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Generalised scalable fault dependent time invariant state space model for large interconnected power systems

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ABSTRACT

In this paper a scalable fault-dependent time invariant nonlinear dynamic state space model of power systems experiencing symmetrical or unsymmetrical fault in the transmission/distribution network is introduced. The power system comprises generating units interconnected to the transmission/distribution networks. Each generating unit is modelled by incorporating full stator and rotor dynamics of a synchronous machine along with the associated excitation and speed governor systems. Proposed modelling approach has been carried out in generic fashion so that power systems of any description can be configured easily by using a user interface simple selection menu. The modelling approach employs a series of coordinate transformations including Park's and symmetrical components. The validity of the derived model is verified through simulation studies carried out on the IEEE 30 bus test system. Such a scalable full fault-dependent model has not been reported in the open literature previously.

1. Introduction

Faults in the transmission/distribution networks of power systems are common and can cause significant disruption to the power supply and in some cases may have the undesirable effect of destabilising the entire system. It is therefore important to be able to develop accurate fault- dependent models of power systems where the occurrence of faults in any of their transmission and or distribution lines can be studied and analysed [1–4]. Moreover accurate power system state space time-invariant models are critical for stability studies [5], model-based fault detection [1,2], controller design [6], contingency analysis, etc. Furthermore existing models of various representations are derived for a specific system of prescribed configuration and under specific fault condition, thus they lack scalability and re-configurability.

Dynamical models of large scale interconnected power systems that have been reported in the open literature to-date may be subdivided into two main categories, namely state space (SS) models and differential and algebraic equation (DAE) models, as shown in Fig. 1. In the following a summary of the main contributions in each of these two categories is given.

1.1. Sate space models

These can be further subdivided into fault-free and fault-dependent models.

1.1.1. SS fault-free models

Among the state space *fault-independent* models that have been reported in the literature are those in [7–14]. The degree of accuracy varies from one publication to another but none of these models represent power systems under fault conditions. As this category of models is not the subject of this paper, we will not provide a critical review on available models.

1.1.2. SS fault-dependent models

To the best of our knowledge there have been no published state space fault-dependent models of large-scale power systems in major international journals or conferences. Therefore we believe that this paper is the first to report a comprehensive scalable fault-dependent full dynamic state-space model of power systems.

1.2. Fault dependent differential and algebraic equation models (FDDAEMs)

In this section we concentrate on fault-dependent models that have been reported in major international journals and conferences. We subdivide these into the following sub-categories:

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Nomenclature

$\bullet_{d,q}$: quantities (voltage (v), current (i), flux (ψ)) in dq rotating frame
$\bullet_f$: field winding quantities, $\bullet_D$, $\bullet_G$, $\bullet_Q$: Damper winding quantities
$\bullet^{(s)}$: 's' sequence quantities. $s = 1$ (positive), 2 (negative), 0 (zero)
$\bullet_d^{(s)}, \bullet_q^{(s)}$: '$s$' sequence quantities in dq rotating frame
$\bullet_{D_N}^{(2)}, \bullet_{Q_N}^{(2)}$: negative sequence quantities in $D_N - Q_N$ rotating frame
$\bullet_{RI}$: quantities in $R - I$ (real and imaginary) co-ordinate,
$\bullet_{LD}$, $\bullet_{GU}$: load bus and generator bus quantities respectively
$\bullet''$,$\bullet'$: sub-transient and transient quantities respectively
$SLG,LLG,LL,3\varphi$: single line to ground, double line to ground, line to line and three phase fault respectively
$\bullet_{\_SLG}$,$\bullet_{\_LLG}$, $\bullet_{\_LL}$, $\bullet_{\_3\phi}$,$\bullet_{\_NF}$: quantities under SLG, LLG, LL, 3φ fault and no fault condition respectively, $\delta, \dot{\delta}$: load angle and speed respectively
ω,ω_s,ω_b: synchronous machine rotor speed, synchronous speed and base speed respectively
y_{ab}: admittance of transmission line connecting buses a and b
$y_{a,load}$: admittance corresponding to constant impedance load at bus a
$0_{x\times y}$: $x \times y$ matrix with all elements being 0, $1_{x\times y}$: $x \times y$ matrix with all elements being 1
I_D: identity matrix of dimension $D \times D$, $Z_{x,y}$: (x,y) element of matrix Z
s_m^l: is a row vector (selection vector) of length l, (where mth element is 1 and rest of the elements are zero)

