Coordinated Initialization of the Load Distribution Equivalent, Load Characteristic, and Load Distributed Generation Models

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January 12, 2016

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Coordinated Initialization of Generator Models

- Generators have included a modular structure for several decades (1970s and onward)
- Synchronous generators needed up to 8 separate modules with coordinated initialization
  - Machine (Generator/Converter Model)
  - Exciter (P and Q controller)
  - Governor (Drive Train)
  - Stabilizer (Pitch Control)
  - Under Excitation Limiter
  - Over Excitation Limiter
  - Compensator Model
  - Relay Model
8 Synchronous Generator Modules

- We have always done this with Generators
Generator Modules Continue to Grow

- In past several years even more modules have been added
  - Aerodynamic Model (Type 3 Wind)
  - Pref Controller (Type 3 wind and LCFB1)
  - Plant Controller (renewable models)
  - AGC Controller (Implemented in Version 19 of PowerWorld Simulator)
Type 3 Wind Turbine model added 3 new modules

- Pref Controller, Plant Controller, Aero
Load Models have not kept up

• Load Models have been stuck with only two modules
  – Load characteristic
  – Load relay
• The MOTORW model introduced in PSLF in the 1990s was a step in the right direction
  – MOTORW included a parameter indicating what percentage of the load was a motor
  – This meant we now had 3 modules
    • Dynamic Model
    • Algebraic Model
    • Relay Model
  – No longer required you to split the power flow load record to permit a load model split
• Relay model is always simple, but so is MOTORW
  – Does not require any coordination in the initialization of the models. Algebraic and Dynamic model just get split
Initial Implementation of Distribution Equivalent

- Composite load model (CMPLDW) was designed within the WECC LMTF in the mid 2000s
  - The distribution equivalent is stuck inside the load characteristic
  - Has meant that new load models are gravitating toward being smashed into the CMPLDW framework

- Load Distributed Generation (Roof-top Solar for example)
  - WECC LMTF is now pushing us toward getting the Load Distributed Generation model out of the CMPLDW
It is Time to Modularize: Just like Generators

- Natural for a load record to have 4 modules associated with transient stability
  - Load Characteristic (can also split algebraic/dynamic)
  - Relay Model
  - Distribution Equivalent
    - Added in PowerWorld Simulator Version 17 in January 2013
  - Load Distributed Generation Model
    - Added in PowerWorld Simulator Version 19 in November 2015

- Initialization of this model must be fully documented though
Load Record:
Distributed Generation

- Discussed in WECC LMTF for a few years and decision was made in 2014 to model with three new user input fields with each Load Record
  - **Dist MW Input**: the user entered MWs of distributed generation at the load
  - **Dist Mvar Input**: the user entered Mvars of distributed generation at the load
  - **Dist Status**: The status of the distributed generation (Open or Closed)

- Available in PowerWorld Simulator 19 now
Other Load Record Fields

- **Dist MW, Dist Mvar**: this is the actual MWs being seen by the power flow solution
  - This will be 0.0 if **DistStatus = Open**
  - This will be reduced if the voltage falls below the minimum voltage for constant power load

- **Net MW**: this is equal to the subtraction of the fields **MW – Dist MW**
Treatment of Distributed Generation in Power Flow

- Summary Information with Areas, Zones, Substations, etc...
  - Dist MW is separate summation from Load MW

- Injection Group Treatment
  - Injected MW = Gen MW – Load MW – Dist Gen MW

- Contingency Actions
  - “Set, Change, Move” actions only act on Load portion
  - Open and Close actions also open the distributed gen
Load Distribution Equivalent

• Supplementary model that defines an equivalent of the distribution system’s transformer, capacitors, and feeder
• Created independently of the load characteristic models
• Can be used with any load characteristic model
• Design assumes small number of Load Distribution Equivalent Types with many different loads assigned to each
Load Distribution Equivalent

- First 17 parameters of the CMPLDW load characteristic model along with MVA base
Assigning Load Distribution Equivalent Models

- Each Load record is assigned to a Distribution Equivalent
What does this look like?
Load Record has Modules

Load Characteristic

Distribution Equivalent

Distributed Generation
Plot of Results:
Right plot shows Distributed Gen

0.90 pu
Initialization

• When using a software model the fundamental details of the model should be known to the user
  – Equipment affects everyone as it is connected to a grid
  – Others need to model your equipment
  – This often means pseudo-code is needed

