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APPENDIX A SATURATED REACTANCE AND TIME CONSTANTS

A.1 Saturated Reactance

It is assumed that leakage flux does not contribute in any way to the saturation of the machine, and that the leakage flux itself does not saturate either. Thus the reactances on the two axes can be given by

$$x_d = x_\sigma + x_{ad} \tag{A.1}$$

$$x_q = x_\sigma + x_{aq} \tag{A.2}$$

The saturated values of the reactances in the above equations are calculated as follows:

$$x_d^{(0)} = x_\sigma + x_{ad}^{(0)} \tag{A.3}$$

$$x_q^{(0)} = x_\sigma + x_{aq}^{(0)} \tag{A.4}$$

$$x_{ad} = kx_{ad}^{(0)} \tag{A.5}$$

$$x_{aq} = kx_{aq}^{(0)} \tag{A.6}$$

$$x_d = x_\sigma + kx_{ad}^{(0)} = kx_d^{(0)} + (1-k)x_\sigma \tag{A.7}$$

$$x_q = x_\sigma + kx_{aq}^{(0)} = kx_q^{(0)} + (1-k)x_\sigma \tag{A.8}$$

$$x_{ad} = x_d - x_\sigma = k(x_d^{(0)} - x_\sigma) \tag{A.9}$$

where the subscript σ denotes flux leakage.

A.2 Time Constants

The single line diagrams of the excitation winding and the two damping windings on the rotor are used to derive the time constants. Figure A.1 represents the open circuit of the excitation winding, from which the transient time constant is given by

$$\tau'_{do} = \tau_f = \frac{\left(x_{f\sigma} + x_{ad}\right)}{r_f} \tag{A.10}$$

Then the saturated time constant can be found from

$$\frac{\tau_{do}^{'}}{\tau_{do}^{'(0)}} = \frac{\dfrac{\left(x_{f\sigma} + x_{ad}\right)}{r_f}}{\dfrac{\left(x_{f\sigma} + x_{ad}^{(0)}\right)}{r_f}}$$

$$= \frac{x_{f\sigma} + k\left(x_d^{(0)} - x_\sigma\right)}{x_{f\sigma} + \left(x_d^{(0)} - x_\sigma\right)} \tag{A.11}$$

$$= k + \left(1 - k\right)\frac{\left(x_d^{'} - x_\sigma\right)}{\left(x_d^{(0)} - x_\sigma\right)}$$

where (A.3) and (A.12)-(A.13) are used:

$$x_{ff} = x_{f\sigma} + x_{ad} \tag{A.12}$$

$$x_d^{'} = x_d - \frac{x_{ad}^2}{x_{ff}} \tag{A.13}$$

It is assumed that $x_{f\sigma}$, the leakage flux of the excitation winding, does not saturate either.

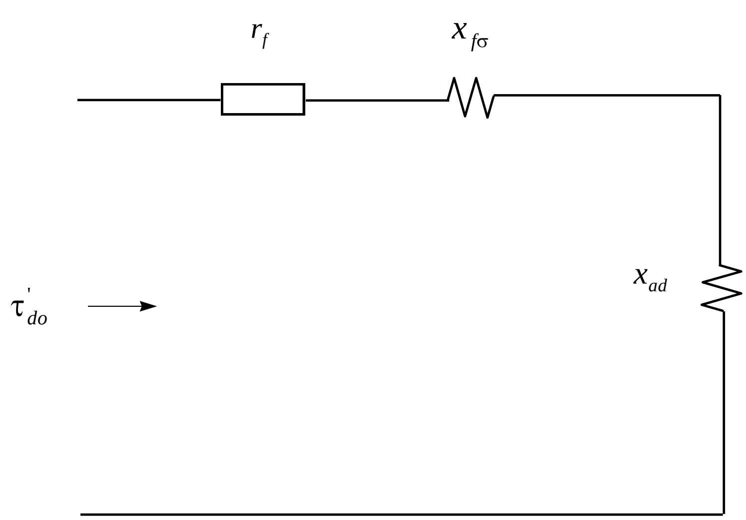

Figure A.1: Diagram for calculation of $\tau_{do}^{'}$

Figure A.2 represents the open circuit of the damper winding on $d-$axis, from which its subtransient time constant is calculated by

$$\tau_{do}^{"} = \frac{\left(x_{D\sigma} + x_{ad} || x_{f\sigma}\right)}{r_D} \tag{A.14}$$

