RELIABILITY EVALUATION OF WIDE AREA MONITORING APPLICATIONS AND EXTREME CONTINGENCIES

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Abstract – In order to perform reliability assessment studies involving the influence of WAMS and extreme contingencies, it is essential to have a good representation of the dynamic behaviour of the system. This paper describes a proposed improvement of the benchmark model IEEE Reliability Test System 1996. The dynamic behaviour of the proposed model is illustrated with results from dynamic simulations.

Keywords: System security, Extreme contingencies, Wide Area Monitoring Systems, Dynamic modelling

1 INTRODUCTION

Power system operation and management requirements are escalating due to society's increased dependency on electricity as well as a continued evolution of the power system. A reliable supply of electricity is recognized as vital for the society, to which extreme contingencies pose a severe threat.

Reliability of the power system is traditionally assessed using adequacy techniques. However, when it comes to the reliability assessment of consequences of extreme contingencies as well as possible remedies using Wide Area Monitoring Systems, the dynamics in the system cannot be neglected. Hence adequacy techniques are inadequate in such analysis.

The IEEE Reliability Test System 1996 [1] is a power system model intended to be used for testing reliability assessment techniques. However, the models' limitations are obvious when it comes to the analysis of dynamic phenomena.

In this paper, an improved dynamic model of the IEEE Reliability Test System 1996 is proposed. The improved dynamic model is suggested to be used for benchmark testing of security assessment techniques.

In this manner, the test system can be used in studies involving consequences of extreme contingencies and the development of various remedial applications based on Wide Area Monitoring Systems.

The paper is organised in the following manner:
Section 2 gives an introduction to reliability assessment with regard to extreme contingencies and prospective applications of wide area monitoring systems. The proposed improvement of the dynamic model for the IEEE Reliability Test System 1996 is described in section 3, while analysis and results of a dynamic study are described in section 4. Discussion and further work is included in section 5.

2 A SMART TRANSMISSION GRID

Smart grid issues have mainly been focusing on making the distribution grid and the demand side smarter, examples on areas of interest are:

- simplified system integration of distributed generation
- demand side management and response
- interaction between many/all components
- smart metering

However, the smart grid approach also relates to improvements of the transmission grid. Such improvements are essential in order to maintain a reliable power supply in a changing power system, of which the society is increasingly dependent. An area of special concern is the power systems' robustness to extreme contingencies.

2.1 Power System Reliability Assessment

Reliability of a power system is composed by two aspects, adequacy and security, where adequacy relates to the ability of the system to satisfy the demand while security is related to the systems capability to withstand disturbances [2-3]. A comprehensive elaboration on the concepts of power system adequacy and security can be found in [4].

When addressing the reliability of power systems, the attention is often towards the steady state adequacy in supply and demand, rather than towards the dynamic robustness and contingency ride through capabilities of the system. One of the reasons for this might be the complexity involved in a proper representation of the dynamic behaviour of the power system. Hence, many reliability assessment techniques are neglecting the dynamic aspect of reliability and only focusing on steady-state security and adequacy assessment of the power system.

Several security assessment techniques are available, with many of the online dynamic security assessment techniques described in [5]. There is, however, a need to further define security assessment indices [6]. Challenges are also related to the modelling requirements for performing adequate dynamic analysis and to the assessment of consequences of extreme contingencies from a simulation point of view.

2.2 Extreme Contingencies

An extreme contingency refers to a disturbance in the power system with a potentially High societal Impact and a Low Probability to occur (also called HILP events), often leading to a wide-area interruption (or blackout).

Due to the unpredictable nature of HILP events, difficulties arise to economically justify major reinforcements on the power systems to prevent such events from occurring [6]. However, with consequences resulting in considerable socio-economic costs, mitigation of extraordinary events has a high social, economical, and political benefit.

Increased insight into and understanding of these events is an important step in order to develop and assign appropriate remedies to limit the consequences of future events. Analyses of historical extreme contingencies, e.g. [7-9], describe several factors identified as root causes to the events. Two aspects of special importance recognised in [10] are:

- insufficient situational awareness
- inadequacy of implemented schemes for controlled islanding

2.3 Wide-Area Situational Awareness

An improved situational awareness of the operating state of the power system on a system wide basis implies an improved system security by e.g. increased operator decision support and enhanced emergency control. In this way, the risk of blackouts can be decreased through more accurate identification of system vulnerabilities. Improved monitoring is one solution to enhance the wide-area situational awareness.

