A MATLAB-BASED SIMULATION TOOL FOR THE ANALYSIS OF UNSYMMETRICAL POWER SYSTEM TRANSIENTS IN LARGE NETWORKS

Michael Kyesswa
Hüseyin K. Çakmak
Uwe Kühnapfel
Veit Hagenmeyer
Institute for Automation and Applied Informatics (IAI)
Karlsruhe Institute of Technology (KIT)
P.O. Box 3640, 76021 Karlsruhe, Germany
E-mail: {michael.kyesswa, hueseyin.cakmak, uwe.kuehnapfel, veit.hagenmeyer}@kit.edu

KEYWORDS

Modeling and simulation, power system dynamics, symmetrical components, unsymmetrical transients.

ABSTRACT

This paper presents an extendable Matlab-based phasor-time domain toolbox for modeling, simulation and analysis of unsymmetrical power system transients in large networks. Unlike most of the existing transient stability simulators which represent the transmission network on a per phase positive sequence basis, the new simulation function introduced in this paper is based on the symmetrical component technique which employs the three sequence networks. This representation allows consideration of network imbalances in order to include a wide range of disturbances during transient stability studies. The main aim of this paper is to describe the model details of the power system components required for unsymmetrical transients analysis and the solution methodology in the introduced simulation function. The performance of the simulation function is tested using standard IEEE test network models and the promising results are positively compared to respective results in DIgSILENT PowerFactory in terms of accuracy.

INTRODUCTION

Transient stability programs used for studying large complex networks usually assume balanced three-phase operating conditions (Kundur 1994) and any discrepancies that exist between the three phases are considered to be small in magnitude. This simplifies the power system model complexity by considering only the positive sequence network. Thereby, in the general large power system, the errors caused by neglecting the differences in the magnitudes of the voltage and the phase difference between the three phases are also considered to be small. However, there are many cases where the system imbalance cannot be ignored, especially due to unbalanced loads and unsymmetrical faults which form the majority of fault types in a real power system. This has become more pronounced in the current power system analysis problem with an increase in dimensions and complexity due to the growth in electricity demand, integration of renewable energy sources as well as expansion in power grids in form of large interconnected networks (IEEE/CIGRE Joint Task Force 2004). Therefore, there is a need to reconsider the methods used in system analysis to account for the changes in complexity of large scale systems and transients due to unbalanced network operation.

Unbalanced conditions can be accurately modeled and analyzed using detailed electromagnetic transient simulations packages (Dommel 1986). These tools are however limited to very small network sections due to the high computational burden involved in analyzing dynamics in large scale power systems. To make the computation as time-efficient as possible, simplifying assumptions in component modeling are considered in validated commercial software packages extensively used to study system wide transient behavior in large networks (Kaberere, et al. 2004). Such tools have proved to be computationally efficient and reasonably user-friendly but have a closed architecture. This implies that it is not possible for users to access the source code in order to modify system models and extend the functionality of the tools and therefore cannot be effectively explored in research to consider the changing network requirements.

In order to address the need for continuous development and improvement of power system analysis methods, several research and educational grade simulation tools have been developed with the advantage of providing easy access to source code and supporting modeling flexibility. A comparison of different open source software packages with their different levels of complexity is reported in (Milano and Vanfretti 2009). Among the listed simulation tools, the available open source simulation tools with a wide range of analysis features are mainly limited to power flow and transient analysis of balanced networks. In the present paper, analysis of unbalanced network transients using the symmetrical component technique is presented. Unlike in the traditional balanced methods where only the positive sequence network is considered, this approach takes the three sequence networks into consideration.

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Earlier research efforts to extend power system analysis to unbalanced transients focused on modeling transformers and synchronous machines (Chen et al. 1991), (Halpin et al. 1993), (Tamura et al. 1997) as individual components using symmetrical component or individual phase modeling techniques. To include analysis of the entire power system, a modeling framework using dynamic phasor technique was introduced in (Stankovic´ and Aydin 2000) for analyzing unbalanced faults in poly-phasor systems. Further research in the field focused on developing models and methods for unbalanced system studies addressing the following issues in general power system:

- Three phase power flow calculations (Abdel-Akher et al. 2005), (Kamh and Iravani 2010), (Demirok et al. 2012),
- Assessment of small signal stability (Salim and Ramos 2012), and
- Analysis of dynamic transients in transmission networks (Saha and Aldeen, 2015) or distribution level systems (Elizondo et al. 2016).

