The Enhanced Binary Single Machine Equivalent Method for Transient Stability Limit Searching

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Abstract

This thesis proposes the novel Enhanced Binary Single-Machine Equivalent Method (EBSIME) to provide a fast, robust and systematic approach to search for the transient stability limits (TSLs) of multi-machine power systems. The algorithm is an extension of the SIME method [1] and provides an approach to estimate a transient stability margin for a given scenario – where the system operating conditions and a contingency are specified. The margins estimated for a pair of different scenarios is used to predict and accelerate an iterative search for the TSLs. The search bisects the search bounds whenever the limit prediction using the transient stability margins cannot be applied, thereby ensuring search convergence. Unlike alternative hybrid-direct TSL searching methods the EBSIME algorithm is general and does not require any model simplification, or heuristic tuning for application to the specific power system under investigation.

The EBSIME algorithm is designed to be implemented as a peripheral add-on to the standard time domain simulation (TDS) and load-flow software; and does not require access to, or modification of, the primary transient stability analysis software. As some important applications of EBSIME are perceived within the Australian power industry the algorithm has been implemented using PSS®E. In this thesis the algorithm is applied to locate the TSLs on the IEEE simplified 14-generator model of the South-East Australian power system. The results indicate that the EBSIME algorithm can locate the TSL up to 30% faster than a plain binary search, and at worst a few simulation seconds longer than a plain binary search.

Statement of Originality

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution to Hui-Min Tan and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

In addition, I certify that no part of this work will, in the future, be used as a submission in my name for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint award of the degree.

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List of Acronyms

ABS	Accelerated Binary Search
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
APBS	Accelerated Parallel Binary Search
AU14GEN	The 14-generator South-East Australian power system model
AVR	Automatic Voltage Regulator
BCU	Boundary of Stability Controlling Unstable Equilibrium Point
CCT	Critical Fault Clearing Time
CM	Critical machine(s)
CT	Fault Clearing Time
COI	Centre of Inertia
CUEP	Controlling Unstable Equilibrium Point
DAD	Differential-Algebraic-Discrete (equations model)
DAE	Differential-Algebraic-Equation
DEEAC	Direct Extended Equal Area Criterion
deg	Degrees
DM	Dynamical Method
DSA	Dynamic Security Analysis
EAC	Equal Area Criterion
EBSIME	The Enhanced Binary Single Machine Equivalent Method
EEAC	Static Extended Equal Area Criterion
ESC	Early Simulation Stopping Criteria
EP	Equilibrium point
EPRI	The Electric Power Research Institute
FS	Forward-Swing
FSL	Forward-Swing (transient stability) Limit
G1	Generator 1
G2	Generator 2
GUI	Graphical User Interface
IEEE	The Institute of Electrical and Electronic Engineers
KE	Kinetic energy
LB	Lower Search Bound
MBASE	Machine Base Power
MG	Machine Groups; (two) Groups of Machines
MOD	Mode of Disturbance
MOI	Mode of Instability
MS	Multi-swing
MSL	Multi-Swing Limit - the transient stability limit
MW	Megawatt
NEM	National Electricity Market
NER	National Electricity Rules
NR	The Newton-Raphson method

NSW	New South Wales, Australia
OMIB	One Machine Infinite Bus power system
ODE	Ordinary Differential Equation
PBS	Parallel Binary Search
PEBS	Potential Energy Boundary Surface
PE	Potential energy
PSS®E	Power System Simulator for Engineering
PT	Power Transfer
PTL	Power Transfer Limit
pu	Per unit
QLD	Queensland, Australia
rad	Radians
SA	South Australia
SBASE	System Base Power
SEEAC	Static EEAC (the same meaning as EEAC)
SEP	Stable Equilibrium Point
SIME	Single Machine Equivalent
sim-s	Simulation seconds
SPM	Structure Preserving Model
SPEF	Structure Preserving Energy Function
SV	Transient Stability Search Variable
SVC	Static Var Compensator
TD	Time Domain
TDS	Time Domain Simulation
TEF	Transient Energy Function
TEM	Transient Stability Energy Margin
TSA	Transient Stability Assessment
TSIM	Time taken to assess transient stability in Simulation Seconds
TSL	Transient Stability Limit (also referred to as the MSL)
TSM	Transient Stability Margin
TSIM	Time in Simulation Seconds
UEP	Unstable Equilibrium Point
ULTC	Under-Load Transformer Tap Changers
UB	Upper Search Boundary
VIC	Victoria, Australia
VSL	Voltage Stability Limit