Then its saturated value can be calculated by

$$\begin{aligned} \frac{\tau_{do}^{"}}{\tau_{do}^{"(0)}} &= \frac{x_{D\sigma} + \left(x_{ad} || x_{f\sigma}\right)}{x_{D\sigma} + \left(x_{ad}^{(0)} || x_{f\sigma}\right)} \\ &= k + (1-k)\frac{\left(x_d^{"} - x_\sigma\right)}{\left(x_d^{(0)} - x_\sigma\right)} \end{aligned} \tag{A.15}$$

where ' || ' denotes parallel connection of reactances. The following (A.16) is used in derivation of (A.15):

$$\begin{aligned} x_d^{"} &= x_\sigma + \frac{x_{D\sigma} x_{f\sigma} x_{ad}^{(0)}}{x_{D\sigma}\left(x_{ad}^{(0)} + x_{\sigma\sigma}\right) + x_{ad} x_{f\sigma}} \\ &= x_\sigma + x_{D\sigma} || x_{f\sigma} || x_{ad}^{(0)} \end{aligned} \tag{A.16}$$

which is the equivalent reactance of Figure A.2 when the damper winding is short circuited and r_D is set to be zero.

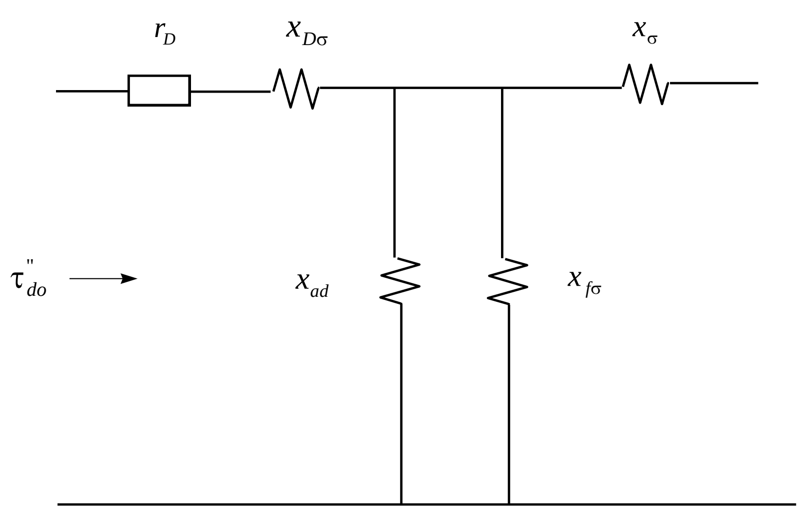

Figure A.2: Diagram for calculation of $\tau_{do}^{"}$

Figure A.3 represents the open circuit of the damper winding on $q-$axis, from which its subtransient time constant is calculated by

$$\tau_{qo}'' = \frac{\left(x_{Q\sigma} + x_{aq}\right)}{r_Q} \tag{A.17}$$

$$\frac{\tau_{qo}''}{\tau_{qo}''^{(0)}} = k + (1-k)\frac{\left(x_q'' - x_\sigma\right)}{\left(x_q^{(0)} - x_\sigma\right)} \tag{A.18}$$

The following (A.19) is used in derivation of (A.18):

$$x_q'' = x_\sigma + x_{Q\sigma} || x_{aq}^{(0)} \tag{A.19}$$

which is the equivalent reactance of Figure A.3 when the damper winding is short circuited and r_Q is set to be zero.

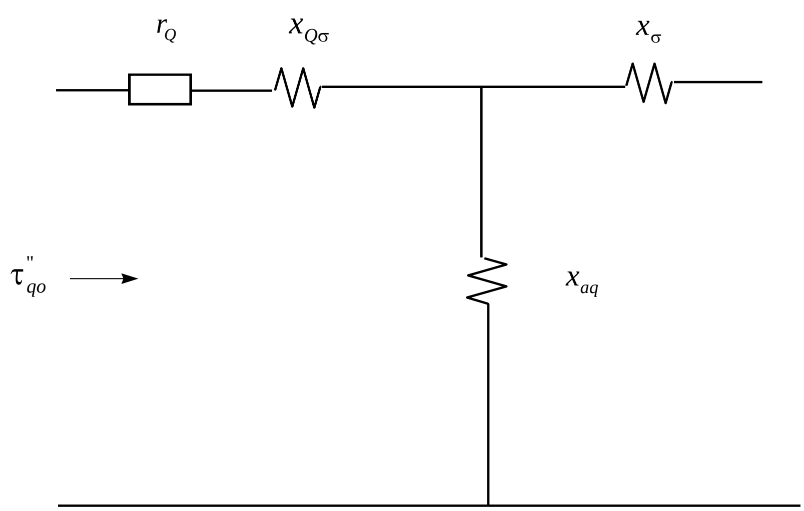

Figure A.3: Diagram for calculation of τ_{qo}''