The research highlighted above mainly focused on component modeling for three-phase unbalanced dynamic analysis and validating the developed models using commercial simulation tools. The main contribution of the present paper is the development of a Matlab algorithm for the analysis of unsymmetrical power system transients based on MatDyn simulation toolbox (Cole and Belmans 2011). The component models applied in the introduced algorithm are derived using the symmetrical component technique as presented in the various literature (Chen et al. 1991) - (Elizondo et al. 2016). In the present paper, the analyzed transients are limited to unbalanced network faults.

SYMMETRICAL COMPONENTS OVERVIEW

The system analysis introduced in this paper is based on quasi-stationary symmetrical components method. In this method, the three-phase time varying phasors are transformed into the positive-, negative- and zero-sequence components using the symmetrical components transformation matrix (Ts)

$$V^{abc} = T_s V^{012} \qquad (1)$$

where $T_s = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}$ and $a = 1\angle 120^o$

$V^{abc} = \left[V^a\ V^b\ V^c\right]^T$ is a vector of a, b, and c phase voltages, and $V^{012} = \left[V^0\ V^1\ V^2\right]^T$ is a vector of zero, positive and negative sequence voltages (Saadat 2010). A similar relation exists for currents.

The simplifying assumptions considered during component modeling include:

- Changes in network voltages and currents are instantaneous and therefore the transmission system can be represented using the lumped line model.
- System voltages and currents are represented using fundamental phasor quantities.
- The network frequency is considered to remain nearly constant (Jalili-Marandi et al. 2009).

The full power system dynamic model is generically represented by a set of differential algebraic equations

$$\dot{x} = f\,(x,y,u) \qquad (2)$$

$$0 = g\,(x,y,u) \qquad (3)$$

where x are dynamic state variables, y are algebraic variables, and u are system parameters. The differential equation is a set of uncoupled subsets representing all machines in the system and their controls coupled to each other through the network. The algebraic equation comprises the stator equations of each machine coupled to the equations of the network and loads.

The equations of the generator and connected controllers are developed in the rotor d/q-reference frame whereas the network is modeled using the common system reference frame. Fig. 1 shows the relationship between the d/q and sequence network coordinates. The d/q-axis is fixed on the field magnetic axis of each machine. The D1/Q1 axis is a network reference frame rotating synchronously in the positive sequence direction while D2/Q2 axis is rotating synchronously in the negative sequence direction. The angle between the D1-axis and the stationary frame is equivalent to ωt, where ω is the synchronous angular velocity. The displacement angle θ_m represents the angular position of the rotor and δ is the machine torque angle.

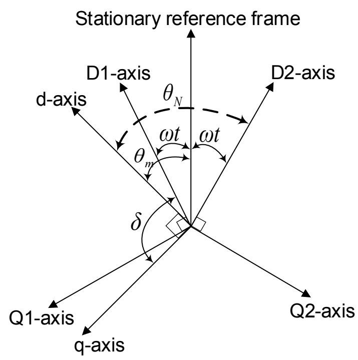

Figure 1: Reference frame transformation

The transformation between machine variables (v_d, v_q) and the respective sequence network variables (U_D, U_Q) as derived from Fig. 1 are

$$\begin{bmatrix} v_{d1} \\ v_{q1} \end{bmatrix} = \begin{bmatrix} \sin\delta & -\cos\delta \\ \cos\delta & \sin\delta \end{bmatrix} \begin{bmatrix} U_{D1} \\ U_{Q1} \end{bmatrix} \qquad (4)$$

$$\begin{bmatrix} v_{d2} \\ v_{q2} \end{bmatrix} = \begin{bmatrix} \cos\theta_N & -\sin\theta_N \\ -\sin\theta_N & -\cos\theta_N \end{bmatrix} \begin{bmatrix} U_{D2} \\ U_{Q2} \end{bmatrix} \qquad (5)$$

where $\theta_N = 2\omega t + \delta - \pi/2$ is the displacement angle between the D2-axis and the d-axis, and ω is the synchronous rotational speed in the negative sequence direction (Tamura et al. 1997). The relations in (4) and (5) hold for both currents and voltages. It has been shown in (Saha and Aldeen 2015) that the zero sequence stator quantities vanish in the d/q-coordinates.