• Describing how a model is initialized is part of this
  – *Software vendor secret:* the hardest thing to do with transient stability models is to initialize them
  – Also some arbitrary decisions are sometimes made about a model during initialization → need pseudo-code

• Before we discuss coordinated initialization of these models → consider initialization of
  – Single Phase Air Conditioner → LD1PAC
  – Induction Motors → MOTORW, CIM5, MOTOR1, etc..
LD1PAC Model: Algebraic Performance Model

- LD1PAC follows algebraic P/Q Curves
  - If $V > V_{brk}$ then
    - $P = [P_o + K_{p1}(V - V_{brk})^{N_{p1}}][1 + CmpKpf \ast \Delta f]$}
    - $Q = [Q_o + K_{q1}(V - V_{brk})^{N_{q1}}][1 + CmpKqf \ast \Delta f]$
  - If $V < V_{brk}$ and $V > V_{stallbrk}$ then
    - $P = [P_o + K_{p2}(V_{brk} - V)^{N_{p2}}][1 + CmpKpf \ast \Delta f]$}
    - $Q = [Q_o + K_{q2}(V_{brk} - V)^{N_{q2}}][1 + CmpKqf \ast \Delta f]$
  - If $V < V_{stallbrk}$ then
    - $P = G_{stall} \ast V^2$
    - $Q = B_{stall} \ast V^2$

- Important somewhat arbitrary decision
  - What is $V_{stallbrk}$? Must fully document this stuff!
$P_o, Q_o, \text{ and } V\text{stallbrk}$

- $P_o = P_{\text{init}} - K_{p1}(V_{\text{init}} - V\text{brk})^{N_{p1}}$
- $V\text{stallbrk} = \text{intersection of the power stall curve and the power curve defined by } K_{p2} \text{ and } N_{p2}$
  - PowerWorld determines this to a tolerance of 0.0001 per unit voltage.
  - If this intersection is calculated as higher than $V\text{stall}$, then instead set $V\text{stallbrk} = V\text{stall}$ (this should be a very rare occurrence as it can result in strange results)
- $Q_o = P_{\text{init}} \left( \sqrt{1 - \frac{\text{CompPF}^2}{\text{CompPF}}} \right) - K_{p1}(1.0 - V\text{brk})^{N_{p1}}$
- As long as the motor is not stalled (Below $V\text{stall}$ for more than $T\text{stall}$ seconds), then the algebraic $P$ and $Q$ values following this yellow highlighted curves
Induction Motor Initialization

- Mvar of an induction motor at initialization (steady state) is \textit{dependent} on the terminal voltage and MW of the motor.
- There will be a mismatch between
  - Motor Mvar
  - Load Flow Record Initial Mvar
- Handled by including a shunt admittance as part of the load model to match the initial condition
  - These will be called \textit{ExtraMvars} in this document
Coordinated Initialization with Distribution Equivalent

The internal model used by the transient stability numerical simulation structurally does the following:

1. Creates two buses called Low Side Bus and Load Bus
2. Creates a transformer between Transmission Bus and Low Side Bus
3. Creates a capacitor at the Low Side Bus
4. Creates a branch between Low Side Bus and Load Bus
5. Moves the Load from the Transmission Bus to the Load Bus
Important:
Input Data Validation Check

- The **NetMW** and **NetMvar** of the load can potentially exceed the maximum power transfer of the Distribution Equivalent
  - Calculation of **DistEquivMVABase**
    - MVABase > 0 means **DistEquivMVABase** = MVABase
    - MVABase < 0 means **DistEquivMVABase** = Abs(NetMW/MVABase)
    - MVABase = 0 means **DistEquivMVABase** = NetMW/0.8
  - Notice that MVABase is a function of **NetMW** for MVABase <=0
- Problem for loads with extremely poor power factor
  - What if load is 1.2 MW and 30 Mvar? Impedances are based on base proportional to 1.2, but 30 Mvars across this may be too much.
- Software Solution: Add a validation error
  - Check if Estimate of Real Power $I^2R$ losses exceeds the **NetMW**
  - Clearly bad input data if

\[
\left(\frac{NewMW^2 + NetMvar^2}{Vpu^2}\right) \times \left(\frac{Rfdr \cdot \text{SystemMVABase}}{\text{DistEquivMVABase}}\right) > NetMW
\]
Important:
Related Validation Check