APPENDIX B M–FILE FIND_VIF.M

```
% Filename: find_vif.m,  network and generator interface
% Line fault can be introduced if desired.

% Inputs: state variables of devices
% Outputs: terminal voltages and currents

% Stephan Z. Ao
% CopyRight Feb 16, 1996

function vi_out = find_vif(u)

cmm
global Y  Yf Yp Yr BUSTYPE
global Ts Tp Tr Ifault
global Xds Xqs  Ts Tp Tr Y0

NBUS = max(size(Y));
A = zeros(2*NBUS,2*NBUS);                %coefficient matrices
B = zeros(2*NBUS,1);
Zi = zeros(2,2);                         %impetance of generator i
Del = [];                                %generator angle
Y0 =zeros(2*NBUS,2*NBUS);
nu = max(size(u));
TIME = u(nu);                            %last element of u is time
if (TIME<Ts)                             %prefault Y
   Y0 = Y;
elseif (TIME>=Ts & TIME<Tp )             %faulted Y
   Y0 = Yf;
elseif (TIME>=Tp & TIME<Tr )             %post-faulted Y
   Y0 = Yp;
elseif (TIME>=Tr )                       %restored Y
   Y0 = Yr;
end                                      %end if

for I=1:NBUS                             %decompose Y into real
for J=1:NBUS                             %and imaginary part
  A(2*I-1,2*J-1) = real(Y0(I,J));
  A(2*I-1,2*J  ) =-imag(Y0(I,J));
  A(2*I  ,2*J-1) = imag(Y0(I,J));
  A(2*I  ,2*J  ) = real(Y0(I,J));
end
end
uix = 1;                                 %point to the first element
I=1;                                     %of input u[]
for J=1:NBUS
id = BUSTYPE(J,2);
  if (id<0)
                                         %handle load buses here
  end
  if (id>=0)                             %handle generator buses
```

```
if (id==4)                              %GEN_4
  Xdbar = XD11(I);
  Xqbar = XQ11(I);
  Epbar = [u(uix+1);                    %Eq"
           u(uix+2)];                   %Ed"
  ang = u(uix+3);                       %angle
  Del = [Del;ang];
  SX(I,2) = u(uix+3);
  SX(I,3) = u(uix);
  SX(I,4) = u(uix+2);
  SX(I,13) = u(uix+1);
  uix = uix + 4;

elseif (id==3)                          %GEN_3
  Xdbar = XD1(I);
  Xqbar = XQ1(I);
  Epbar = [u(uix);                      %Eq'
           u(uix+1)];                   %Ed'
  ang = u(uix+2);                       %angle
  Del = [Del;ang];
  SX(I,2) = u(uix+2);
  SX(I,3) = u(uix);
  SX(I,4) = u(uix+1);
  uix = uix + 3;

elseif (id==2)                          %GEN_2
  Xdbar = XD1(I);
  Xqbar = Xqs(I);
  Epbar = [u(uix); 0];                  %Eq', Ed'=0
  ang = u(uix+1);                       %angle
  Del = [Del;ang];
  SX(I,2) = u(uix+1);
  SX(I,3) = u(uix);
  SX(I,4) = 0.0;
  uix = uix + 2;

  elseif (id==1)                        %GEN_1
  Xdbar = Xds(I);
  Xqbar = Xqs(I);
  Epbar = [u(uix); 0];                  %Eq=cont, Ed=0
  ang = u(uix+1);                       %angle
  Del = [Del;ang];
  SX(I,2) = u(uix+1);
  SX(I,3) = u(uix);
  SX(I,4) = 0.0;
 uix = uix + 2;

 elseif (id==0)                         %Infinite Bus
  Xdbar = XD(I);
  Xqbar = XQ(I);
  Epbar = [u(uix); 0];                  %Vinf
  ang = u(uix+1);                       %angle
  Del = [Del;ang];
```

```
    SX(I,2) = u(uix+1);
    SX(I,3) = u(uix);
    SX(I,4) = 0.0;
   uix = uix + 2;
  end                                   %end internal if statement
Zi = [-R(I), -Xdbar;
      Xqbar, -R(I)];
T = [cos(ang)  sin(ang);                %transformation
     sin(ang) -cos(ang)];
YIP = T*inv(Zi)*T;                      %impetance matrix
                                        %of generator i
                                        %modify A matrix
A(2*J-1,2*J-1) =A(2*J-1,2*J-1)-YIP(1,1);
  A(2*J-1,2*J  ) =A(2*J-1,2*J  )-YIP(1,2);
  A(2*J  ,2*J-1) =A(2*J  ,2*J-1)-YIP(2,1);
  A(2*J  ,2*J  ) =A(2*J  ,2*J  )-YIP(2,2);
vn = [u(nu-2);u(nu-1)];                 %voltage at slack bus
Zi = YIP*T*Epbar;                       %Yi'*Ti*E'--Zi as temp use
                                        % T as temp use
T  = [A(2*J-1,2*NBUS-1), A(2*J-1,2*NBUS);
      A(2*J  ,2*NBUS-1), A(2*J  ,2*NBUS)];

  TEM = T*vn;                           %element of last column
                                        %of Y multiplied by vn
B(2*J-1,1) = -Zi(1,1) - TEM(1,1);
  B(2*J  ,1) = -Zi(2,1) - TEM(2,1);
  I = I+1;
  end                                   %end external if statement
  end                                   %end for  I loop
                                        %solve Ax = B equation
                                        %for voltage:Vxy--real&imag
                                        %Vcp--complex x+j*y vectors
  if (TIME>=Ts & TIME<Tp)               %fault handling
    Iff = Ifault;
    AP = zeros(2*NBUS-4,2*NBUS-4);
        I1 = 1;
    for I=1:2*NBUS-2
     if ( (I<2*Iff-1)  |  (I>2*Iff) )

        J1 = 1;
      for J=1:2*NBUS-2
          if ( (J<2*Iff-1)  |  (J>2*Iff) )
          AP(I1,J1) = A(I,J);
          J1 = J1 + 1;
          end
      end                               %for J
     BP(I1,1) = B(I,1);
     I1 = I1 + 1;
     end
    end

   VxyP = inv(AP(1:2*NBUS-4,1:2*NBUS-4))*BP(1:2*NBUS-4,1);
```

```
I1 = 1;
     for I=1:2*NBUS-2
     if (I<2*Iff-1|I>2*Iff)
        Vxy(I,1) = VxyP(I1,1);
        I1 = I1 + 1;
     else
        Vxy(I,1) = 0.0;
     end;
     end                                             %for I
  end                                                %for fault period

  if (TIME<Ts | TIME>=Tp)
    Vxy = inv(A(1:2*NBUS-2,1:2*NBUS-2))*B(1:2*NBUS-2,1);
  end

Vcp = [];
    for I=1:NBUS-1
    Vcp = [Vcp;Vxy(2*I-1)+i*Vxy(2*I)];
    end
  Vcp = [Vcp;u(nu-2)];
  Vxy = [Vxy;u(nu-2);0];

  Ixy = Y*Vcp;                                       %calculate injected current
                                                     %transform Ixy into
  vi_out = [];                                       %machine refence:Iqd=(2*NGEN-1,1)
I=1;
  for J=1:NBUS
    if (BUSTYPE(J,2)>=0)

    T = [cos(Del(I))  sin(Del(I));
         sin(Del(I)) -cos(Del(I))];
    Iqd = T*[real(Ixy(J));
             imag(Ixy(J))];

  vi_out = [vi_out;                                  % output Iqd,Vxy &
        Iqd(1,1);Iqd(2,1);                           %Ixy for each generator
        Vxy(2*J-1,1);Vxy(2*J,1);
        real(Ixy(J));imag(Ixy(J))];
    I = I + 1;
    end
  end

%update saturated parameters

saturat

%END OF PROGRAM
```

