and applicability of the conventional ERM to modeling of modern active distribution networks (ADNs).

Indeed, the conventional ERM is formulated assuming unidirectional power flows. Thus, it cannot replicate the dynamic behavior of ADNs, where bi-directional power flows may occur during or after a voltage disturbance. To solve this issue, in this paper, the mathematical formulation of the conventional ERM is modified by adopting polynomial functions for the representation of the transient and steady-state characteristics of the grid. The applicability of the proposed method and the required proof-of-concept are demonstrated on a medium voltage (MV) distribution grid using dynamic simulations.

II. The Exponential Recovery Model

The general dynamic response of distribution networks subjected to a random step-down voltage disturbance is illustrated in Fig. 1. After the voltage disturbance, a transient power decrement Δy_t occurs and the total power demand drops to y_+. Here, y can represent both the real and reactive power responses. Subsequently, a recovery phase takes place and the power demand gradually recovers to y_{ss}, presenting a Δy_s steady-state offset compared to the initial power demand y_0. The conventional ERM approximates this dynamic behavior using the following set of equations [2]:

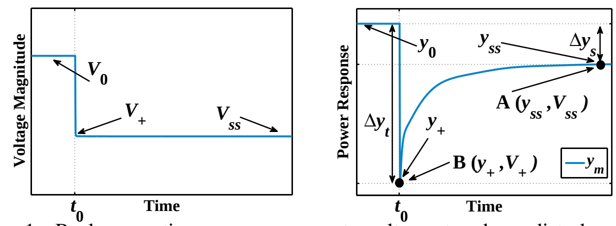

Fig. 1. Real or reactive power response to voltage step down disturbance.

$$y_{ERM}(t) = y_s(V)(1 - e^{-t/T_y}) + y_t(V)e^{-t/T_y} \quad (1)$$

$$y_s(V) = y_0(V/V_0)^{n_s}, \qquad y_t(V) = y_0(V/V_0)^{n_t} \quad (2)$$

where y_{ERM} denotes the estimated by the ERM power demand, $y_s(V)$ and $y_t(V)$ are two exponential functions used to describe the Δy_s and Δy_t offsets, V is the network voltage, and T_y is the recovery time constant of the power demand. V_0 and y_0 are the voltage magnitude and power demand before the voltage disturbance, while n_s and n_t are the steady-state and transient voltage dependence coefficients, respectively, defined by operating points $A(y_{ss}, V_{ss})$ and $B(y_+, V_+)$ as:

$$n_s = [log(y_{ss}/y_0)]/[log(V_{ss}/V_0)] \quad (3)$$

$$n_t = [log(y_+/y_0)]/[log(V_+/V_0)] \quad (4)$$

where V_+ and V_{ss} are the voltage magnitudes immediately after the voltage disturbance and at the new steady-state, respectively. As shown in (1), the output of the ERM is a nonlinear function of T_y. Therefore, non-linear least squares (NLS) optimization, targeting to minimize (5), is used for the accurate identification of this parameter [4].

$$J(T_y) = \sum_{n=1}^{N} (y_m[n] - y_{est}[n])^2 \quad (5)$$

Where N stands for the total number of samples, $y_m[n]$ is the measured power demand at the n-th sample, and $y_{est}[n]$ denotes the estimated response.

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E. O. Kontis and G. K. Papagiannis are with the Power Systems Laboratory, School of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece, GR 54124, (e-mail: kontislefteris@gmail.com; grigoris@eng.auth.gr).

T. A. Papadopoulos is with the Power Systems Laboratory, Dept. of Electrical and Computer Engineering, Democritus University of Thrace, Xanthi, Greece, GR 67100, (e-mail: thpapad@ee.duth.gr).

A. I. Chrysochos is with the Cablel® Hellenic Cables S.A., Viohalco Group, Sousaki Korinthias, Korinthos, Greece, GR 20100 (e-mail: achrysochos@fulgor.vionet.gr).

III. Proposed Formulation

It is evident that in cases of bi-directional power flows, exponents n_s and n_t cannot be determined using (3) and (4), since y_0, y_+ and y_{ss} have opposite signs and the associated logarithmic functions cannot be defined and evaluated. Moreover, as shown in (1), due to the use of exponential functions $y_s(V)$ and $y_t(V)$, y_{ERM} presents always the same sign as the power demand prior to the disturbance, i.e. y_0. This, reveals the inapplicability of the ERM for the modeling of ADNs, where reverse power flows may occur during or after voltage disturbances.