2.4 Wide Area Monitoring Systems

Wide Area Monitoring Systems (WAMS) is identified as a field where applications could be efficiently utilised in order to increase the system security to extreme contingencies without major economical investments. The breakthrough in wide area monitoring arrived with the development and installation of fast, reliable, and highly accurate Phasor Measurement Units, PMUs [11]. PMUs are utilised to supply a WAMS with time synchronised phasor data from a widely dispersed system. Typically WAMS have a relatively low time delay, providing almost real-time observability either of selected parts of the power system, such as vital transfer corridors, or of the entire power system if sufficient PMU installations are available.

The enhanced information made available by a WAMS enables improvements in many fields, related to monitoring, control, and protection of the power system, some of them being:

- Post-mortem analysis
- State estimation & prediction
- Situational awareness
- Security assessment
- System utilization
- Robustness & coordination of protection and control

3 DYNAMIC MODEL OF THE IEEE RELIABILITY TEST SYSTEM 1996

In order to properly perform benchmark reliability assessment of various WAMS applications and extreme contingencies, the widely known IEEE Reliability Test System 1996 is used as a starting point.

3.1 Background

The IEEE Reliability Test System 1996, described in [1], (hereinafter referred to as the test system) is designed with the purpose to be used for benchmark studies on new and existing reliability evaluation techniques. The test system is an extended successor of the original IEEE Reliability Test System 1979, see [12], and consists of an interconnected power system with three areas and six sub-areas. The test system is described by a generation and transmission system supplying loads represented at bulk load points. The representation of a power system by its generation and transmission systems, neglecting the effects of the distribution systems, is often referred to as hierarchical level 2 model, HL-II, which is a usual level of modelling when performing power system reliability assessment.

Several studies have been made on this system, where e.g. [13] presents a reliability (adequacy) assessment of the system and compares the results with the predecessor from 1979, and [14] proposes a full three-phase description of one of the areas of the test system. As far as the authors are aware of, there are no publications available where the limitations of the dynamic model presented in [1] are discussed or the implications this might have when assessing the reliability, including security, of the test system.

3.2 Dynamic modelling

The description in [1] lacks vital information on the dynamical behaviour of the test system; hence the description is mainly useful when addressing the steady state adequacy of generation and transmission rather than the dynamic robustness of the system related to various contingencies. In order to utilise this system for security analysis, further definition of the dynamic parts of the test system is needed.

Depending on the goal of a dynamic power system study, the modelling of the physical behaviour of various items is important, such as: generators, loads, tap-changers, and control & protection systems.

In the following sub-section, the modelling of synchronous generators is discussed, and an improved dynamic model of the generators in the test system is proposed.

3.3 Generator system dynamic models

Several generating plants are defined in [1], where the dynamic generator models are grouped into four unit types: oil, coal, nuclear, and hydro.

The generators are described using the so called classical machine model, i.e. a constant voltage behind a transient reactance. The generators are parameterised using the parameters: H (inertia constant), D (damping constant), and X_d' (transient reactance). The damping constant D is used to represent electrical damping in the classical model, where the effect of damper windings is not included. When the damping constant is set to zero, the model fully neglects any electrical and mechanical damping of the machine.

The dynamic generator data presented in [1] is based on the study described in [15], where the classical machine model is introduced for assessing the security of the IEEE Reliability Test System 1979. It should be noticed that the classical machine model is a highly simplified model, lacking much valuable information of the machines' non-stationary behaviour, and when neglecting the damping of the machines the model may produce highly conservative results in a dynamic simulation.

Hence, in order to more properly reproduce the transient and sub-transient behaviour of the generators, models representing the rotor circuits are proposed. Including the field winding together with one damper circuit in each of the d- and the q-axes, respectively, sub-transient effects and rotor related magnetic saliency are considered. To further increase model accuracy, it is common to include one additional circuit in the q-axis. These model types are in [16] referred to as *Model 2.1* and *Model 2.2*, respectively. Model 2.1 is normally considered sufficiently detailed to represent machines of salient pole type, which typically is the case with generator units in hydro plants. Generator units in thermal plants are often of round-rotor type, for which model 2.2 is normally considered suitable.

The parameters needed in order to represent the generators in the test system with machine models 2.1 and 2.2 are listed in Table 1. The selected data is based on data from [17] and [18], and is supposed to represent typical machine parameter values.