Table C.1 Parameters of the Two Generators

	Test Machine	Equivalent Machine
S_b	175.0	900.0
H	3.91	6.175
R_a	0.0032	0.0025
x_l	0.22	0.20
x_d	0.74	1.80
$x_d^{'}$	0.51	0.30
$x_d^{''}$	0.40	—
x_q	0.63	1.70
$x_q^{'}$	—	0.55
$x_q^{''}$	0.41	—
$\tau_{d0}^{'}$	4.73	8.00
$\tau_{d0}^{''}$	0.03	—
$\tau_{q0}^{'}$	—	0.40
$\tau_{q0}^{''}$	0.05	—
D	2.00	4.00
A_G	0.00003	0.00011
B_G	6.00	7.2

Table C.2 Parameters of the Excitation Systems

	Test Machine	Equivalent Machine
T_a	1.00	1.00
T_b	1.00–10.00	1.00–10.00
K_e	115.0	60.0
T_e	0.05	0.05
$E_{fd\,\min}$	–7.00	–7.00
$E_{fd\,\max}$	7.00	7.00

Table C.3 Parameters of the Speed-Governing and Turbine Systems

	Test Machine	Equivalent Machine
T_s	0.10	0.10
T_r	10.3	10.3
T_w	2.20	1.90
σ	0.05	0.05
δ	0.32	0.40
$(dG/dt)_{\min}$	–0.10	–0.10
$(dG/dt)_{\max}$	0.10	0.10
$G_{\min}$	0.00	0.00
$G_{\max}$	1.10	1.10