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Advanced Modeling of Electromagnetic Transients in Power Systems.

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Advanced Modeling of Electromagnetic Transients in Power Systems

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Abstract

Simulation of fast and slow dynamic behavior of electrical power systems is needed for many industrial applications. The results influence the development of electrical and mechanical components and the design of control elements in power systems. Examples are

- Mechanical stresses on network elements
- Control systems of turbines and generators
- Settings of protective relays
- Transient stability of power systems

Important phenomena to be simulated are i.e. synchronous stability, machine dynamics, subsynchronous resonance, influence of load variations, switching and lightning overvoltages, and saturation effects.
The conventional and functional grouping of simulation tools into power flow-, short circuit- and dynamic calculations was necessary in the past for computation reasons. Traditional simulation tools are especially designed for each application, seperated by the different time constant of interest.
Power flow calculations are needed for stability investigations in electrical power systems. Simulation tools like PSS/E and Simpow, [10, 11] are able to compute the long term dynamics.
In order to calculate fast transients caused by switching and lightning, etc. detailled models of the network components are needed (realized i.e. in EMTP, EMTDC, Netomac, etc. [7, 8, 9]) The numerical schemes implemented are based on [4] and discussed in detail in [5]. Drawbacks have been identified and compared to a pure state space representation.
The effizient object-oriented hierarchical modelling language *Modelica* enables the graphical definition of complex networks. The used components are defined by their differential algebraic equations (DAE). Simulation tools [1] transform the overall differential algebraic system to a state space representation. The individual components are depending on the application (time constraints) and can be variied in compexity. The component interfaces are kept equal, which enables an easy exchange of simple to complex components. This concept enables the simulation of electrical, mechanical and control application and combines power flow-, short circuit- and dynamic calculations within one simulation environment.

1 Introduction

Important for object-oriented modelling of a physical domain is the determination of the component interfaces. For electrical power systems, this is done by the following considerations.
The simulation of the dynamical behavior of a synchronous machine is usually formulated using the two-axis theory of Park [2, 6]. This theory is based on the mathematical description (Park-Transformation P) of a 3-phase rotating system (voltages U_{abc} and currents I_{abc}) by the diagonal components of the rotor (U_{dq0}, I_{dq0}). For $\theta = \omega t + \phi$, with ω angular velocity, t simulation time and ϕ initial angle, the following mathematical relations hold:

$$P = \sqrt{\frac{2}{3}} \begin{pmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta - \frac{4\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{4\pi}{3}) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}$$

$$P \cdot P^T = Id$$

$$\frac{1}{\omega} \cdot P \cdot der(P)^T = \begin{pmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} =: y$$

$$\begin{aligned} U_{abc} &= P^T \cdot U_{dq0} \;,\; I_{abc} = P^T \cdot I_{dq0} \\ P \cdot der(I_{abc}) &= der(I_{dq0}) + \omega \cdot y \cdot I_{dq0} \end{aligned}$$

The quantaties U_{dq0} and I_{dq0} are constant in case of a non-disturbed steady state, e.g. fixed rotating frequency of the rotor. (see figure 3, 4). These consideartions can be generalized to all model components of electrical power systems that are described in this paper. Therefore, the definition of the *interfaces* is dependend on U_{dq0} as *potential variable* and I_{dq0} as *flow variable*.
The following example of an inductive element describes the changes in the differential equations (in the $dq0$-system), which are due to the Park-transformation.

$$\begin{aligned} der(L \cdot I_{abc}) &= U_{abc} \\ L_P \cdot der(I_{dq0}) + \omega \cdot y \cdot L_P \cdot I_{dq0} &= U_{dq0} \end{aligned}$$

The matrix $L_P = P \cdot L \cdot P^T$ is for all model components (generator, transformer, load, etc.) constant (e.g. independent of time). This finally leads to a system of DAEs, that can be solved very efficiently.
When modelling electrical power systems, it is common to formulate the equations of different components dependend on a base voltage U_{base} and a base power P_{base}. The so-called per unit modelling allows, therefore, a description of the model component independent of the surrounding system. This results in the following re-calculations:

$$\begin{aligned} I_{dq0} &= I_{base} \cdot i_{dq0} \\ U_{dq0} &= U_{base} \cdot u_{dq0} \end{aligned}$$

The differential equation for the inductive element can be rewritten in per-unit quantaties as follows:

$$x \cdot der(i_{dq0}) + \omega \cdot yx \cdot i_{dq0} = u_{dq0}$$

Due to the Park-transformation, x and y are the resulting normalized reactance-matrix and rotating matrix, respectively.