POWER SYSTEM COMPONENT MODELS

Synchronous Machine Model

The synchronous machine equations comprise rotor electrical and mechanical, excitation system, and turbine-governor equations. The synchronous generator is represented by the fourth order model (Machowski et al. 2008), which is a simplified model generally assumed to accurately represent synchronous generators for studying the electromechanical dynamic behavior. The effects of the rotor damper windings are neglected in this model and results into a generator represented by transient emfs ($E_d^{'}$ and $E_q^{'}$) behind transient reactances ($X_d^{'}$ and $X_q^{'}$). The generator stator transients are also neglected and the stator becomes represented as a simple impedance with reactance components in the d- and q-axes. The stator equations are therefore algebraic equations.

The machine dynamics are divided into the respective sequence components which are isolated from each other. The positive sequence circuit is represented using the traditional synchronous generator models since the models used in balanced transient stability studies are developed considering only the positive sequence operation of the generator. The voltages and currents in the negative and zero sequence circuits are a result of unbalanced operations and therefore no power generation occurs in these circuits. A braking torque is included in the mechanical equation of the generator to account for sizeable negative sequence currents. The zero sequence currents do not produce an effective torque in the machine and are not included in the mechanical equation.

Positive Sequence Circuit

The differential and algebraic equations of the positive sequence circuit are similar to the traditional transient analysis studies. The difference is that the voltage and currents only refer to the positive sequence of the machine, and not the total machine quantities as in the balanced mode simulation. The differential equations describing the change in flux are given as

$$T_{do}^{'}\dot{E}_q^{'} = E_f - E_q^{'} + (X_d - X_d^{'})I_d \tag{6}$$

$$T_{qo}^{'}\dot{E}_d^{'} = -E_d^{'} - (X_q - X_q^{'})I_q \tag{7}$$

and the resulting algebraic equations of the positive sequence circuit that show the relation between the voltages and current components are given by

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} E_d^{'} \\ E_q^{'} \end{bmatrix} - \begin{bmatrix} R & X_q^{'} \\ -X_d^{'} & R \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} \tag{8}$$

The parameters and variables (6) – (8) are described in (Machowski et al. 2008). For given initial conditions, the differential equations describing the change in flux can be solved, from which the stator and rotor positive sequence currents can be obtained using (8). The positive sequence generator current in network reference frame is obtained from (4).

Negative Sequence Circuit

The negative sequence circuit has no current source and is therefore represented by a pure impedance connected between the machine bus and ground. The resulting algebraic equation of the negative sequence stator voltage-current relationship is

$$\begin{aligned} 0 &= V_2 + Z_2 I_2 \\ Z_2 &= R_s + jX_2 \end{aligned} \tag{9}$$

where I_2 is the complex negative sequence current and V_2 is the complex voltage at the generator bus. Impedance Z_2 is the negative sequence impedance, and R_s, X_2 denote the stator resistance and negative sequence reactance. The value of X_2 can be approximated by $(X_d^{''} + X_q^{''})/2$, where $X_d^{''}$, $X_q^{''}$ are the direct axis and quadrature axis subtransient reactances. However, If transient saliency is neglected, then $X_2 = X_d^{''} = X_q^{''}$. The transformation matrix between the negative sequence components in network reference (U_{D2}, U_{Q2}) and the rotor d-q reference coordinates (v_{d2}, v_{q2}) is given in (5).

Zero Sequence Circuit

The zero sequence circuit is also represented by a pure impedance connected between the machine bus and ground. The resulting algebraic equation of the zero sequence stator voltage-current relationship is

$$\begin{aligned} 0 &= V_0 + Z_0 I_0 \\ Z_0 &= R_s + jX_0 \end{aligned} \tag{10}$$

where Z_0 is the zero sequence impedance, and R_s, X_0 denote the stator resistance and zero sequence reactance. I_0 is the complex zero sequence current and V_0 is the complex zero voltage at the generator bus. However, no zero sequence stator component exist in the d-q coordinate. These dynamics are expressed in the real and imaginary coordinates as

$$\begin{aligned} v_0(t) &= V_0(t)\cos(\omega_s t + \theta_0) \\ v_0(t) &= V_R(t)\cos(\omega_s t) - V_I(t)\sin(\omega_s t) \end{aligned} \tag{11}$$

where V_0 is the magnitude and θ_0 is the phase angle of the zero sequence quantity. $V_R(t) = V_0 \cos\theta_0$ and $V_I(t) = V_0 \sin\theta_0$ are the real and imaginary components of the phasor representing the zero sequence stator quantity, respectively (Saha and Aldeen 2015).