• A lot of these weird validation errors actually occur with extremely small loads
  – How about MW = 0.001 and Mvar = 0.020
  – This kind of thing happens a lot when you get a real-time state estimation case → just noise from measurements and the state estimator solution

• PowerWorld Simulator has a hard-coded threshold
  – Any MW Load < 0.001 per unit (0.1 MW for 100 MVABase system) is never modeled with anything but an algebraic load model
  – Silly to model motors this small anyway
  – You will see warning messages inside Simulator indicating this is occurring
Initialization Process

- Goal of Initialization is to calculate $Tap$, $Bf_1$, $Bf_2$, $VLS$, $PLS$, $QLS$, $VLB$, $P_{new}$, and $Q_{new}$. (Also might change $Bss$, $R_{fdr}$, and $X_{fdr}$)
- If you want the same results you need to define the rules precisely
  - It is quite likely that multiple values of $Tap$ will get you inside the $V_{min}$ and $V_{max}$ range specified in the distribution equivalent
  - How you split $Bf_1$, $Bf_2$, and $Bss$ might change results
  - How to reduce the $R_{fdr}$ and $X_{fdr}$ when the load bus voltage falls below 0.95 matters
- Define “precisely” → means psuedo-code
Initialization Steps 1 – 2: Impedance Base Conversion

- **Step 1: Calculation of DistEquivMVABase**
  - MVABase > 0 means \( \text{DistEquivMVABase} = \text{MVABase} \)
  - MVABase < 0 means \( \text{DistEquivMVABase} = \text{Abs}(\text{NetMW}/\text{MVABase}) \)
  - MVABase = 0 means \( \text{DistEquivMVABase} = \text{Abs}(\text{NetMW}/0.8) \)
  - Note: This is a function of NetMW, so that means MW – DistMW of the distributed generation

- **Step 2: Impedance parameters are given on this DistEquivMVABase base, so convert them to the SystemMVABase**
  - \( X_{xf} = X_{xf} \times \frac{\text{SystemMVABase}}{\text{DistEquivMVABase}} \)
  - \( R_{fdr} = R_{fdr} \times \frac{\text{SystemMVABase}}{\text{DistEquivMVABase}} \)
  - \( X_{fdr} = X_{fdr} \times \frac{\text{SystemMVABase}}{\text{DistEquivMVABase}} \)
  - \( R_{cmp} = R_{cmp} \times \frac{\text{SystemMVABase}}{\text{DistEquivMVABase}} \)
  - \( X_{cmp} = X_{cmp} \times \frac{\text{SystemMVABase}}{\text{DistEquivMVABase}} \)
  - \( \text{Bss} = \text{Bss} \times \frac{\text{SystemMVABase}}{\text{DistEquivMVABase}} \)
Initialization Steps 3 – 4: Transformer Setup

• Step 3: Convert Transformer Tap values and impedances to the SystemMVABase
  – Variable tab is on the low side bus
  – \( X_{xf} = X_{xf} \times (T_{fixhs})^2 \)
  – \( \text{Step} = \text{Step}/T_{fixhs} \)
  – \( T_{min} = (T_{min} + T_{fixls} - 1)/T_{fixhs} \)
  – \( T_{max} = (T_{max} + T_{fixls} - 1)/T_{fixhs} \)

• Step 4: Set tap ratio (\( \text{Tap} \)) needed.
  – Sending end flow is Net values so (Load – DistGen)
  – Calculate exact tap ratio needed to give Low Side Bus Voltage of \( (V_{min} + V_{max})/2 \) (arbitrary decision)
    • See Section 3.2.1 of companion PDF document for exact equations
  – Round to nearest discrete step and enforce \( T_{min} \) and \( T_{max} \)

There are likely a few Tap values which get you inside \( V_{min} \) and \( V_{max} \)
Initialization Steps 5 – 7:

- **Step 5:** Calculate the Low Side Bus Voltage (VLS) and the Low Side Bus P and Q flow *exactly* (PLS, QLS)
  - See Section 3.2.2 of companion PDF document for exact equations
- **Step 6:** Initialize $Bf_1$ and $Bf_2$ to zero
- **Step 7:** If $VLS < 0.95$ then automatically set $Rfdr$ and $Xfdr$ to minimum value
  - $Rfdr = 0.0000001$ per unit
  - $Xfdr = 0.00001$ per unit