The identification and determination of the model parameters of a component within electrical power systems is very difficult and time-consuming. The model parameters are often determined based on measurement data. The calculations are in general well-known, and in example for the generator described in [3]. These pre-calculations should not be mixed with the dynamical simulation and be done in advance. This can be realized in Modelica by using corresponding functions, so that the user has only to input the given measurement data for a simulation run. For the following model component equations these pre-calculations are considered as given.

basic components

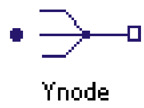
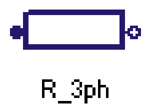
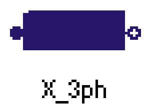
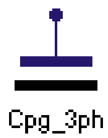
3Phase-Star		$\{0, 0, \sqrt{3} \cdot u_n\} = u_{dq0}$ $\sqrt{3} \cdot i_0 = i_n$
3Phase-Resistor		$r \cdot i_{dq0} = u_{dq0}$
3Phase-Inductor		$x \cdot der(i_{dq0}) +$ $\omega \cdot yx \cdot i_{dq0} = u_{dq0}$
3Phase-Capacitor		$c \cdot der(u_{dq0}) +$ $\omega \cdot yc \cdot u_{dq0} = i_{dq0}$

Table 1: Basic component models

2 Basic Components

The most simple 3-phase basic model components necessary for building an electrical power system are shown in table 1. The component equations on the right column of the table are given in per unit (p.u.). The star-connector gives the possibility to couple also 1-phase electrical model components, necessary i.e. for grounding

Figure 1: Object-diagram of a linear Δ/Y-Transformer.

elements of transformers and generators. Using hierarchical connections of these basic components, other linear models can be easily generated (i.e. inductive-capacitive load, pi-element of a transmission-line, etc.).

3 Transformer and Generator

When modelling transformers in Modelica, a special treatment can be done in order to seperate the topology information (Δ- / Y- Connectors) from the magnetic coupling of the individual phases (see figure 1).
As a result, the magnetic coupling can be described with different complexity based on the phenomena of interest, i.e. losses, saturation and internal faults can be include if important for the corresponding simulation application. The differential algebraic equations of a linear transformer model are given as follows:

- *Delta-Connector*

$$v_{dq} = \{u_q, -u_d\},\ i_{dq} = \{-j_q, j_d\},$$
$$v_0 = 0,\ i_0 = 0$$

- *Y-Connector*

$$v_{dq0} = u_{dq0} - \{0, 0, \sqrt{3} \cdot u_n\},\ i_{dq0} = j_{dq0},$$
$$u_n = r_n \cdot i_n,\ i_n = \sqrt{3} \cdot i_0$$

- *Trafo-Coupling*

$$x_1 \cdot der(j1_{dq0}) + (\omega \cdot yx + r)_1 \cdot j1_{dq0} = (v1_{dq0} - v0_{dq0})$$
$$x_2 \cdot der(j2_{dq0}) + (\omega \cdot yx + r)_2 \cdot j2_{dq0} = (v2_{dq0} - v0_{dq0})$$
$$x_{cpl} \cdot der(jm_{dq0}) + \omega \cdot yx_{cpl} \cdot jm_{dq0} = v0_{dq0}$$
$$jm_{dq0} = j1_{dq0} + j2_{dq0}$$

Modelling of generators leads to equations with analog structur as described in [2, 6].

4 Mechanical Components and Control System

The turbine model components can be described in different complexity by using the Modelica library Rotational1D. For applications, where stress effects of turbine and generator, or the movement of masses of generator, exciter and turbine group can be neglected, all masses can be combined to one mass or it can be assumed that an infinite mass is given. This corresponds to simulation with constant velocity. The control system can be defined by using the model components of the Modelica Block library.