Glossary

A_{acc}	Acceleration area for the equation area criterion	[pu-rad]
A_{dec}	Deceleration area for the equation area criterion	[pu-rad]
A_{0ij}	Amplitude of the dominant pole for a stable post-fault voltage response	
A_{1ij}	Amplitude of the DC component for a post-fault voltage response	
B	SVC susceptance	[pu]
d_{q0}	The direct-quadrature-zero transformation to represent the rotor, and three-phase stator, quantities in terms of a two-axis rotating reference frame	
θ, δ	Generator rotor angle	[deg or rad]
δ_0	OMIB rotor angle when system operation is in the steady state	[deg or rad]
δ_{clr}	OMIB rotor angle at the instant an applied fault is cleared	[deg or rad]
δ_{limit}	The OMIB rotor angle threshold for forward-swing stability	[deg or rad]
$\delta_{\max}$	Maximum OMIB rotor angle, at the instant when a perturbed system returns to synchronism on the forward-swing	[deg or rad]
$\delta_{SIMEmax}$	A tuned parameter used by the SIME method to check that a diagnosis of the transient stability is correct	[deg or rad]
$\tilde{\theta}$	A vector of machine rotor angles at a given post-fault operating point	[deg or rad]
$\tilde{\theta}_s$	A vector of machine angles at the post-fault stable equilibrium point	[deg or rad]
$\tilde{\theta}_{si}$	The machine angles of a generator at the post-fault stable equilibrium point	[deg or rad]
$\hat{\theta}^{UEP}$	Vector of system machine angles at the unstable equilibrium point (i.e. the operating point where the system is marginally unstable)	[deg or rad]

$\hat{\theta}^{S2}$	Vector of machine angles at the post-fault stable equilibrium point	[deg or rad]
$\hat{\theta}^{cl}$	Vector of machine angles at the point of fault clearance	[deg or rad]
$\hat{\theta}^{S1}$	Vector of machine angles at the pre-fault stable equilibrium point	[deg or rad]
ε_k	The transient energy function margin	
H	The machine inertia coefficient	
k	The iteration number of the current search scenario	
$\mathbf{M}$	Matrix of 2 x Machine Inertia Constants	
M	Twice the machine inertia coefficient	
mmf	Magneto-motive force	
N	The number of machine groups that are considered in the SIME method for TSA at each time-step of a TDS	
n_{tol}	Margin tolerance, used by the SIME limit prediction search	[pu-rad]
ω	Generator rotor speed	[rad/s]
ω_{limit}	The OMIB rotor speed when the OMIB rotor angle = δ_{limit}	[rad/s]
ω_{0ij}	Angular frequency of the dominant pole for a stable post-fault voltage response	[rad]
P_a	Generator acceleration power	[pu]
P_e	Generator electrical power output	[pu]
P_m	Mechanical input power to a generator shaft	[pu]
$\mathbf{P_e}$	Vector of machine electrical power outputs	[pu]
$\mathbf{P_m}$	Vector of machine mechanical power inputs	[pu]
P_a^T	A vector of acceleration power of all the machines in a power system	[pu]
P_a-δ_{OMIB}	The OMIB acceleration power versus angle characteristic	[pu-rad]

(s)	Standard international (SI) units	
σ_{0ij}	Damping constant of the dominant pole for a post-fault voltage response	
σ_{1ij}	Damping constant of the dominant pole for a stable post-fault voltage response	
t	Time	[s]
T	Time Vector	[s]
t_f	The instant when a fault is applied to a power system	[s]
t_r	The instant when a perturbed system returns to synchronous operation on the forward-swing	[s]
t_u	The instant in time when a generators in a power system lose synchronism	[s]
t_{obs}	The time instant at which an unstable TDS is halted	[s]
V_{cl}	The system energy at the instant of fault clearance for the energy function	
V_{cr}	The change in potential energy between the operating points described by $\hat{\theta}^{UEP}$ and $\hat{\theta}^{S2}$	
$V_{\text{correction}}$	Residual kinetic energy correction factor	
$V_{KE\cdot corr}$	The corrected kinetic energy	

Maximum simulation time	Typically the maximum prescribed simulation time is 10s to 20s
Limit prediction search phase	The phase of the EBSIME search where the SIME limit prediction steps are performed to determine the TSL. Also referred to as the “forward-swing search phase”.