- **This is where things get complicated**
  - Calculation Load Bus Voltage (VLB) depends on $Bf_1$
  - As mentioned in induction motor initialization, there are *ExtraVars* that come from that initialization which depends on VLB
  - The distribution equivalent model specifies that these *ExtraVars* be split between the from and to end of the feeder according to $Fb$ input option
    - $Bf_1 = (Fb)(Bf_1 + Bf_2)$
    - $Bf_2 = (1-Fb)(Bf_1 + Bf_2)$
    - But $Bf_1$ is used to calculate VLB
      - If $Fb = 0$, things are a LOT easier!
Initialization Steps 8 – 9

• Step 8: Using present values of \(\text{Bf1}\) and \(\text{Bf2}\), estimate both the Load Bus Voltage (\(\text{VLB}\)) and the flow reaching the Load Bus (\(\text{Pnew, Qnew}\))
  – See Section 3.2.2 of companion PDF document for exact equations

• Step 9: If magnitude of \(\text{VLB} < 0.95\) then the feeder impedances are reduced by a factor such that \(\text{VLB} = 0.95\) (exactly) and update \(\text{Pnew, Qnew}\)
  – See Section 3.2.3 of companion PDF document for exact equations
Initialization Steps 10 – 11

- **Step 10:** Using Values of VLB, Pnew, Qnew initialize the dynamic load characteristic models
  - If Distributed Generation Model is present, then the Load Characteristic Models will use $(P\text{new} + \text{DistMW})$ and $(Q\text{new} + \text{DistMvar})$
  - Part of Load Characteristic initialization will result in ExtraMvars

- **Step 11:** If we have reduced $Rfdr$ and $Xfdr$ to minimum value already, then Exit Initialization and leave ExtraMvars with Load Bus
Initialization Steps 12

ExtraMvars $\rightarrow$ Bf1, Bf2

• Step 12: Allocate ExtraMvars to Bf1 and Bf2
  – If \((\text{ExtraMvars} < 1E-4 \text{ per unit}) \text{ OR } (\mathbf{Fb} < 0.001)\), then stick them all at the Load Bus
    • \(Bf2 = Bf2 + \frac{\text{ExtraMvars}}{\mathbf{VLB}^2}\)
    • ExitShortly = True
  – Else
    • \(Bf1 = Bf1 + \frac{\mathbf{Fb}\times\text{ExtraMvars}}{\mathbf{VLS}^2}\)
    • \(Bf2 = Bf2 + (1 - \mathbf{Fb})\times\frac{\text{ExtraMvars}}{\mathbf{VLB}^2}\)
    • ExitShortly = False
Initialization Steps 13: Coordinate Bf1, Bf2 with Bss

- Step 13: If Bf1 and Bf2 are negative and Bss > 0 then reduce Bss toward zero to cancel out Bf1 and Bf2.
  - ExitShortly = False
  - Bf1var = Bf1 * VLS^2
  - Bf2var = Bf2 * VLB^2
  - Bssvar = Bss * VLS^2
  - If abs( Bf1var + Bf2Var ) > Bssvar then
    - tempVar = BssVar
    - Bss = 0
    - If Fb = 1 then
      - tempVar = abs(Bf1Var)
      - Bss = Bss – tempVar / VLS^2
    - Else
      - tempVar = abs(Bf2var) / (1 – Fb)
      - Bss = Bss – tempVar / VLS^2
    - Bf1 = Bf1 + Fb * tempVar / VLS^2
    - Bf2 = Bf2 + (1 – Fb) * tempVar / VLS^2

// Set Bss=0 and reduce magnitude of Bf1 and Bf2
// Reduce Bss by Bf1Var and reallocate Mvars to Bf1 and Bf2
// attempt to push Bf2 toward zero
Initialization Steps 14: Finish Off

- Step 14:
  - If (ExitShortly) then Exit Initialization
  - Else go back to Step 8 and repeat
Summary

• Transparency of stability models is vital if you want to share models
  – Need good documentation
  – Often need some pseudo-code as block diagrams aren’t enough
    • Various ways to implement non-windup PI limits
    • Algebraic models get weird (Bf1, Bf2, Bss coordination of distribution equivalent)
    • Calculation of Vstallbrk on LD1PAC