Unit Type / Parameter	Thermal			Hydro
	Oil	Coal	Nuclear	
Model Type[1]	2.2			2.1
H [s] [2]	2.8	3	5	3.5
T_{d0}' [s]	8	8	8	6
T_{d0}'' [s]	0.05	0.05	0.05	0.03
T_{q0}' [s]	1	1	1	-
T_{q0}'' [s]	0.05	0.05	0.05	0.06
T_a [s]	0.2	0.2	0.2	0.2
X_d [pu]	1.8	1.7	2.0	1.1
X_d' [pu][2]	0.32	0.3	0.4	0.28
X_d'' [pu]	0.2	0.18	0.23	0.19
X_q [pu]	1.8	1.7	2.0	0.7
X_q' [pu]	0.55	0.52	0.65	-
X_q'' [pu]	0.23	0.21	0.26	0.22
X_l [pu]	0.15	0.13	0.18	0.11

Table 1: Proposed data for machine models

An example of the differences in dynamic behaviour between the classical machine model and models 2.1 and 2.2 is illustrated by Figure 1. In this figure, the speed deviation (from nominal speed) is shown for three different machine models, after a 100 ms 3-phase short-circuit applied at bus 119. The red curve describes the response when all machines in the test system are modelled using the classical model with parameters as described in [1]. The blue and black curves describes the response when modelling the machines as suggested in Table 1, with the governor and excitation systems explicitly modelled in the system described by the black curve.

It is obvious that the speed deviation in the case with the classical machine model oscillates in an undamped manner. Hence, this contingency would result in instability and loss of load in a study where the machines were modelled using this type of model parameterised as in [1].

See [19] for further description on how the complexity of the machine model influences the dynamic response of the modelled power system.

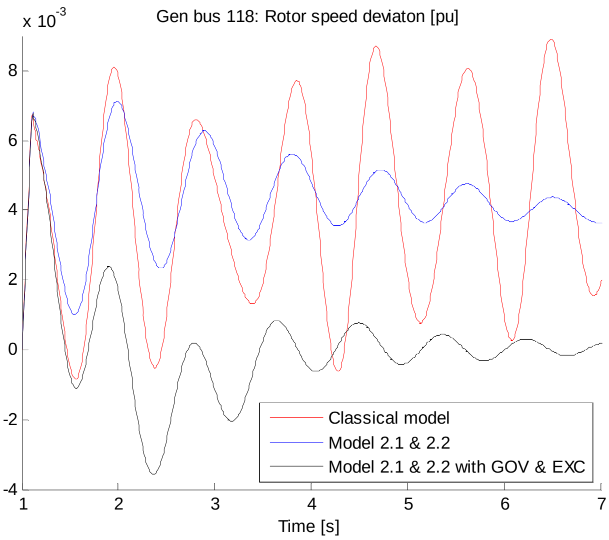

Figure 1: Rotor speed deviation of the machine at bus 118 for different dynamical models, when the system is exposed to a 3-phase fault on bus 119

3.4 *Governor and Excitation system models*

A brief description of the governor and excitation system models is included in this sub-section. As shown in Figure 1, the governor and excitation systems have a significant impact during the transient state of a dynamic simulation, and it can be shown that the stability of the power system is greatly affected by these controls. In order to include the dynamic effects of governors and excitation systems, simplified models together with rather typical data are presented here.

The excitation system model used for all generators is represented by a simplified version of the model referred to as Type AC4A described in [20]. The following simplifications are made: the regulator input filter time constant (T_R) is set to zero, the under excitation limiter (V_{UEL}) and the commutating reactance (K_C) are neglected, and no limit is set on the regulator input (V_I). This simplified model can be represented by

[1] Model type classification as in the *Guide for Synchronous Generator Modeling Practices in Stability Analyses*, [16].

[2] Data as given in *The IEEE reliability test system - 1996*, [1]

the block diagram shown in Figure 2, with suggested typical parameters listed in Table 2.

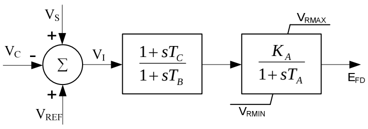

Figure 2: Excitation system model

Unit Type Parameter	All generator types
Model Type[3]	AC4A
T_A [s]	0.1
T_B [s]	10
T_C [s]	1
K_A	400
V_{RMAX} [pu]	3
V_{RMIN} [pu]	0

Table 2: Excitation system model parameters

The turbine and governor system model used for the thermal units is a very simple model, only describing the droop and governor time constant. The model can be represented by the block diagram shown in Figure 3. The parameters suggested for this model are listed in Table 3.