To overcome the two above-mentioned limitations and to extend the applicability of the ERM for the dynamic simulation of ADNs, this letter introduces the use of polynomial functions, instead of exponentials, for the analysis of the steady-state and transient characteristics of the grid. For this purpose, $y_s(V)$ and $y_t(V)$ of (2) are replaced with (6) and (7), respectively. In this case, the output of the modified ERM y_{MERM} is described in (8):

$$y_{M,s}(V) = y_0[\alpha_1(V/V_0) + \alpha_2], \qquad \alpha_1 + \alpha_2 = 1 \quad (6)$$

$$y_{M,t}(V) = y_0[\beta_1(V/V_0) + \beta_2], \qquad \beta_1 + \beta_2 = 1 \quad (7)$$

$$y_{MERM}(t) = y_{M,s}(V)(1 - e^{-t/T_y}) + y_{M,t}(V)e^{-t/T_y} \quad (8)$$

The required parameters are identified using the measurement-based approach [2]. Thus, when a measurement data set is available, coefficients α_1, α_2, β_1 and β_2 are determined from the corresponding operating points $A(y_{ss}, V_{ss})$ and $B(y_+, V_+)$ as:

$$\alpha_1 = [V_0(y_{ss} - y_0)]/[y_0(V_{ss} - V_0)], \qquad \alpha_2 = 1 - \alpha_1 \quad (9)$$

$$\beta_1 = [V_0(y_+ - y_0)]/[y_0(V_+ - V_0)], \qquad \beta_2 = 1 - \beta_1 \quad (10)$$

Finally, similar to the conventional approach, parameter T_y of (8) is identified through NLS optimization.

IV. Numerical Evaluation

The performance of the modified ERM is demonstrated by simulations in the distribution grid of Fig. 2, implemented in the NEPLAN® software. The examined network consists of several MV/LV transformers, inductions motors, static loads and PVs. To investigate network dynamics, a -7% voltage disturbance is introduced. The simulated real and reactive power responses are presented in Fig. 3, and compared with the estimates provided by the conventional ERM and the modified ERM. Here, a plus sign denotes that the power is consumed at the downstream side, while a minus sign that the power is exported.

Initially, P_0 and Q_0 are equal to $0.46\ MW$ and $2.2\ MVAr$, respectively. Immediately after the voltage disturbance, real and reactive power demand drop to $P_+ = -0.27\ MW$ and $Q_+ = -0.77\ MVAr$ values, respectively. The real power recovers to $P_{ss} = 0.05\ MW$, while the reactive power to $Q_{ss} = -0.23\ MVAr$. As shown in both cases, the conventional ERM cannot simulate the reverse power flow during the voltage disturbance. Thus, it fails to replicate real and reactive power overshoots, which are of high importance in

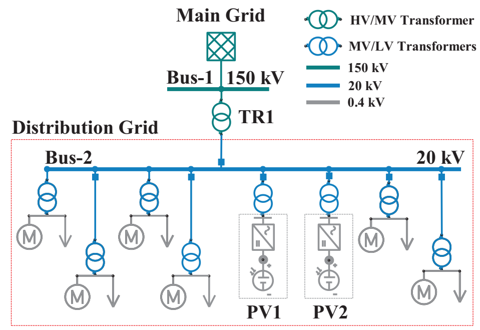

Fig. 2. Examined distribution grid.

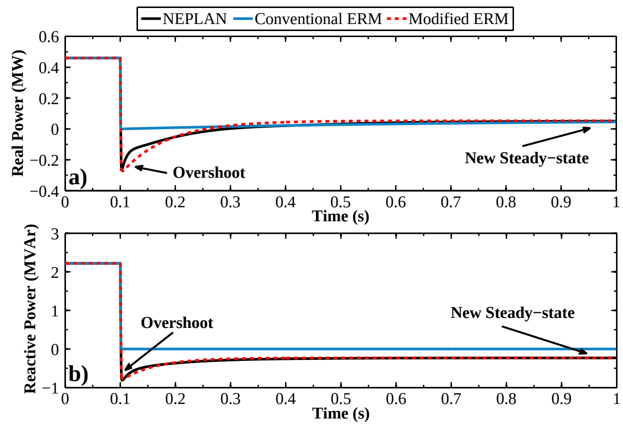

Fig. 3. Modeling of a) real and b) reactive power.

stability studies. Moreover, the new reactive power steady-state is not accurately simulated, since Q_0 and Q_{ss} have opposite signs. On the contrary, these issues are not observed in the case of the modified ERM, since bi-directional power flows are successfully simulated. Thus, the transient overshoot and the new real and reactive power steady-states are accurately captured.

V. Conclusions

The conventional ERM uses exponential functions to represent the transient and steady-state characteristics of the grid. Therefore, it fails to simulate reverse power flow phenomena which occur in ADNs during or after voltage disturbances. This letter, extends the applicability of the conventional ERM to simulate also the dynamic performance of ADNs, by employing polynomial functions, instead of exponentials. Validation results reveal that the proposed ERM can be readily used for the dynamic modeling of ADNs.

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