Mechanical Equations

The mechanical equation differs from the traditional transient stability equation in that it is modified to include the effect of unbalanced system operation. The positive sequence current represents the main electrical torque and the negative sequence current produces an opposing torque referred to as the braking torque. The resulting mechanical part of the dynamic equations is given by

$$\dot{\delta} = \omega_b(\omega - \omega_0) \tag{12}$$

$$\dot{\omega} = \frac{1}{2H}\left[P_m - D(\omega - \omega_0) - P_e - (R_2 - R_s)I_2^{\,2}\right] \tag{13}$$

where R_2 is the negative sequence resistance and R_s is the stator resistance (Elizondo et al. 2016). The air gap power of the generator is only due to the positive sequence component since there are no voltage sources in the negative and zero sequence circuits. The power is given by

$$P_e = \left(E_d^{'}I_d + E_q^{'}I_q\right) + \left(X_q^{'} - X_q^{'}\right)I_dI_q \tag{14}$$

The changes in mechanical power P_m and emf E_f are computed as described in the turbine-governor and excitation system model definitions. The parameters and variables in (12) – (14) are described in (Machowski et al. 2008).

Synchronous Machine Controllers

Excitation System
The excitation system is used to control the terminal voltage by modifying the generator field voltage. The dynamic behavior of the excitation system implemented in the presented tool is according to the model of the type DC1A excitation system described in (IEEE Std 421.5-2005 2006).

Turbine-Governor
The turbine-governor model is developed using a proportional-integral (PI) controller. The dynamics of the system are given by (15) - (19).

$$y_1 = P_{ref} - K_R(\omega - \omega_{ref}) - P_m \tag{15}$$

$$\dot{y}_2 = \frac{1}{T_p}y_1 \tag{16}$$

$$y_3 = K_p y_1 + y_2 \tag{17}$$

$$\dot{y} = \frac{1}{T_m}\left(y_3 - y\right) \tag{18}$$

$$\dot{P}_m = \frac{1}{T_k}(y - P_m) \tag{19}$$

where y is the valve position, P_{ref} is reference power, P_m is mechanical power, ω_{ref} is reference speed, ω rotor speed, K_R=1/R, R is the droop constant, K_p and T_p are the gain and time constant of the PI controller. The variables y_1 and y_3 are the integrator input and output signals, respectively, y_2 is the servo motor output signal, T_m and T_k are the servo motor and turbine time constants.

Network Model

The modeling of the transmission network is based on Matpower (Zimmerman et al. 2011) representation as applied in steady state power flow solutions. This is an acceptable simplification due to the assumption that during transient events, changes in network voltages and currents are instantaneous as compared to the machine dynamics. However, unlike in the balanced transient stability studies, the symmetrical components technique is used to model the network in the present paper. Positive, negative, and zero sequence networks are constructed using equivalent admittances and the resulting nodal network equation is represented in complex current balance form as

$$I_{012}^{inj} = Y_{012}^{bus}V_{012}^{bus} \tag{20}$$

where the matrix Y_{012}^{bus} represents the nodal admittance matrix for the corresponding sequence network, and vectors V and I contain the sequence voltage and current phasors at fundamental frequency.
The nodal admittance matrices for the corresponding sequence networks are modified by inserting the generator and load admittances as diagonal shunt admittances.

Generator Admittance
The equivalent admittances of the generator model (Y_{g1}, Y_{g2} and Y_{g0}) are given by

$$\begin{aligned} Y_{g1} &= 1/Z_1 \\ Y_{g2} &= 1/Z_2 \\ Y_{g0} &= 1/Z_0 \end{aligned} \tag{21}$$

Load Admittance
Unlike in power flow analysis where loads are treated as constant power, static loads are treated as constant admittances in dynamic studies. This simplifies the analysis by inserting the load admittances directly into the admittance matrix and ignoring the load current injections. The elements of the load admittance diagonal matrix Y_{abc}^{l} at a bus are given in terms of the initial load power $P_{abc}^{l} + jQ_{abc}^{l}$ and the load bus voltage V_{abc}^{i}

$$Y_{abc}^{l} = \frac{P_{abc}^{l} - jQ_{abc}^{l}}{\left|V_{abc}^{i}\right|^2} \tag{22}$$

$$Y_{012}^{l} = [T_s]^{-1}\left[Y_{abc}^{l}\right][T_s] \tag{23}$$

In (23), the admittance Y_{012}^{l} in terms of sequence components is calculated using the symmetrical components transformation matrix T_s (Saadat 2010). In the simulation tool, the load implementation assumes balanced load models on the three phases.
The network equations (20) – (23) and the equations of the dynamic components (6) – (19) complete the model of unbalanced power systems for a phasor-time domain simulation. The system components are modelled separately and connected together using well-known analysis techniques depending on the fault type (Saadat 2010).