• Good examples of how to share model specifications
  – H6B governor model from John Undrill and implemented in PSLF
    • I implemented this in PowerWorld Simulator in February 2014 very quickly because documentation was excellent
    • Pseudo-code was important because of unique non-windup PI limit
  – Colstrip Acceleration Trend Relay from Jamie Weber implemented in PowerWorld Simulator
    http://www.powerworld.com/WebHelp/Content/TransientModels_PDF/Generator/Others/Relay%20Model%20ATRRELAY.pdf
  – Generic Wind and Solar Models
    • However, input units on which MVABase is still not clear on a few of these models...
    • Pseudo-code would have made that more clear
Tap Calculation Equation
(Section 3.2.1 of PDF)

- Initial condition and the input parameters $P_{km}, Q_{km}, V_k,$ and $X_{xf}$. 

- We use $V_m = \frac{V_{min}+V_{max}}{2}$

- PDF document shows derivation of required $Tap$.

- $Tap = \sqrt{\frac{(V_kV_m)^2}{(Q_{km}X_{xf}-V_k^2)^2 + (X_{xf}P_{km})^2}}$
Calculation of Far Bus Complex Voltage and PQ Flows (Section 3.2.2)

- **General Network as Follows**

  ![Diagram](image)

  \[ g_{kk} = \frac{R}{(R^2 + X^2)} \quad b_{kk} = \frac{-x}{(R^2 + X^2)} + B_1 \]

  \[ g_{mm} = \frac{R}{(R^2 + X^2)t^2} \quad b_{mm} = \frac{-x}{(R^2 + X^2)t^2} + B_2 \]

- **Calculate Complex Vm**

  \[
  \begin{bmatrix}
  e_k g_{km} + f_k b_{km} \\
  f_k g_{km} - e_k b_{km}
  \end{bmatrix}
  \begin{bmatrix}
  e_m \\
  f_m
  \end{bmatrix}
  =
  \begin{bmatrix}
  P_{km} - e_k^2 g_{kk} - f_k^2 g_{kk} \\
  Q_{km} + f_k^2 b_{kk} + e_k^2 b_{kk}
  \end{bmatrix}
  \]

- **Calculate far end flows**

  \[
  P_{mk} = +e_m^2 g_{mm} + e_m e_k g_{mk} - e_m f_k b_{mk} + f_m^2 g_{mm} + f_m f_k g_{mk} + f_m e_k b_{mk}
  \]

  \[
  Q_{mk} = -f_k^2 b_{mm} + f_m e_k g_{mk} - f_m f_k b_{mk} - e_m^2 b_{mm} - e_m f_k g_{mk} - e_m e_k b_{mk}
  \]
Section 3.2.2 Admittance Values
Transformer and Feeder Branch

For our Transformer branch the admittance parameters are as follows.

\[ g_{kk} = 0 \]
\[ b_{kk} = -\frac{1}{x_{xf}} \]
\[ g_{mm} = 0 \]
\[ b_{mm} = -\frac{1}{x_{xf} \text{Tap}^2} \]
\[ g_{km} = g_{mk} = 0 \]
\[ b_{km} = b_{mk} = \frac{1}{x_{xf} \text{Tap}} \]

For our Feeder branch the admittance parameters are as follows.
(Note: the capacitors are lumped into the feeder admittances for calculation purposes here.)

\[ g_{kk} = \frac{R_{dfr}}{R_{fdr}^2 + X_{fdr}^2} \]
\[ b_{kk} = \frac{-X_{dfr}}{R_{fdr}^2 + X_{fdr}^2} + B_{f1} + B_{ss} \]
\[ g_{mm} = \frac{R_{dfr}}{R_{fdr}^2 + X_{fdr}^2} \]
\[ b_{mm} = \frac{-X_{dfr}}{R_{fdr}^2 + X_{fdr}^2} + B_{f2} \]
\[ g_{km} = g_{mk} = \frac{-R_{dfr}}{R_{fdr}^2 + X_{fdr}^2} \]
\[ b_{km} = b_{mk} = \frac{X_{dfr}}{R_{fdr}^2 + X_{fdr}^2} \]
Calculation of Far Bus Values with a Voltage Constraint

- Feeder Network at this point is

- Group the Bss and Bf1 terms in Q flow and define

- The solve following three nonlinear equations using Newton’s method

- Convergence Tolerance of
  - P and Q equation $1E-5$
  - Voltage equation $1E-8$

- Jacobian Matrix