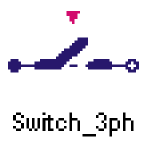
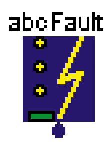
hybrid elements		
3Phase-Switch		$0 = \text{if } (Open_a) \text{ then } der(i_a) \text{ else } u_a$ $0 = \text{if } (Open_b) \text{ then } der(i_b) \text{ else } u_b$ $0 = \text{if } (Open_c) \text{ then } der(i_c) \text{ else } u_c$
ABC-Fault		$\{0,0,0\} = \text{if } Fault \text{ then } \{u_a - u_b, u_b - u_c, sum(der(i_{abc}))\} \text{ else } der(i_{abc})$

Table 2: Switch and 3-phase fault

5 Ideal Switches and Faults

When simulating switches and faults, the 3 phases of a model component have to be considered seperately and be written in abc-representation. Table 2 shows the corresponding equations for the switch and the 3-phase fault. Having switches or faults in a differential algebraic equation system results in general in

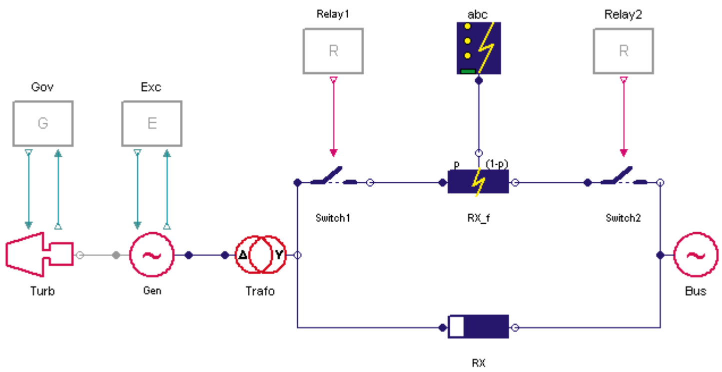


Figure 2: Object-diagram of the simulation

so-called higher index problems and variing index of the DAE during switching and fault scenario. Therefore, the equations have to be formulated differentiated. The boolean variables $Open_a, Open_b, Open_c$ and $Fault$ have to be determined, so that the switch can only be operated, when the current crosses the zero line. This is true for simulating a fault or switch in series to an inductive element. If a capacitive element is parallel to a switch or fault analog considerations result in differentiating the voltages u_{abc}. In this case, operating the switch or fault can only be done when the corresponding voltage crosses zero. Other 3-phase fault types are given by:

- *ABCG-Fault:*

$$\{0,0,0\} = \text{if } Fault \text{ then } u_{abc} \text{ else } der(i_{abc})$$

- *AB-Fault:*

$$\{0,0\} = \text{if } Fault \text{ then } \{u_a - u_b, sum(der(i_{ab}))\} \text{ else } der(i_{ab})$$
$$0 = der(i_c)$$

- *ABG-Fault:*

$$\{0,0\} = \text{if } Fault \text{ then } u_{ab} \text{ else } der(i_{ab})$$
$$0 = der(i_c)$$

- *AG-Fault*

$$0 = \text{if } Fault \text{ then } u_a \text{ else } der(i_a)$$
$$\{0,0\} = der(i_{bc})$$

Cyclic permutations of the variables i_a, i_b, i_c and u_a, u_b, u_c result in further fault-types.

6 Initialization

Due to the representation of the overall system in dq0-coordinates, the initialization can be done with the same differential algebraic system that is later used for the dynamic simulation. In existing simulation tools (EMTP, EMTDC, Netomac, etc.) a seperate equation system for the initialization process has to be generated. This is only necessary, when representing the equations in the abc-system. In this case, the currents and voltages are not constant for the stationary state (see figure 3).
The initialization of the switch and fault model components is simple, since in example the switch is either open ($I_{abc} = \{0,0,0\}$) or closed ($U_{abc} = \{0,0,0\}$), before the simulation starts. Similarly, the fault is not present when initializing the system ($I_{abc} = \{0,0,0\}$).