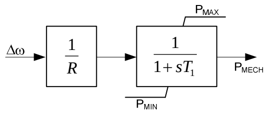

Figure 3: Steam turbine-governor system model

Unit Type Parameter	Thermal
T_1 [s]	0.5
R	0.05
P_{MAX} [pu]	1
P_{MIN} [pu]	0.3

Table 3: Steam turbine-governor system model parameters

For the hydro units, a more elaborate turbine and governor system model is used. The turbine is modelled as a non-linear model with a non-elastic water column, as described in [21], with the simplification that the penstock head losses (f_P) are ignored. The simplified model can be represented by the block diagram shown in Figure 4.

The governor system includes temporary and permanent droop, filter-, governor-, and servo- time constants, together with gate velocity and position limiters. The governor system can be represented by the block diagram shown in Figure 5. The parameters of the hydro turbine and governor systems used in the study are listed in Table 4 and Table 5.

[3] Model type classification as in the *Recommended Practice for Excitation System Models for Power System Stability Studies*, [20].

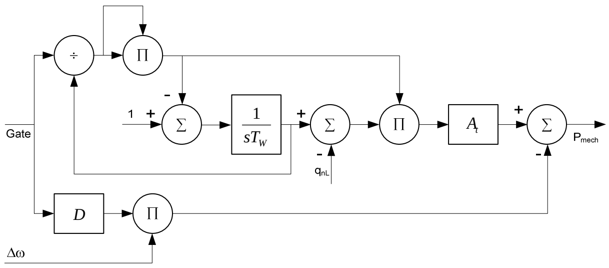

Figure 4: Hydro turbine system model

Unit Type Parameter	Hydro
D	0.5
T_W [s]	1.3
A_t	1.1
q_{nL}	0.08

Table 4: Hydro turbine system model parameters

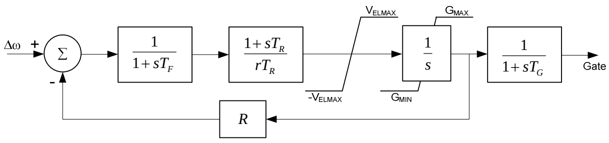

Figure 5: Hydro governor system model

Unit Type Parameter	Hydro
R	0.05
r	0.3
T_F [s]	0.05
T_R [s]	5.2
T_G [s]	0.5
V_{ELMAX} [pu]	0.2
G_{MAX} [pu]	1
G_{MIN} [pu]	0

Table 5: Hydro governor system model parameters

4 ANALYSIS & RESULTS

In this section, the dynamic response of the test system is discussed. The studied scenario corresponds to a high transfer scenario, with load and production distributed as described in Figure 6. The system load is approximately 75 % of the peak load scenario described in [1], with implemented dynamic models as proposed in the previous section. All other data and information regarding the test system are found in [1].

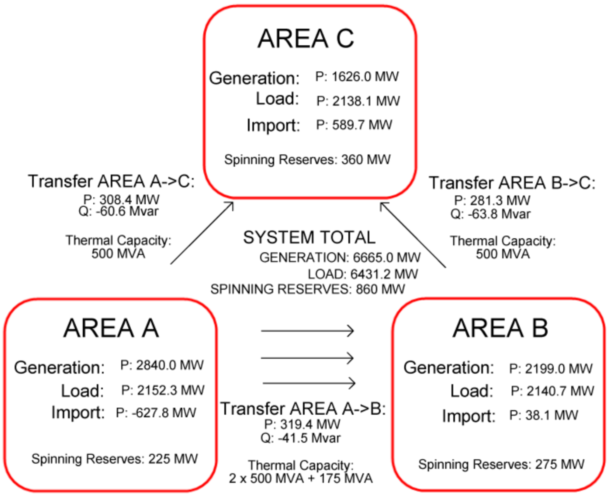

Figure 6: Overview of the IEEE Reliability Test System 1996 showing distribution of load and generation in the studied operating scenario

Important dynamic aspects are studied by linearising the test system. The eigenvalues related to the electro-mechanical oscillatory modes of the linearised system are displayed in Figure 7, where the most influencing modes are seen to be in the range of 0.8–1.5 Hz with damping ratio of around 5 %. Table 6 lists further information on the five lowest damped modes, together with the equipment having the highest participation factor of each mode.