SOLUTION METHODOLOGY

Solution Methods

The system of differential and algebraic equations (6) – (23) form the mathematical description of the full power system model. The solution of this system starts from steady state values obtained from a power flow calculation. In this simulation, Matpower is used for the power flow computation to obtain the system voltages, angles, active and reactive power generation at time t = 0. These values are used to compute the initial dynamic state variables x in order to progress the system solution from a steady state operation.

Numerical methods are applied to solve the system of differential algebraic equations for the dynamic state variables x and algebraic variables y at each time step. In the presented simulation tool, the partitioned approach is used to interface the differential equations in (2) and algebraic equations in (3). This implies that the two equations are solved alternately (Soman et al. 2002). Explicit integration methods are used to numerically integrate the differential equations.

The solution of the algebraic equation is simplified by the following assumptions: 1) The system loads are represented as constant admittance loads. This eliminates the nonlinear behavior of the overall network equations which is caused by current injections at load buses if the loads are represented by constant power; 2) Transient saliency of the generator is neglected whereby $X_d^{'} = X_q^{'}$ and this simplifies the stator algebraic equation in (8). This results into linear network algebraic equations which are solved using the sparsity-oriented triangular factorization direct linear solver (Crow 2009).

Transient Analysis Procedure

A power flow calculation is initially carried out to determine the internal operating states of the connected generators and their respective controllers. The system is assumed to start from a balanced state and therefore the Matpower power flow calculation based on a single phase positive sequence network is applied. As a result, system bus voltages are calculated in terms of magnitude and angle as well as the active and reactive power generation at the buses. The initial generator current is calculated using

$$i_{gen,i} = \frac{P_{gen,i} - jQ_{gen,i}}{V_i^*} \tag{24}$$

where $P_{gen,i} + jQ_{gen,i}$ is the generated power obtained from the power flow solution and V_i is the i^{th} generator terminal voltage. It is important to note that this current only represents the positive sequence value. The negative and zero sequence current values are set to zero due to the physical symmetry of the generator (Chen et al. 1991).

The initial steady state internal emf and rotor angle for each generator in the system is calculated using;

$$\begin{gathered} E_{0,i} = V_i + (R_s + jx_{q,i}^{'})i_{gen,i} \\ \delta_{0,i} = \text{angle}\,(E_{0,i}) \end{gathered} \tag{25}$$

and the initial transient emfs $E_{q0}^{'}$, $E_{d0}^{'}$ are calculated using (6) and (7), respectively.

The original node admittance matrix is augmented by adding the generator internal admittance and the equivalent load admittance to the diagonal components. This is carried out at every occurrence of a system transient to re-compute the admittance matrix. For the pre-transient and post-transient condition, only the positive sequence network is considered corresponding to balanced system operation. During the unbalanced transient period, the system components are connected together using the well-known analysis techniques depending on the fault type.

System stability state is analyzed from the plots of the system variables. The important variables analyzed include generator power or torque, speed, angle, and bus voltages for a period of up to several seconds after the transient is cleared. The system is unstable if the responses diverge from one another or exhibit growing oscillations.

SIMULATION AND ANALYSIS

The main aim of the introduced simulation function is to analyze different kinds of unsymmetrical network transients. The simulated transients include single line-to-ground fault, line-to-line fault, and double line-to-ground fault. Other transients such as three phase-to-ground fault and load variations can also be simulated. In the present paper, simulation results for a single line-to-ground fault and a three-phase fault are presented. The results are compared to those obtained using the commercial software package DIgSILENT PowerFactor-y (DIgSILENT 2016) to assess the level of accuracy in capturing transient responses, as well as validate the component models used in the simulation tool.