1.2.1. Time-invariant FDDAEMs (no stator dynamics)

There exist a number of power system models that have been used for stability, fault and other studies. However the major shortcoming of these models is the common practice of ignoring the stator transients of the synchronous machine [15–22]. The reason for this is the obvious difficulty of modelling such transients. As a result the stator circuits of the synchronous machine are represented by algebraic equations, commonly known as *voltage behind sub-transient (or transient or steady state, depending on requirement) reactance*. The implication of ignoring the stator dynamics is that the stator transient currents are assumed to change instantaneously after faults, which is obviously not true according to the constant flux linkage theorem that states that stator currents cannot change instantaneously.

1.2.2. Time-invariant FDDAEMs (approximate stator dynamics)

In order to overcome the inaccuracy resulting from ignoring stator transients, decaying DC "offset" currents are introduced from the instant of fault in references [23,24]. The DC offset currents are calculated from the differences of stator currents immediately before and after the fault. The corresponding decaying time constants are difficult to compute accurately for even modest size power systems, as it requires Thevenin equivalent of the complete system. For this reason, in this modelling approach the time constants are approximated instead of being calculated. Thus, it is quite clear that replacing full stator dynamics by DC decaying terms has the following shortcomings: (a) this approach approximates stator transient under fault conditions; (b) for large power systems the accuracy of this modelling approach depends on the accuracy of approximated decaying time constants.

1.2.3. Time-variant FDDAEMs (full stator dynamics)

n [25–27] fault-dependent power system models including stator transients are presented in well known $d - q - 0$ synchronously rotating frame. However these models are time-variant as the stator quantities exhibit second harmonics component during unsymmetrical fault (detail is given in Section 2.1.1). Hence state space representations of these models, if derived, would be time-variant, and may not be suitable for many studies that require time-invariant models, such as model-based fault detection, controller design, stability analysis, etc.

The lack of a scalable fault-dependent full dynamic state-space model is reflected in the commonly used commercial software packages as shown in the comparison Table 1, where the main features of those packages are highlighted.

In contrast to existing models, the state space model presented in this paper has the following attributes:

(i) it is scalable, configurable (i.e. any number of generating units, loads and any configuration of transmission/distribution network may be included) and generalised such that any fault (symmetrical and unsymmetrical) in any transmission or distribution line may be simulated.

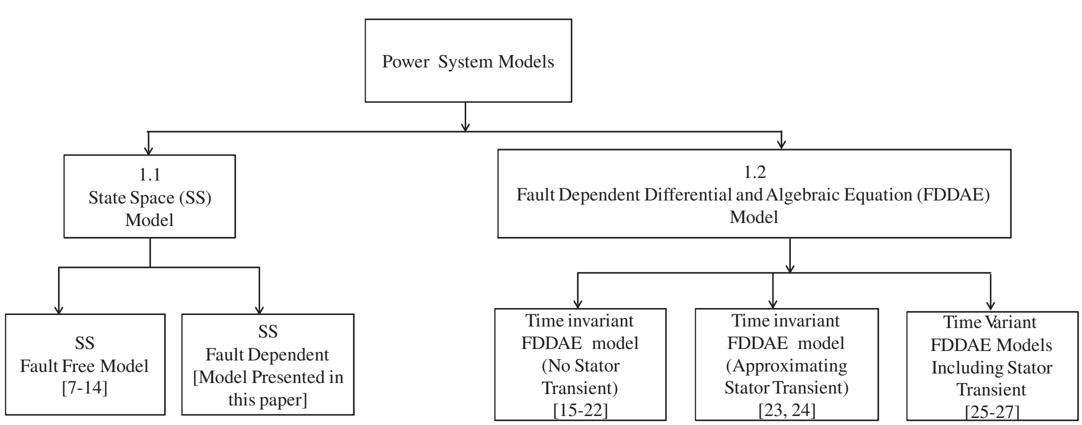

Fig. 1. Flowchart summarising existing power system models.