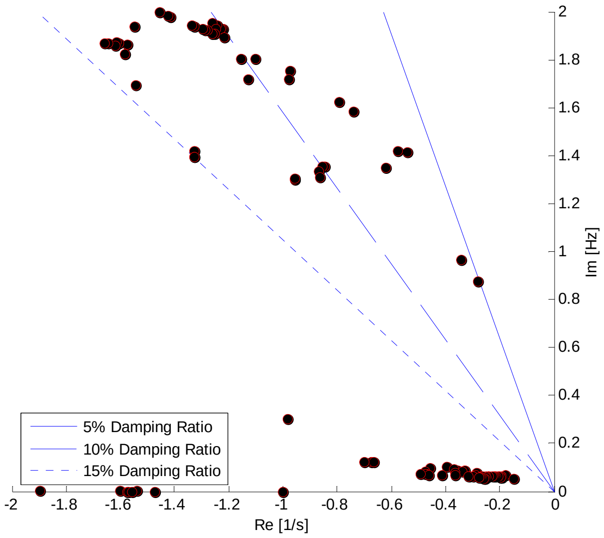

Figure 7: Electro-mechanical modes

no	f [Hz]	Damping [%]	Participation Factor
1	0.87	5.1	Gen1, bus 321
2	0.96	5.6	Gen1, bus 118
3	1.41	6.1	Gen3 & 4, bus 202
4	1.42	6.4	Gen3 & 4, bus 302
5	1.35	7.3	Gen1, bus 218

Table 6: Low damped oscillatory modes

A mode shape plot, describing the observability level using bus voltage angles for the 0.96 Hz mode is displayed in Figure 8. This mode is identified as an interarea mode, where mainly generators in Area A and B are swinging against each other. The 0.87 Hz mode is mainly observable as generators in Area C are swinging against the rest of the system.

Utilising the observability information, it is possible to identify optimal monitoring quantities and locations in order to best observe the level of oscillations in the system. With voltage angles as monitoring unit, the optimal measurements to observe the 0.87 Hz mode is identified as the angle difference between buses 222 (Area B) and 322 (Area C), while the 0.96 Hz mode is best observed as the angle difference between buses 118 (Area A) and 222 (Area B). Such information could be used in a wide area monitoring system to keep track on power oscillations in the system, with possibilities to monitor damping levels of different modes.

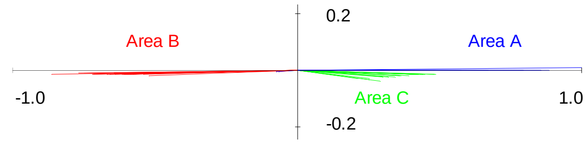

Figure 8: Mode shape plot of bus voltage angles for 0.93 Hz oscillatory mode

The low damped modes are easily triggered, and in Figure 9 the voltage angle difference between buses 222 and 322 is displayed in the wake of a small disturbance, where the oscillatory frequency can be approximated to 0.9 Hz, with damping of around 7 %.

For the same disturbance, Figure 10 depicts the speed deviation of the generators in the system. After a couple of seconds, the 0.87 Hz mode is the most significant mode in the oscillation, with most participation from the generators in Area C, which are distinctly swinging in opposite phase to the generators in Area A and B.

It should be noticed that the damping of the low damped modes could be improved by the implementation of properly tuned power system stabilisers at the generators in the system.