Simulation Case1: 9-Bus Network

The standard IEEE-9 bus test feeder is considered for the simulation results presented in this section. The network consists of three generators, nine buses, and three loads. Excitation and turbine-governor systems are connected to the synchronous machines at bus 1, 2 and 3. Similar components are selected for the example network in DIgSILENT PowerFactory which are; a synchronous generator model with IEEET1 exciter, and TGOV1 type governor. The model parameters are modified to match the parameters in the Matlab-based simulation function. The network structure and parameters of the test feeder are given in (Anderson and Fouad 2003).

A single line-to-ground fault on phase-A with zero fault impedance is applied on bus 6 at 5s and cleared at 15s. The response of the phase voltages, sequence voltages, generator rotational speed and mechanical power at the generator buses (bus 1, 2 and 3) and the faulty bus are shown in Fig. 2 – Fig. 9 for the simulated fault scenario in the new simulation function and DIgSILENT PowerFactory.

Analysis Of Bus Voltages

The responses of the phase and sequence voltages at the buses are shown in Fig. 2 – Fig. 7 for the simulations in the introduced function and PowerFactory. It can be observed that the introduced simulation function captures the transient behavior of the bus voltages following the fault condition. Fig. 2 – Fig. 4 show the responses of the bus phase voltages with voltage transients recorded at the switching instant and during the fault period. Phase-A voltage experiences the largest sag, as expected, compared to Phase-B and C. The voltage sag at the faulty bus 6 is up to zero, reflecting the zero fault impedance applied in this simulation scenario. Voltage transients are also captured in sequence voltages (Fig. 5 – Fig. 7). It is observed that the voltages in the negative and zero sequence networks are a result of the network imbalance due to the applied unsymmetrical fault. The positive sequence bus voltages experience a sag which is largest at the faulty bus.

The transient response of the bus voltage is due to the action of the excitation systems and can be explained as follows: The voltages are initially in steady state until the fault occurs resulting into a change of voltage levels at the buses. The change in voltage at the generator terminals initiates the operation of the excitation systems connected to the generation units which adjust the internal field voltages of the respective machines and attain new steady state operating voltage levels at the respective terminals. When the fault is cleared, the initial network structure is re-established and the action of the excitation system recovers the initial operating voltage levels as seen from the captured responses. Similar system response can be observed in the PowerFactory simulation results. However, there is a slight difference in voltage levels reached during the transient period.