7 Simulation

For the application example defined in figure 2 the following fault szenario has been simulated. First, the stationay state has been initialized and kept for 0.03 seconds (see figure 3,4).
During the stationary state a constant power is flowing across both transmission lines into the infinite bus. Then a 3-phase fault is initiated in the middle of the transmission line RX_f. At 0.05 seconds the two switches Switch1, Switch2 receive a signal to take off the faulted transmission line. The abc-currents have been cut off when crossing the zero line (see figure 5). This

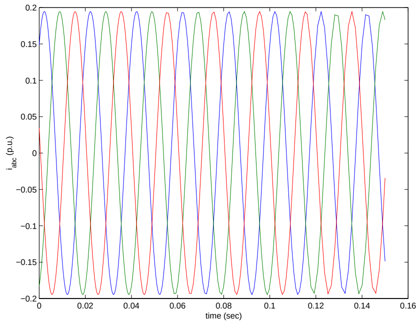


Figure 3: Stationary state (abc-phase-system)

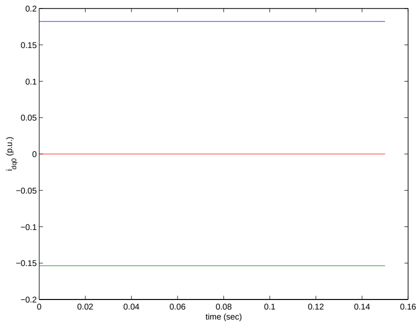


Figure 4: Stationary state (dq0-phase-system)

corresponds to an ideal description of a switch. The signals are in general given by a protection relay. Later in the simulation the transmission line is again inserted in the system by re-closing the switch. After a certain time the stationary case is again reached. This can be seen most clearly in the dq0-system (see figure 6).

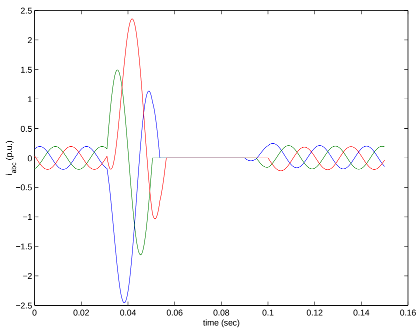


Figure 5: Fault szenario (abc-phase-system)

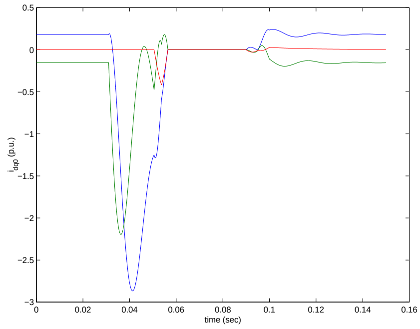


Figure 6: Fault szenario (dq0-phase-system)

References

[1] *Dymola:* Homepage: http://www.dynasim.se/

[2] *Canay, I.M.:* Modeling of Alternating-Current Machines having Multiple Rotor Circuits. IEEE Transactions on Energy Conversion, Vol. 8, No. 2, pp. 280-296, June 1993.

[3] *Canay, I.M.:* Determination of the Model Parameters of Machine from the Reactance Operators $x_d(p), x_q(p)$. IEEE Transactions on Energy Conversion, Vol. 8, No. 2, pp. 272-279, June 1993.

[4] *Dommel, H.W.:* Digital Computer Solution of Electromagnetic Transients in Single- and Multiphase Networks, IEEE Transactions on Power Apparatus and Systems, Vol. 88, No. 4, pp 388-399, April 1969.

[5] *Linnert, U. und Hosemann, G.:* Neue Methoden zur Netzsimulation im Zustandsraum verglichen mit dem Differenzenleitwertverfahren, Arch f. Elektrotech. 77, pp. 415-423, 1994.

[6] *Anderson, P.M. und Fouad, A.A.:* Power System Control and Stability, IEEE Press Power Systems Engineering Series, 1994.

[7] *EMTP:* Homepage: http://www.emtp96.com/

[8] *EMTDC:* Homepage: http://www.hvdc.ca/

[9] *Netomac:* Homepage: http://www.ev.siemens.de/

[10] *PSS/E:* Homepage: http://www.pti-us.com/

[11] *Simpow:* Homepage: http://www.abb.com/powersystems