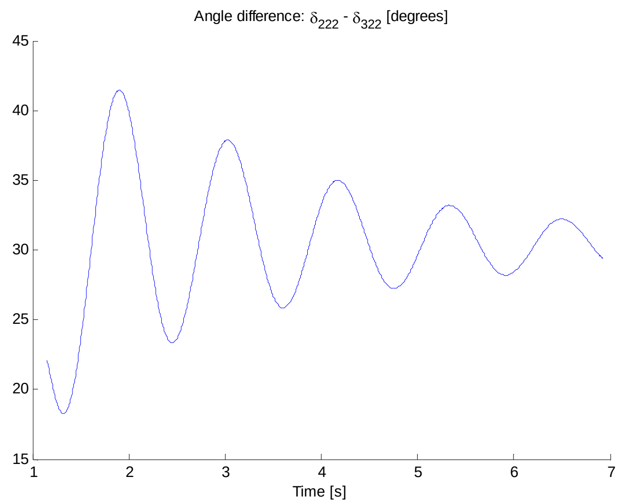

Figure 9: Voltage angle difference between bus 222 and 322

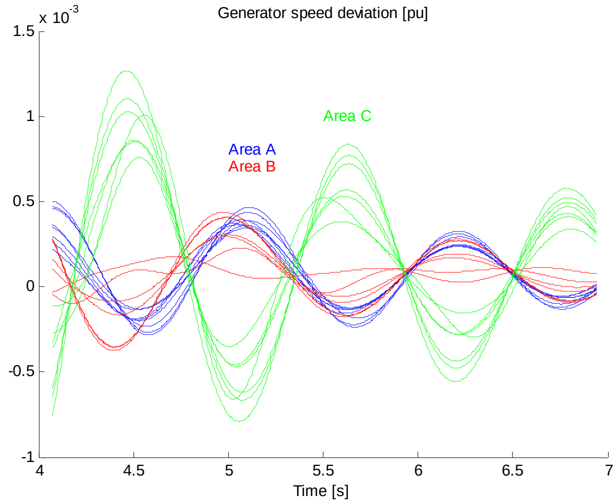

Figure 10: Generator speed deviation (showing inter-area oscillations identifying three groups of generators)

The proximity to voltage collapse can be studied using various indices and calculation techniques. In [22] and [23], it is described how local measurement can be used to estimate the stability margin. At any given bus in the system, the Thevenin equivalent impedance of the network (Z_{NET}) is estimated using phasor measurements and compared to the apparent load impedance of the bus (Z_{APP}). Maximum power transfer to the bus occurs when $Z_{NET} = Z_{APP}$, hence the proximity to voltage collapse can be estimated by studying these two impedances.

Figure 11 displays the impedance ratio Z_{APP} / Z_{NET} (equal to the ratio of short-circuit apparent power and load apparent power) at bus 109. As the system load increases, the voltage stability margin is decreasing. Although the system is far from voltage collapse, the outage of the two transformers connecting bus 109 with buses 111 & 112, respectively, moves the system towards voltage collapse, showing a significant effect on the impedance ratio of the bus.

In this case the apparent load impedance at bus 109 is equal to the local bulk load impedance. However also other impedances could be monitored for example the equivalent impedance of the sub-systems on each side of a tie line.

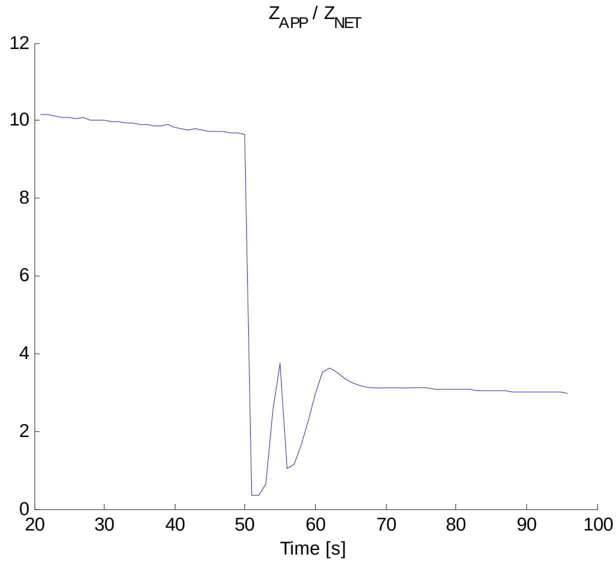

Figure 11: Impedance ratio between load and system at bus 109 during outage of transformers 109-111 & 109-112

This technique is useful in order to improve voltage collapse proximity estimation of a widely distributed system. Using a wide area monitoring system, this information could also be made available on an operator level, where key buses in the system could be specifically monitored as described in [24].

5 DISCUSSION

Development of a wide area monitoring, protection, and control system is a topic of high interest. However, the R&D community need good power system models to develop relevant applications. The main contribution in this paper is the development of a test system for dynamic system analysis based on the well-known IEEE Reliability Test System 1996.

Further work includes specification of improved models, describing: dynamic behaviour of loads, reactive power compensation, power system stabilisers, tap-changer control, and equipment protection.

Planned studies involve security assessment analysis of the impact of WAMS applications as well as HVDC interconnections between the areas of the test system.

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