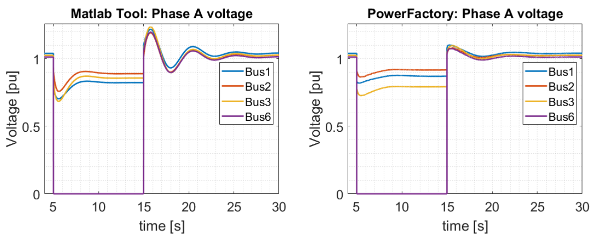

Figure 2: Phase-A voltage response

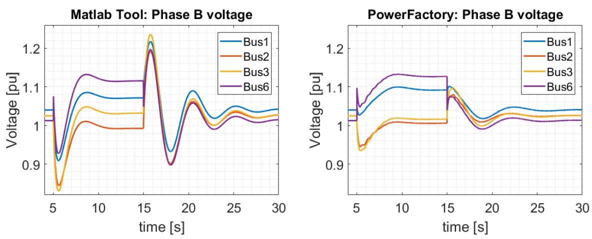

Figure 3: Phase-B voltage response

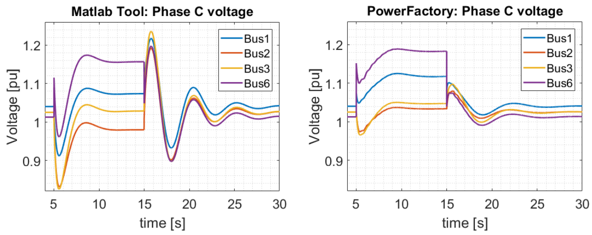

Figure 4: Phase-C voltage response

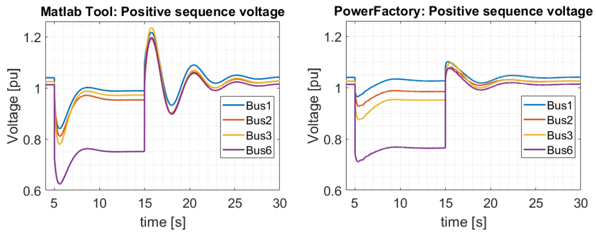

Figure 5: Positive-sequence voltage response

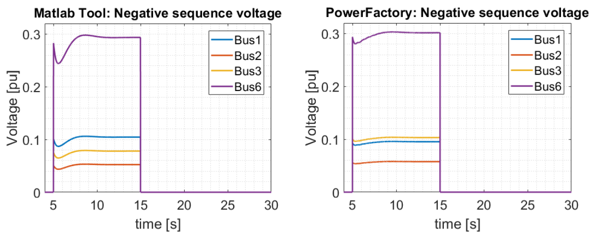

Figure 6: Negative-sequence voltage response

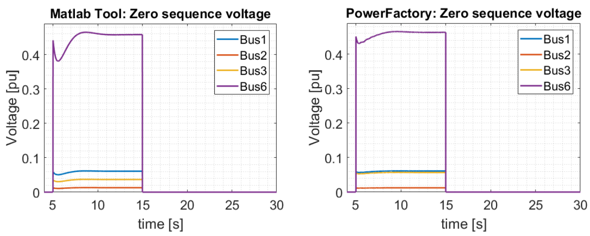

Figure 7: Zero-sequence voltage response

Analysis of Rotational Speed and Mechanical Power

The responses of the generator rotational speed and turbine mechanical power are shown in Fig. 8 and Fig. 9, respectively. It can be observed that the change in network structure due to the fault occurrence causes a change in accelerating power of the generation units. In this simulation case, there is a resulting acceleration of the units which initiates the action of the turbine–governor system of each unit to adjust the mechanical power contribution as shown in Fig. 9 during the fault period. The action of the governor controllers reduces the speed deviation until synchronous operation of the interconnected machines is achieved at a new operating point as shown in Fig. 8 during the fault period.

Clearing the fault results into restoration of the network structure to the initial state. In this case, the generation units experience a decrease in rotational speed as can be observed in Fig. 8. The speed deviation triggers further action of the governor systems to increase the mechanical power as shown in Fig. 9 during the post-fault period until the speeds of the interconnected machines synchronize. The final operating point is observed to be similar to the initial operating point, as expected, since the initial structure is re-established. The results of the rotational speed and turbine-power responses of the introduced simulation function are seen to closely match the responses in DIgSILENT PowerFactory.

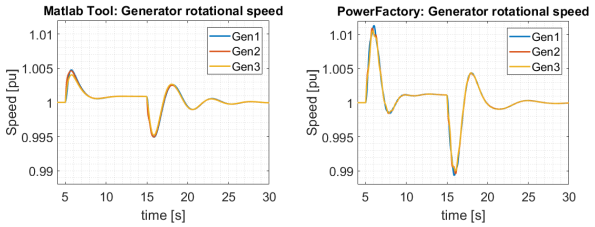

Figure 8: Generator rotational speed response

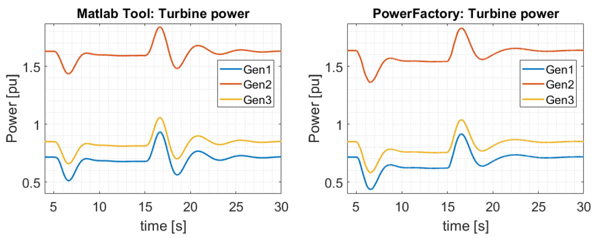

Figure 9: Mechanical power response

Simulation Case II: 9241-Bus Network

The simulation function is tested in a larger network representing the size and complexity of the European high voltage network. The test feeder (Case9241pegase) consists of 9,241 buses, 1,445 generators, and 16,049 branches operating at 750, 400, 380, 330, 220, 154, 150, 120, and 110 kV (Josz, et al. 2016).

In this simulation case, a three-phase fault is applied on bus 28 at time t = 3.0s and on bus 143 at time t = 5.0, each for a duration of 100ms. The results of bus voltage and generator rotational speed response obtained using the Matlab tool are shown in Fig. 10 and Fig. 11. The bus voltage response is presented for a single phase.

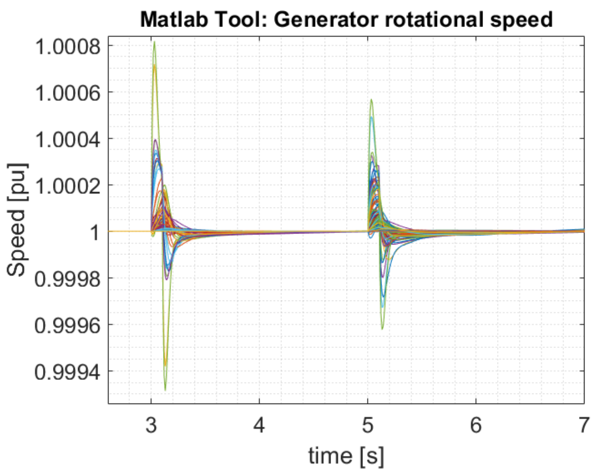

Figure 10: Generator rotational speed response

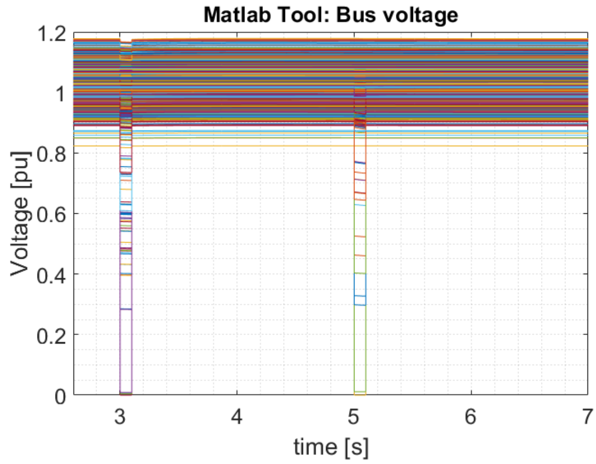

Figure 11: Bus voltage response

The results obtained from the simulation of the 9241-bus network reflect the expected behavior of the bus voltage and generator rotational speed in response to a network fault. This shows the ability of the tool to analyze network transients in complex networks as well.

Discussion of Results

It can be observed that the introduced Matlab-based function is able to capture the network transient responses. Qualitative analysis of the simulation results shows a close match with the DIgSILENT PowerFactory results. Similar steady state operating values are reached in both tools in the post-transient period. However, there is a noticeable difference in the response overshoot at the instant of change in the network structure, as well as in the steady state operating point attained during the transient period. Part of the ongoing work is to address the cause of the differences in simulation results and validation of the results through experimental setups.

CONCLUSION

The present paper has presented a new Matlab-based simulation function for analysis of unsymmetrical power system transients using the symmetrical component technique. The introduced approach provides the advantage of representing the power system using the three sequence networks which allows network imbalances to be taken into consideration during system analysis. The presented simulation function is an extension of MatDyn, a Matlab-based toolbox, which is only limited to analysis of balanced transients. This extension can facilitate the analysis of a wider range of transients especially due to unsymmetrical faults which form the majority of fault types in a real power system. The accuracy of the simulation algorithm and the developed models is verified against the commercial software package DIgSILENT PowerFactory for a single line-to-ground fault and the results are observed to closely match. The algorithm can be applied to analyze different types of faults in large networks. Part of the ongoing work is focused on including analysis of system imbalances due to unbalanced static or dynamic loads and modeling renewable energy sources to analyze their effect on system stability. After including the above mentioned features and experimental validation of the simulation tool functionality, the toolbox extension will be made freely accessible to the research community.

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AUTHOR BIOGRAPHIES

MICHAEL KYESSWA is a Ph.D student at the Institute for Automation and Applied Informatics at Karlsruhe Institute of Technology. His main areas of research are power system dynamic modeling, transient stability and analysis of the dynamic behavior of large power systems. His e-mail address is: michael.kyesswa@kit.edu.

HÜSEYIN KEMÂL ÇAKMAK is scientific staff at the Institute for Automation and Applied Informatics at Karlsruhe Institute of Technology. His research interests are modeling, simulation, visualization, 3d/VR/AR, big data analysis, web systems, parallel computing and software development for energy system analysis. His e-mail address is: hueseyin.cakmak@kit.edu.

UWE G. KÜHNAPFEL is head of the working group energy systems simulation and visualization at the Institute for Automation and Applied Informatics at Karlsruhe Institute of Technology. His main research fields are energy systems (modeling, simulation, monit- or ing, analysis), mechatronics, virtual and augmented reality. His e-mail address is: uwe.kuehnapfel@kit.edu.

VEIT HAGENMEYER is director of the Institute for Automation and Applied Informatics at Karlsruhe Institute of Technology. His main field of research is automation technology, control engineering and energy informatics. His e-mail address is: veit.hagenmeyer@kit .edu.